



# An economic evaluation of adaptation pathways in coastal mega cities: An illustration for Los Angeles

Lars T. de Ruig<sup>a,\*</sup>, Patrick L. Barnard<sup>b</sup>, W.J. Wouter Botzen<sup>a,c,d</sup>, Phyllis Grifman<sup>e</sup>, Juliette Finzi Hart<sup>b</sup>, Hans de Moel<sup>a</sup>, Nick Sadrpour<sup>e</sup>, Jeroen C.J.H. Aerts<sup>a</sup>

<sup>a</sup> Institute for Environmental Studies (IVM), VU University Amsterdam, De Boelelaan 1085, 1081, HV, Amsterdam, the Netherlands

<sup>b</sup> United States Geological Survey, Pacific Coastal and Marine Science Center, 2885 Mission St, Santa Cruz, CA 95060, USA

<sup>c</sup> Center for Risk Management and Decision Processes, The Wharton School, University of Pennsylvania, Philadelphia, USA

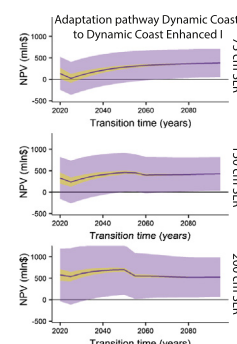
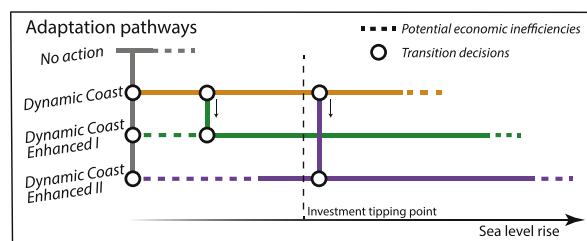
<sup>d</sup> Utrecht University School of Economics, Utrecht University, Kriekenpitplein 21-22, 3584 EC Utrecht, the Netherlands

<sup>e</sup> University of Southern California Sea Grant, 3454 Trousdale Pkwy, CAS 200, Los Angeles, CA 90089, USA

## HIGHLIGHTS

- Adaptation pathways can provide flexibility in difficult adaptation investment choices.
- A coastal flood risk analysis with a cost-benefit framework evaluates adaptation pathways.
- Adaptation pathways can be more economically efficient than a single adaptation strategy.
- If a transition is made after an investment tipping point, economic efficiency of a pathway decreases.
- Adaptation pathways should be adopted in conventional flood risk evaluation studies.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Sea level rise and uncertainty in its projections pose a major challenge to flood risk management and adaptation investments in coastal mega cities. This study presents a comparative economic evaluation method for flood adaptation measures, which couples a cost-benefit analysis with the concept of adaptation pathways. Our approach accounts for uncertainty in sea level rise projections by allowing for flexibility of adaptation strategies over time. Our method is illustrated for Los Angeles County which is vulnerable to flooding and sea level rise. Results for different sea level rise scenarios show that applying adaptation pathways can result in higher economic efficiency (up to 10%) than individual adaptation strategies, despite the loss of efficiency at the initial strategy. However, we identified 'investment tipping points', after which a transition could decrease the economic efficiencies of a pathway significantly. Overall, we recommend that studies evaluating adaptation strategies should integrate cost-benefit analysis frameworks with adaptation pathways since this allows for better informing decision makers about the robustness and economic desirability of their investment choices.

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\* Corresponding author at: Institute for Environmental Studies (IVM), VU University Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, the Netherlands.

E-mail address: [Lars.de.Ruig@vu.nl](mailto:Lars.de.Ruig@vu.nl) (L.T. de Ruig).

## 1. Introduction

Coastal floods are devastating natural disasters, particularly in highly urbanized regions, causing the loss of life for thousands of people in 2017 alone (Munich, 2018; Vitousek et al., 2017a). Climate change and sea level rise further increase the frequency and severity of flood hazards (IPCC, 2014), while population growth and economic growth further exacerbate flood exposure in low-lying coastal areas. Urgent action is needed to anticipate future losses, but designing and evaluating long-term adaptation strategies is a complex and challenging process for decision makers (Hinkel et al., 2018). For example, a recent study by DeConto and Pollard (2016) reveals that future global sea level rise projections of approximately 0.5 m to 1 m (~1.6 to 3 ft) by 2100 (Horton et al., 2014; IPCC, 2014) may be underestimated due to a better understanding of the instability of the Antarctic Ice Sheet. The rates of sea level rise are likely to accelerate more rapidly than initially anticipated, possibly resulting in a sea level rise of ~3 m (~10 ft) or even higher by 2100 (Hansen et al., 2016; Le Bars et al., 2017; Sweet et al., 2017). Such uncertainty in sea level rise projections poses a challenge to flood management, because flood adaptation often requires large capital investments over a long lifespan. In such cases, decision makers fear making suboptimal, irreversible choices. Consequently, adaptation decisions are often postponed until the next disaster strikes the region (Aerts et al., 2018a, 2018b).

Several techniques of economic appraisal have been developed to support policy makers with adaptation decisions, but these often have limitations in coping with climate change uncertainty (Simpson et al., 2016; Watkiss et al., 2015). Real options analysis (ROA), robust decision making (RDM), and iterative risk management (IRM) are examples of tools or frameworks that specifically address future uncertainty. As illustrated by Kind et al. (2018), ROA can identify optimal short-term investments in flood risk management, and values options of taking adaptation measures in the future, for example under high climate scenarios. Other illustrations of how to apply ROA for evaluating flood risk adaptation measures are Buurman and Babovic (2016) and Hino and Hall (2017). However, ROA is often constrained by data limitations (Simpson et al., 2016; Watkiss et al., 2015). As illustrated by Kind et al. (2018), ROA requires the recognition of relevant sources of uncertainty which need to be quantified, integrated and discretized in scenarios, requiring subjective choices and expert judgement. RDM aims to identify options for adaptation strategies that are expected to perform well over a wide range of future scenarios, but it does not optimize the economic efficiency of these strategies. For example, Sriver et al. (2018) have applied RDM to evaluate a range of climate and socio-economic scenarios for the port of Los Angeles. Similar to ROA, due to RDM's probabilistic nature, a lack of quantitative probabilistic data can limit the effectiveness or applicability (Watkiss et al., 2015). IRM is a framework that iteratively cycles through the different steps of identification, quantification and assessment of risk, to adjust or change adaptation management strategies when necessary. Within this framework, policy makers and analysts are able to await new information on uncertainties over time (Simpson et al., 2016).

In line with IRM, Haasnoot (2013) and others (e.g., Kwakkel et al., 2016; Reeder and Ranger, 2011) suggest the use of “adaptation pathways” to deal with the uncertainty of future conditions. Adaptation pathways are defined as a sequence of adaptation actions or strategies over time, such as beach nourishment, building new levees, and floodproofing buildings, which anticipate uncertain and changing risk conditions, such as sea level rise (Haasnoot, 2013; Kwakkel et al., 2016). The use of adaptation pathways aims to enable a transition from one strategy to another over time, allow for flexibility among policies, cope with uncertainty, and potentially spread the adaptation costs over time. The approach has predominantly been applied in conceptual adaptation studies (e.g., Dawson et al., 2011; Haasnoot, 2013; Haasnoot et al., 2012; Reeder and Ranger, 2011), or in physically based models in which thresholds are estimated for determining pathway transitions

(e.g., Kwakkel et al., 2015). Adaptation pathways are getting more traction recently in economic evaluation studies, such as in combination with ROV (e.g., Buurman and Babovic, 2016; Erfani et al., 2018; Greater Wellington Regional Council, 2015; Infometrics, 2017; Lawrence et al., 2019) or as applied in Haasnoot et al. (2019) and Lawrence and Haasnoot (2017).

Cost–benefit analyses (CBAs) are commonly used to support decision makers in adaptation decisions, as they are often easy to implement and communicate (Hallegatte et al., 2012; Hunt and Watkiss, 2011; Kunreuther et al., 2014). However, they are ‘static’ in nature, and not designed to consider uncertainty. A few studies have addressed future uncertainties by using scenarios to simulate changes in exposure, hazard, or vulnerability (e.g., Aerts et al., 2014a; Mechler, 2016; Ward et al., 2017). Such an approach offers insights into which adaptation strategies are economically desirable in certain flood risk scenarios. However, a disadvantage of such “static” scenario-based approaches is that they have little flexibility in assessing the economic feasibility of changing adaptation options or are bound to a set of climate change projections that have a high degree of uncertainty (Hunt and Watkiss, 2011; Kunreuther et al., 2014). Some initial studies have applied a scenario-based CBA to assess the feasibility of implementing adaptation measures at different points in time—for example, by delaying investments that are not cost effective in the present (Aerts et al., 2014a; Mechler, 2003). However, these assessments still use static, inflexible adaptation strategies that generate suboptimal outcomes.

In this paper, we present a comparative risk evaluation method that couples a scenario-based CBA approach with the concept of adaptation pathways. In doing so, the framework allows us to assess triggers that indicate if a pathway transition is economically efficient, without requiring localized probabilistic data of scenarios, like would be needed in a realistic ROA application (Kind et al., 2018). Applied to coastal flood adaptation in Los Angeles County (LAC), both current- and future coastal flood risk has been simulated for various sea level rise scenarios. Using the risk projections, three CBAs were conducted: CBA-I, a standard scenario-based CBA of potential adaptation strategies; CBA-II, with different investment timings of adaptation strategies, and; CBA-III, a CBA of an adaptation pathway following a transition from one strategy to another over time, that allows for flexibility of adaptation over time. The three different CBA approaches are compared and provide insights in the individual economic efficiency of the strategies and the timing of investments.

## 2. The impact of sea level rise in Los Angeles County

Los Angeles County is an illustrative example of a major metropolitan area (population of 9.8 million) that is vulnerable to coastal flooding due to its low-lying geography and high exposure of economic assets (DeConto and Pollard, 2016; Hallegatte et al., 2013). With 120 km of coastline on the Pacific Ocean, flooding in Los Angeles County is primarily caused by tides, storm surges, wave-driven run-up, or a combination of these factors (Barnard et al., 2014; Erikson et al., 2018; O'Neill et al., 2018). Los Angeles County is currently already vulnerable to high tides and coastal storms. For example, in 2010, a storm fueled by El Niño produced waves of 7.5 m (22 ft) in height, causing significant coastal erosion and flooding in some of the coastal communities (Barboza, 2010; Lin, 2010). Sea level rise is expected to exacerbate these conditions; the National Research Council projects a sea level rise of 0.93 m (3 ft) by 2100 for the State of California (NRC, 2012). However, a recent study presents a worst-case sea level rise scenario for Southern California of 3 m (10 ft) by 2100 (Griggs et al., 2017). In addition, socioeconomic projections (population and economic growth) indicate an increase in the exposure of assets in the future (e.g., in the ports of Los Angeles and Long Beach (Aerts et al., 2018a, 2018b)). The exposure of current buildings and infrastructure for a 100-year flood is estimated at >\$6 billion (Aerts et al., 2018a, 2018b; Grifman et al., 2013) in a high sea level rise scenario of 1.5–2 m (4.5–6 ft). Studies have focused

on the physical aspects of sea level rise, such as beach erosion rates (USGS, 2015), or have assessed beach nourishment volumes required to compensate for different erosion rates due to sea level rise (Flick and Ewing, 2009). In addition, King et al. (2016, 2011) assessed the economic costs (e.g., loss of tourism revenues) of a 100-year probability storm in various sea level rise scenarios for California.

As the Los Angeles County's coast is geographically diverse in terms of natural environment and built-up development, various types of adaptation measures have been proposed for different areas to reduce the effects of sea level rise (Grifman et al., 2013). We identified six main coastal segments of Los Angeles County (see Fig. 1): Malibu, Santa Monica & Venice Beach, South Bay, the Ports of Los Angeles and Long Beach (LA & LB), the residential back area of the ports (Wilmington/West Side), and Long Beach. Each of these subsections of the coast have a certain vulnerability to flooding, but often specific characteristics. For example, risk in Malibu is mainly composed of damages to high-value residential properties on the beach, while Santa Monica & Venice Beach experience most damages after overtopping of the marina in high sea level rise events. In the results, we will mainly focus on Long Beach, as it shows some observations most clearly. The full results of all areas are attached in the supplementary data (SI2).

### 3. Methods

Fig. 2 shows an overview of the methodological framework used in this paper. The designs of the adaptation strategies are developed by Aerts et al. (2018a), and they are briefly summarized in Section 3.1. Flood risk, in terms of expected annual damage (EAD), is calculated based on the flood hazard, vulnerability, and exposure of the assets. The flood hazard is derived from the Coastal Storm Modelling System (CoSMoS) model (Barnard et al., 2014; Erikson et al., 2018; O'Neill et al., 2018), which simulates flood hazard (extent and depth) for storms of different return periods in different sea level rise scenarios (75-, 150- and 200 cm by 2100). Exposure of buildings is derived from a local building footprint map and vulnerability information is based on the HAZUS MH model (FEMA, 2013). With this, flood damage (for a single flood map) and risk (combining various return periods) can be calculated, which is described in Section 3.2. In addition, the loss in co-benefits from beaches (area and width of a beach) in terms of recreational values of coastal ecosystems are estimated (Ghermandi and Nunes, 2013), using CoSMoS' (future) changes in beach extent due to

erosion (Section 3.2.2; Vitousek et al., 2017b). The risk projections (with and without adaptation) are used as input for three CBAs: (CBA-I) a scenario-based CBA for the different adaptation strategies, (CBA-II) a CBA where investments are delayed, and (CBA-III) a CBA of adaptation pathways, allowing change from one strategy to another – each described in Section 3.3. Within our framework, the economic efficiency indicators act as triggers to determine the timing of a transition from one strategy to another. Therefore, monitoring of sea level rise is essential to collect new information over time. For example, a sudden increase of the observed rate of sea level rise, acting as a signpost or an early warning, can shift the economic efficiency of the adaptation strategies or pathways.

#### 3.1. Adaptation strategies

Based on the designs of adaptation strategies for Los Angeles made by a recent study (Aerts et al., 2018a, 2018b), three main adaptation strategies were evaluated in the CBA framework: Dynamic Coast (DC), Dynamic Coast Enhanced I (DCE-I), and Dynamic Coast Enhanced II (DCE-II). In a 3-year participatory stakeholder approach (see also Aerts et al., 2018a), each strategy was designed to protect the municipality against three sea level rise scenarios: 75-, 150- and 200 cm (2.5 ft., 4.9 ft. and 6.6 ft., respectively), by 2100 (following Griggs et al., 2017). Beaches are an important asset in LAC, and current policies strive to preserve the current shape and dynamics of beaches. Therefore, all adaptation strategies were based on beach nourishment and dune restoration projects, keeping the coastline as it currently is. Each strategy was tailored using specific measures for the six main coastal segments of LAC: Malibu, Santa Monica, South Bay, the Ports of Los Angeles & Long Beach (LA&LB), the residential back-area of the ports (Wilmington/West Side), and Long Beach. Table 1 gives an overview of the different measures per subsection of the LAC coast, with an estimate of the costs. The combination of measures per strategy is necessary to protect the LAC coast, while satisfying the needs of stakeholders. The adaptation strategies include measures being implemented over time based on the pace of sea level rise (e.g., beach nourishment), and between strategies some measures overlap while others supersede. While the number of possible pathways might seem limited at first sight, the intricacy of individual measures (over time or stationary) within the strategies and the major differences between areas (in terms of risk and measures, e.g., floodproofing, sluices or dikes

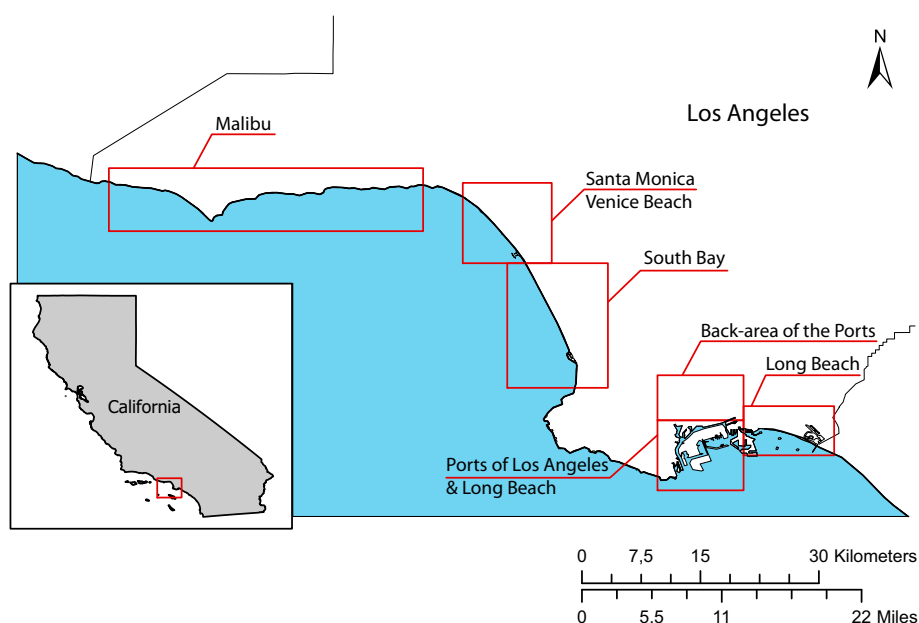
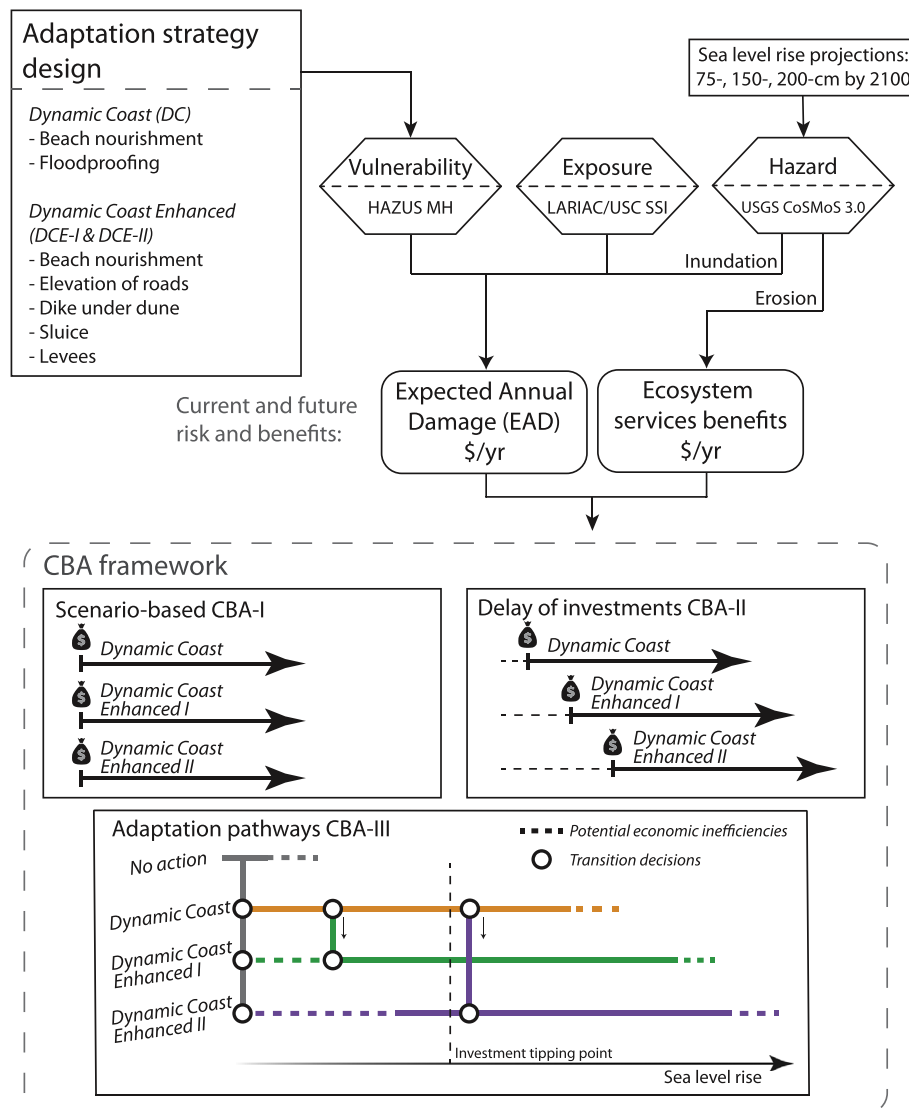


Fig. 1. An overview of the different regions of the Los Angeles County coast, as referred to in the paper.



**Fig. 2.** An overview of the methodological framework used in this paper. A flood risk model is used to compute the flood risk for three sea level rise scenarios and with- or without adaptation measures. In addition, the ecosystem service benefits are calculated. The cost-benefit analysis framework consists of three components: (i) a scenario-based CBA, (ii) a delay of investments over time, and (iii) adaptation pathways.

underneath beaches) should provide insights into the complex interactions of a transition from one strategy to another.

In the DC strategy, open entrances to harbors and ports were maintained, but because sea level rise will increasingly threaten low-lying neighborhoods, buildings in the (future) 100-year flood<sup>1</sup> zone are floodproofed or elevated (FEMA, 2014). We applied two floodproofing measures each with a height of 1.2 m (4 ft): wet-floodproofing (minimizing damage when flood waters enter buildings) and dry-floodproofing (preventing flood water from entering the structure). According to FEMA regulations (FEMA, 2014), dry-floodproofing is not suitable for coastal storm surge zones and should be wet-floodproofed or elevated instead. Hence, in areas with coastal storm surge zones, dry-floodproofing is avoided. Dry-floodproofing and wet-floodproofing were only applied to residential and commercial buildings and not to other types of buildings, such as education-, agriculture-, and industry buildings. All floodproofing and elevation measures are implemented in phases based on the different sea level rise scenarios. In 2020, the first investment is made for all buildings in

the 100-year flood extent including 75 cm of sea level rise. Based on the average inundation depths, additional investments are made in the 150 cm scenario to increase the mandatory floodproofing extent (in 2059), and additional investments are made twice in the 200 cm scenario (in 2051 and 2076). If a flood zone reaches an average inundation depth of 1.2 m (4 ft), the effectiveness of each measure changes: (a) For dry-floodproofing, the risk reduction efficiency drops to 0%, as flood water overtops the measure and still enters and damages the property, and (b) for elevation and wetproofing the benefits of the adaptation measure stagnate and do not increase further. The average inundation was calculated per area for the 100-year flood extents for each sea level rise scenario.

In DCE strategies, beach nourishment is complemented with protective measures, such as sluices to protect harbors, and highly vulnerable areas are reinforced with additional levees—in some locations buried under dunes to preserve landscape values. As seen in Table 1, DCE-I is a strategy that protects the Ports and their back area, including outwards expansion of the Ports and major land-use and infrastructural changes in its surroundings. This strategy is further referred to as DCE-I Ports of LA & LB. The suggested combination of measures in the DCE strategies was designed for a future 1/1000-year protection standard.

<sup>1</sup> A 100-year storm is defined as a flood event that statistically has a 1% chance of occurring per year.



**Table 1**

An overview of the three adaptation strategies and their estimated costs per subsection of the Los Angeles County coast (some subsections do not have all strategies, depicted as n.a.).

Area	Dynamic Coast (DC)		Dynamic Coast Enhanced I (DCE-I)		Dynamic Coast Enhanced II (DCE-II)	
	Adaptation measures	Cost estimates <sup>a</sup> (mln\$)	Adaptation measures	Cost estimates <sup>a</sup> (mln\$)	Adaptation measures	Cost estimates <sup>a</sup> (mln\$)
Malibu	- Beach nourishment - Elevation of buildings - Pacific Coastal Highway elevation	378–502	n.a.	n.a.	n.a.	n.a.
Santa Monica/Venice	- Beach nourishment - Dry floodproofing - Breakwater, groins, jetties, bulkheads	547–1147	- Beach nourishment - Dike under beach - Road as levee - Wet flood proofing - Breakwater, groins, jetties and bulkheads	735–1146	- Beach nourishment - Dike under beach - Sluice - Breakwater, groins, jetties and bulkheads	880–1052
South Bay	- Beach nourishment - Elevation of buildings - Breakwater, groins bulkheads	338–685	- Beach nourishment - Road as levee - Breakwater, groins, bulkheads	467–791	n.a.	n.a.
Ports of LA&LB	- Beach nourishment - Elevation of buildings - Breakwater, bulkheads	1160–2193	<sup>b</sup> - Expansion of the port + levees - Sluice - Dike	1232–1237	n.a.	n.a.
Port back area (Wilmington/West Side)	- Dry floodproofing	103–232			- Road as levee	203–310
Long Beach	- Beach nourishment - Elevation of buildings - Jetties, bulkheads	548–963	- Beach nourishment - Sluice - Dike under beach	786–952	- Beach nourishment - Sluice - Road as levee - Elevation of buildings	712–878

<sup>a</sup> Some strategies have investments in the future, and all strategies have maintenance costs. The estimates shown here are total present value costs, discounted using a 4% discount rate.

<sup>b</sup> Referred to as Ports of LA&LB DCE-I.

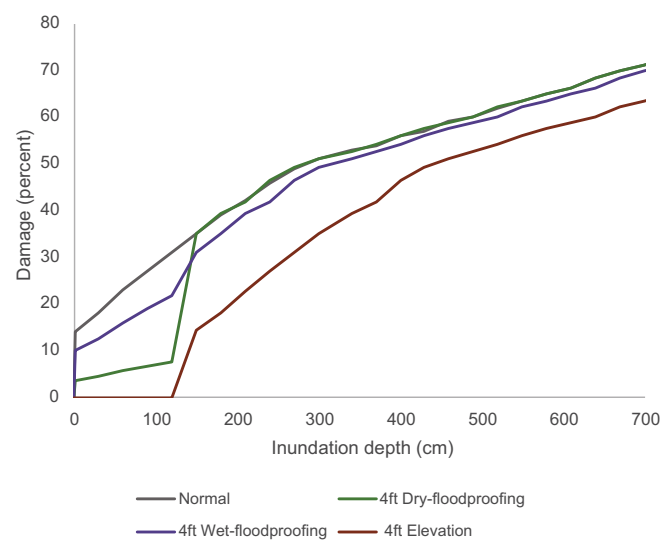
For both DC and DCE strategies, the lifespan of all measures was assumed to be 100 years. For the delayed investments and adaptation pathways, floodproofing or structural adaptation measures can therefore provide benefits after 2100. However, beach nourishment volumes and reinforced flood management infrastructures (e.g., groins, breakwaters, jetties, and levees) were upgraded for every 0.6 m (2 ft) of sea level rise. If we would expand these measures beyond 2100, more upgrades per 0.6 m (2 ft) of sea level rise are necessary beyond 2100. However, this would change the undiscounted investment costs of the static and delayed strategies and would make them incomparable in terms of economic efficiency. Therefore, the benefits to tourism, ecosystems and limiting erosion from beach nourishment, only last until the last upgrade before 2100 has been exceeded by sea level rise. In the 75 cm scenario, the benefits can last until 2140, in the 150 cm scenario until 2113, and in the 200 cm scenario until 2112. To stay consistent, we linearly extrapolated beach nourishment volumes at the same rate as we did with sea level rise (see Section 3.2.1).

### 3.2. Models & data

In this study, storm simulations for current and future climate conditions were calculated using the U.S. Geological Survey (USGS) Coastal Storm Modeling System (CoSMoS 3.0) (Barnard et al., 2014). These simulations form the basis for determining what assets and people are vulnerable to sea level rise in combination with storms and which locations may require adaptation measures to reduce future flood risk. CoSMoS couples atmospheric and hydrodynamic computer models to estimate flood hazard potential from coastal storms, sea level rise, and shoreline change. Winds, sea level pressures, and sea surface temperatures are derived from global climate models to compute total water levels on a regional scale until 2100 (for details, see Barnard et al., 2014). Regional storm conditions are then dynamically downscaled using a set of nested Delft3D wave (SWAN) and tide (FLOW) models and linked at the coast-to-river discharge projections, fine-scale estuary models, and along the open coast to closely spaced XBeach (eXtreme Beach) cross-shore profile models. The results provide projected total water levels along the California coast for different storms (e.g. 20-, and 100-year flood

events), and they include modeling of 10 different sea level rise scenarios ranging from 0 to 2 m (0–6.6 ft), as well as an extreme five-meter (16 ft) sea level rise.

Building exposure data was derived from the Los Angeles Region Imagery Acquisition Consortium (LAR IAC) (Greninger, 2014) and University of Southern California Spatial Sciences Institute (USC SSI) parcel data (USC SSI, 2016), providing a dataset with characteristics of individual buildings. Exposure and flood hazard data were combined in the HAZUS MH model to estimate losses per building, using depth-damage curves and maximum damage values for each type of building (Aerts et al., 2013; de Moel et al., 2013; FEMA, 2013). We modified the depth-damage curves in the HAZUS MH model to simulate the risk reducing effect of building scale adaptation measures. For dry-



**Fig. 3.** An example of a depth-damage curve for a residential single-family dwelling without adaptation, and with 4 ft. of each adaptation measure based on FEMA (2013) and Aerts et al. (2014a).

floodproofing and wet-floodproofing, we used the lower bound of the effectiveness of the measures in reducing risk, as used in Aerts et al. (2014b); namely, 75% and 30% reduction in risk, respectively. For elevation, the depth-damage curve remains zero until the elevation height. Example depth-damage curves are shown in Fig. 3.

### 3.2.1. Expected annual damage

Current expected annual damage (EAD) or 'risk' (\$/yr) is calculated based on the damage per storm, as the integral of the exceedance probability curve. The EAD was calculated for different sea level rise scenarios, and for each area (Malibu, Santa Monica, etc.) for both the current and future situation (Table S4). Due to the limited number of events provided by CoSMoS, we assume (i) no damage for more frequent events with probability higher than 10-year, and (ii) the 100-year storm damages are used as the potential maximum lower probability event. While we are aware that nuisance flooding and more extreme events can contribute to total risk (Moftakhari et al., 2017), this approach will provide us with a conservative estimate of risk despite the limited number of available events. However, similar studies (e.g., Ward et al., 2017) often assume no damages for frequent events as nuisance flooding is often prevented by homeowners themselves. For example, in Malibu homeowners have privately funded temporary revetments and are planning beach nourishment efforts to reduce flood risk (Mofatt and Nichol, 2011).

In addition, since HAZUS simulations only pertain to direct damages to buildings, we use two scaling factors: (a) for estimating indirect economic damages (e.g., business interruption) following Aerts et al. (2014a). The literature shows that indirect damage could increase direct damages by a factor of 1.5 (Hallegatte, 2015, 2006). However, we recognize that different areas would face different indirect impacts (Koks, 2016). For example, the industrial ports are two of the largest ports of the U.S. and are expected to suffer a significantly higher indirect impact than, for example, the residential Malibu area. Therefore, we applied an indirect damage factor of 2 to the port, and a factor of 1.16 to the other areas so that the total indirect damage averaged to a factor 1.5, calibrated on the present risk. (b) another scaling factor was applied to include direct damages to infrastructure and vehicles. A factor has been applied, based on the detailed damage assessments by the U.S. government after Hurricane Sandy (NYS, 2012). These factors were applied to our risk estimates, assuming a constant ratio between total direct damage of an event and risk.

The benefit for each adaptation strategy was calculated according to how much the EAD was reduced over the lifetime of the adaptation measures. Because some adaptation measures have a lifespan beyond 2100, the sea level rise projections were extrapolated to estimate (reduced) risk beyond 2100, and these extended risk estimates were used in the CBA. We linearly extrapolated the sea level rise curves with a rate of 1.1 cm, 2.6 cm and 3.6 cm per year for the 75-, 150- and 200 cm sea level rise scenarios respectively, which is in the conservative bounds of Griggs et al.'s (2017) projections. Subsequently, the CoSMoS 500 cm sea level rise scenario (+16.4 ft) was used to interpolate risk.

### 3.2.2. Co-benefits from beach nourishment

Co-benefits from beach nourishment, such as ecosystem services, were also calculated. We used the study by Ghermandi and Nunes (2013) to determine the potential economic loss for ecosystem services from the decline of future beach width and surface due to erosion and sea level rise, as simulated by CoSMoS. In our analysis, these losses are avoided by beach nourishment, resulting in an average economic benefit of 48,316.09 \$/ha/yr through beach nourishment (see Table S1). In addition, beaches will retain their protective qualities when nourished. While CoSMoS' inundation maps include erosion, we sampled a proxy to account for these benefits (see SI1.1.).

To test the robustness of the overall modeling approach, we performed a sensitivity analysis using an uncertainty range similar to Aerts et al. (2014a) who did a comprehensive uncertainty analysis of

another flood damage model with a similar overall setup as ours. Depth-damage curves and hydraulic boundary conditions are found to be the two most important sources of uncertainty. As these are completely uncorrelated, their effect can be added up to derive total uncertainty in risk –estimated to be around –50% and +50% (Aerts et al., 2014b). In addition, costs estimations of adaptation strategies are associated with uncertainty for both investment costs and maintenance costs. We adopt an uncertainty interval of –20% and +20% on the cost estimates of the adaptation strategies following Aerts (2018). Both intervals are applied one at a time.

### 3.3. Cost-benefits analysis

We here describe the CBA framework: (CBA-I) a *scenario-based* approach, with an analysis of (CBA-II) the effect of a *delay* of investments in the three strategies (DC, DCE I and DCE II), and (CBA-III) a CBA of *adaptation pathways*, transitioning from one strategy to another.

#### 3.3.1. CBA-I, Scenario-based

With the conventional scenario-based CBA, investments are made in 2020 and the same measures remain in place for their lifespan (100 years). We adopted discount rates of 4% and 7%, respectively, which are commonly applied in such studies in the United States (Aerts et al., 2014a; Hallegatte et al., 2012), and we used the Net Present Value (NPV) and Benefit-Cost Ratio (BCR) as economic efficiency indicators:

$$NPV = \sum_{t=1}^T \frac{B_t - C_t}{(1+r)^t} - C_0 \quad (1.1)$$

$$BCR = \frac{\sum_{t=1}^T \frac{B_t}{(1+r)^t}}{\left( \sum_{t=1}^T \frac{C_t}{(1+r)^t} - C_0 \right)} \quad (1.2)$$

Eq. (1.1) shows the NPV and Eq. (1.2) the BCR with  $t$  the time in years, starting in 2020,  $T$  the lifespan of the measures,  $r$  the discount rate,  $C_0$  the initial investment costs, and  $B_t$  and  $C_t$  the benefits and costs per year, respectively.

#### 3.3.2. CBA-II, delayed investments

In some instances, it can be economically more efficient to postpone the implementation of adaptation strategies: flood risk will increase over time and thus the effects of adaptation measures become relatively more beneficial in the future. The delayed NPV<sub>d</sub> (Eq. (2.1)) and BCR<sub>d</sub> (Eq. (2.2)) require the initial investment costs also to be discounted in the delayed year  $t_d$ :

$$NPV_d = \sum_{t=t_d}^{T+t_d} \left( \frac{B_t - C_t}{(1+r)^t} - \frac{C_i}{(1+r)^{t_d}} \right) \quad (2.1)$$

$$BCR_d = \frac{\sum_{t=t_d}^T \frac{B_t}{(1+r)^t}}{\sum_{t=t_d}^T \left( \frac{C_t}{(1+r)^t} - \frac{C_i}{(1+r)^{t_d}} \right)} \quad (2.2)$$

$$t_d > 1$$

#### 3.3.3. CBA-III, pathways

To address the option of adaptation pathways, we first simulated a transition from the DC strategy to DCE strategies, in varying time periods. Because the DCE strategy is designed according to higher flood protection standards, it only makes sense to transition from DC towards the DCE, and not in reverse. In such a transition, some adaptation

measures (e.g., beach nourishment and upgrade of groins) are already implemented, and their costs are (partly) accounted for in the old DC strategy. A transition into a new DCE strategy (e.g., dike under beach, elevation of roads as levees or sluices) would require additional investments at the time of transition. DC is always implemented in 2020, while a transition to DCE-I or DCE-II can occur in 5-year intervals from 2025 until 2095. In such transitions, full investment costs are taken into account for floodproofing and elevating buildings according to the DC strategy, while the economic efficiency of these measures significantly decreases if their lifespan overlaps with the implementation of an investment in a new levee. In such cases, floodproofing measures for buildings only reduce damages of storms with a probability of 1/1000-years or lower (i.e. when the new levees are overtopped by floodwaters). In Eqs. (3.1) and (3.2), subscript 1 indicates the initial DC strategy, while subscript 2 indicates the transition into the DCE strategy.

$$NPV_a = \sum_{t=1}^{t_d} \frac{B_{1,t} - C_{1,t}}{(1+r)^t} - C_{1,i} + \sum_{t=t_d}^{T+t_d} \left( \frac{B_{2,t} - C_{2,t}}{(1+r)^t} - \frac{C_{2,i}}{(1+r)^{t_d}} \right) \quad (3.1)$$

$$BCR_a = \frac{\sum_{t=1}^{t_d} \frac{B_{1,t}}{(1+r)^t} + \sum_{t=t_d}^{T+t_d} \frac{B_{2,t}}{(1+r)^t}}{\sum_{t=1}^{t_d} \frac{C_{1,t}}{(1+r)^t} + C_{1,i} + \sum_{t=t_d}^{T+t_d} \left( \frac{C_{2,t}}{(1+r)^t} + \frac{C_{2,i}}{(1+r)^{t_d}} \right)} \quad (3.2)$$

$t_d > 5$

## 4. Results

### 4.1. Scenario-based cost-benefit analysis (CBA-I) and delays in investments (CBA-II)

We first applied the scenario-based CBA-I method to assess the economic desirability of implementing the three adaptation strategies (DC, DCE-I, DCE-II) in 2020, assuming the three sea level rise scenarios 75-, 150- and 200 cm by 2100. Uncertainty bands were provided for economic efficiency indicators (NPVs and BCRs), related to uncertainty in risk and cost estimates. Here, we discuss the results for Long Beach (Table 2), the other areas are presented in the electronic supplementary information; Table S5. The results for Long Beach indicate that the DC, DCE-I, and DCE-II strategies are all economically efficient in each sea level rise scenario when the strategies are implemented in 2020, with NPVs ranging between \$137.1 (DCE-I, 75 cm sea level rise) and \$662.8 mln (DCE-II, 200 cm sea level rise) and BCRs ranging between 1.21 and 2.17. While the DC strategy performs best for the lower sea level rise scenarios (higher BCRs and more robust), the DCE-II results in the highest economic efficiency for a 200 cm sea level rise scenario. The uncertainty interval for cost estimates is relatively robust for all strategies,

but the interval for risk shows a bigger uncertainty range. In most scenarios the lower bound of the risk uncertainty interval drops below zero. DC in the 75 cm sea level rise scenario and DCE-II in the 200 cm sea level rise scenario show robustness for both uncertainty intervals.

We further explored the effects of a delayed investment in CBA-II. Fig. 4 depicts the NPV of implementing the strategies in different moments in time due to a delay in investments for Long Beach. As an illustration, when the DC strategy in a 75 cm sea level rise scenario is implemented in 2020 it will yield an NPV of \$331.8 mln, but if the investments are delayed until 2040, the strategy will only yield an NPV of \$249.5 mln. The upper panels of Fig. 4 show that for the DC strategy, a delay in investments will only decrease economic efficiency under each of the three sea level rise scenarios. However, for the DCE-I strategy, Fig. 4 shows that economic efficiencies increase after a slight delay of investments but decrease if the delay in investments is too long. For example, under the 200 cm sea level rise scenario, the optimal moment to invest in DCE-I is around the year 2035 yielding the highest NPV of \$636.1 mln, compared to \$576.5 mln if DEC-I is implemented in 2020. The delay to 2035 results in a 10.3% increase in efficiency. Nonetheless, waiting too long to invest may result in significant decreases in economic efficiency. For instance, delaying DCE-I until around 2055 sea level results in an NPV that is below the level that can be reached by investing in 2020 under the 200 cm sea level rise scenario. The other areas and the outcomes with a 7% discount rate are presented in the electronic supplementary information; Figs. S1 to S12.

### 4.2. Adaptation pathways (CBA-III)

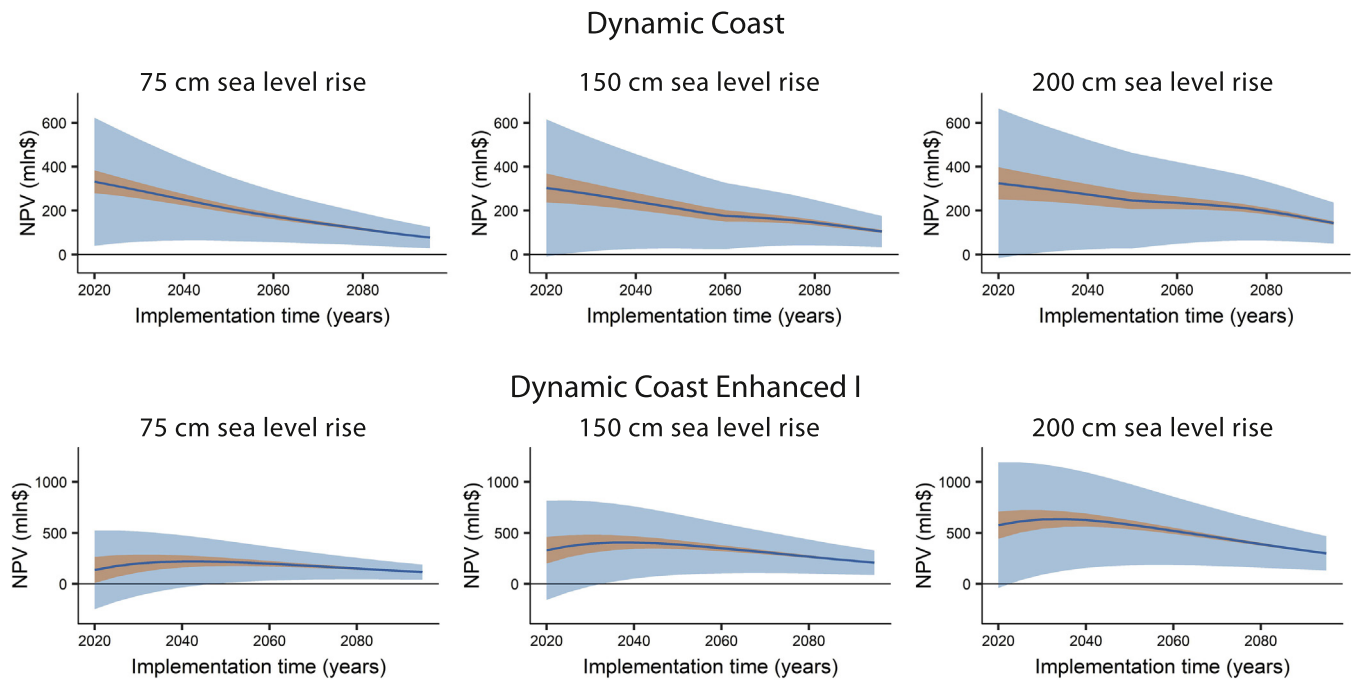
The DC strategy often performs better under the lower sea level rise scenarios when it is directly implemented in 2020, especially considering robustness (see CBA-I results). The delayed investment results indicate that some DCE-I and DCE-II strategies yield more optimal NPVs under high sea level rise scenarios and when investments of these strategies are delayed in time. Hence, pursuing an adaptation pathway that initially implements a DC strategy and eventually transitions to one of the DCE strategies might be economically beneficial. Fig. 5 presents the NPV values of such a pathway for Long Beach under each sea level rise scenario. The x-axis represents the year in which a transition is made. Therefore, the first time step (2020) is a direct transition to DCE, without implementing DC. Subsequently, in 5-year increments, the NPV is shown when DC is implemented in 2020, and a transition is made to one of the DCE strategies in the associated transition years.

The initial drop of the NPV in 2025 is explained by a significant loss of investments of the DC strategy. The adaptation strategy is only fully effective for 5 years; after a transition to DCE is made, the building level adaptation measure will only provide benefits if the 1/1000-year protection standard of DCE is exceeded. If a transition is made later in time, economic efficiency increases, even exceeding the highest efficiencies reached by any of the delayed investment options, which will be discussed in more detail in Section 4.3. For a pathway with a

**Table 2**

Scenario-based CBA-I results for Long Beach showing the economic efficiency of the three adaptation strategies in terms of NPV and BCR per sea level rise scenario. Uncertainty ranges are provided between parentheses for risk estimates ( $\pm 50\%$ ) and cost factors ( $\pm 20\%$ ). The NPV and BCR simulations for the other areas are found in the electronic supplementary information; Table S5.

Long beach		Dynamic coast		Dynamic coast enhanced-I		Dynamic coast enhanced-II	
SLR	Discount rate 4%	NPV (mln\$)	BCR	NPV (mln\$)	BCR	NPV (mln\$)	BCR
75 cm	Baseline	331.8	2.28	137.1	1.21	198.6	1.35
	Risk uncertainty	(40.4;623.3)	(1.16;3.4)	(-247.8;521.9)	(0.61;1.81)	(-184.0;581.3)	(0.68;2.01)
	Costs uncertainty	(280.0;383.7)	(1.9;2.85)	(8.9;265.2)	(1.01;1.52)	(83.7;313.6)	(1.12;1.68)
150 cm	Baseline	303.8	1.92	329.6	1.5	388.0	1.66
	Risk uncertainty	(-8.1;615.8)	(0.98;2.87)	(-157.2;816.4)	(0.76;2.25)	(-95.0;871.0)	(0.84;2.48)
	Costs uncertainty	(237.9;369.7)	(1.6;2.4)	(199.0;460.3)	(1.25;1.88)	(270.6;505.5)	(1.38;2.08)
200 cm	Baseline	324.5	1.88	576.5	1.87	662.8	2.17
	Risk uncertainty	(-15.8;664.8)	(0.96;2.81)	(-38.9;1191.9)	(0.94;2.79)	(52.7;1272.8)	(1.09;3.24)
	Costs uncertainty	(251.0;398.0)	(1.57;2.35)	(443.3;709.6)	(1.55;2.33)	(549.0;776.5)	(1.8;2.71)

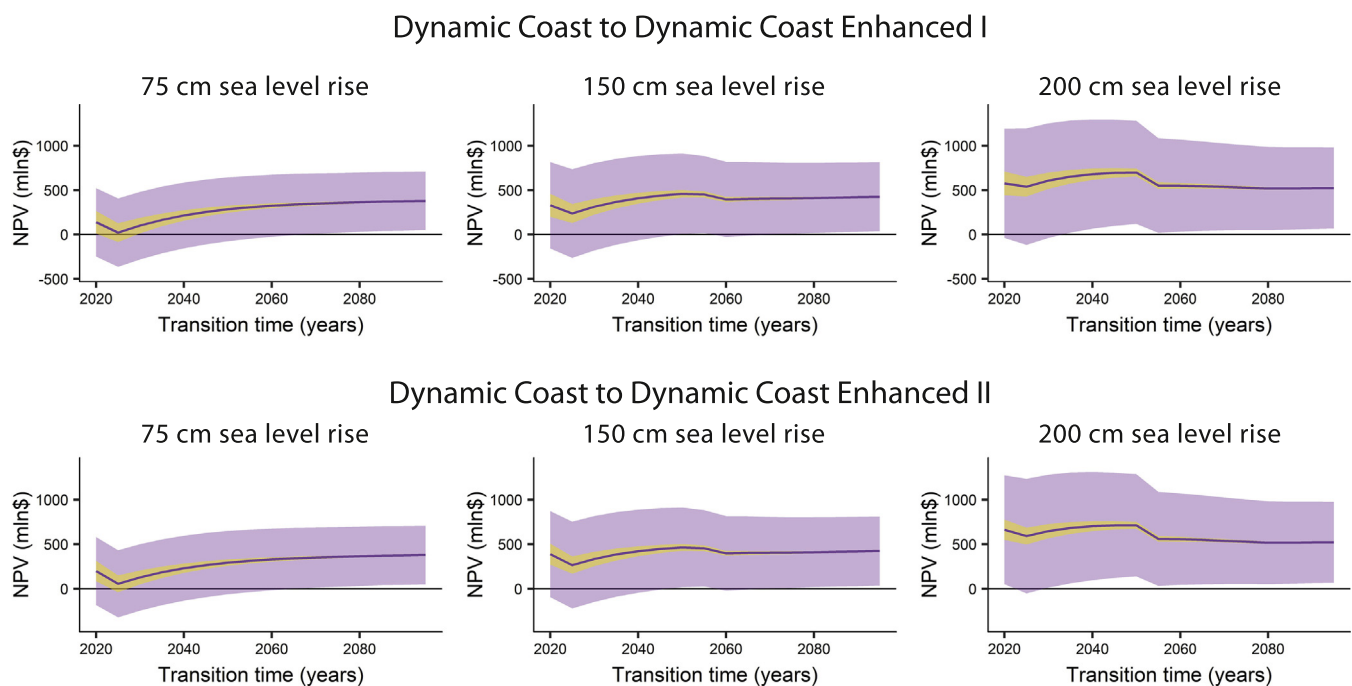


**Fig. 4.** Economic efficiency of delayed investment using CBA-II; for Long Beach of strategies DC and DCE-I shown for different implementation moments; NPV in million \$ per year if the implementation of either strategy is delayed; 4% discount rate; the blue interval indicates risk uncertainty, whereas the orange interval indicates cost uncertainty.

transition from DC to DCE-I, the maximum efficiencies reached are \$380.2 mln (transition in 2095), \$459.4 mln (transition in 2050), and \$699.7 mln (transition in 2050) for the 75-, 150- and 200 cm sea level rise scenarios respectively. Similarly, for a pathway from DC to DCE-II, the maximum efficiencies reached are \$379.6 mln (transition in 2095), \$464.6 mln (transition in 2050), and \$712.1 mln (transition in 2045) for the 75-, 150- and 200 cm sea level rise scenarios respectively. Both pathways show economic efficiencies, with slight changes in

timing and NPVs. The other areas and the outcomes with a 7% discount rate are presented in the electronic supplementary information; Figs. S13 to S20.

For the 150- and 200 cm sea level scenarios, a noticeable drop in NPVs from the pathway is shown in Fig. 5 if transitions occur around 2060 and 2055, respectively. We define such a drop as ‘investment tipping points’; an inefficient investment in time of the initial strategy, that will prevent further transitions later in time to reach economic



**Fig. 5.** Economic efficiencies of adaptation pathways (CBA-III); NPV in million \$ for a transition from an investment in DC in 2020, to DCE I/II in different future years, for Long Beach; 4% discount rate, the purple interval indicates risk uncertainty, whereas the yellow interval depicts cost uncertainty.



efficiencies that were possible before the investment tipping point. This is illustrated in Fig. 5, where the economic efficiency of a transition after 2060 or 2055 (for 150- and 200 cm sea level rise scenario respectively) will always stay below the level of before the investment tipping point. As mentioned before, the 150- and 200 cm sea level rise scenarios of the DC strategy have different investment moments over time, in which more buildings are floodproofed or elevated to protect the 100-year flood zone. These investments are highly inefficient if they are made right before a transition to one of the DCE strategies, as again they will only reduce risk if a flood event exceeds the 1/1000-year protection standard of DCE. Consequently, these inefficient investments right before a transition will cause an investment tipping point. However, in the used adaptation strategy design, not all measures of the DC strategy will become inefficient if the transition to DCE is made. Some measures, such as the reinforced breakwaters or beach nourishments, are continued in the DCE strategy and do not influence the economic efficiency of a transition. Therefore, before committing to a transition within an adaptation pathway, it is necessary to identify which investments of the initial strategy could cause investment tipping points.

#### 4.3. Maximalization of economic efficiency

Fig. 6 shows the optimal NPVs under a 200 cm sea level rise scenario for the delayed investments and adaptation pathways. The implementation years or transition years for which these optimal returns are reached are also shown. The 75- and 150 cm sea level rise scenario results are found in the supplementary materials (Figs. S21 and S22). Fig. 6 shows that the DC strategy is clearly the least favorable for Long Beach, even though economic returns are positive. Comparing the pathways with the associated delayed investments, a 10.0% (or \$63.6 mln) and 3.4% (or \$23.2 mln) increase in economic efficiency is reached for the DCE-I and DCE-II respectively.

The Ports of LA & LB show high economic efficiency for the DC strategy with an NPV of \$768.2 mln. The DCE-I and the pathway however are a combination of the industrial Ports and the back-area of the Ports. As Fig. 6 shows, the DC strategy for the back-area of the Ports never reaches a positive NPV, but almost breaks even when implemented in 2085. As the DC strategy of the back-area of the Ports is part of the Ports' pathway transition from DC to DCE-I, it negatively influences the economic efficiency. Still, based on our results, the most economically efficient outcome would be implementing the DC strategy in 2020 for the industrial Ports, while implementing DCE-II in 2045 for the residential back-area of the Ports. It should also be noted that the adaptation pathway from DC to DCE-I for the Ports also offers new expansion

opportunities, which are not considered as a benefit in this study but could influence the economic desirability of this pathway.

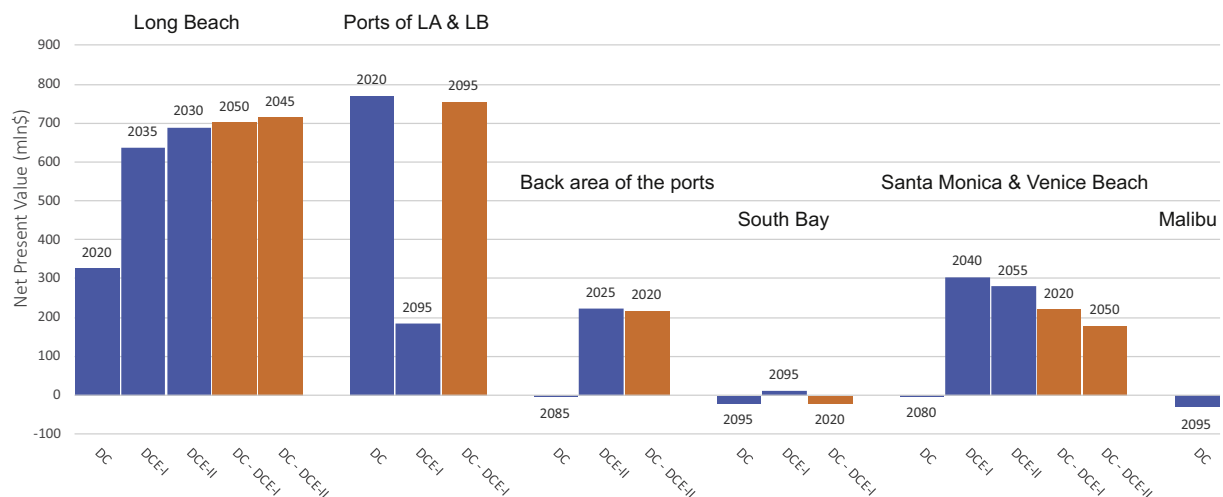
Fig. 6 shows for South Bay, Santa Monica & Venice Beach and Malibu that DC is economically inefficient even when investments are delayed until the far future (>2080). Therefore, starting with DC in 2020 to then transition to a DCE strategy would always be less economically efficient than solely implementing one of the DCE strategies, but potentially delayed in time (except for Malibu, as it only has a DC strategy).

## 5. Discussion

### 5.1. The potential of adaptation pathways

Future uncertainty in climate change and sea level rise requires the improvement of risk evaluation tools to support coastal mega cities in adaptation decisions (Hallegatte et al., 2012; Kunreuther et al., 2014). Our CBA framework, which combines scenario-based methods with adaptation pathways, demonstrates the potential benefit of introducing flexibility into adaptation strategies. The outcomes already show that implementation of adaptation in 2020 is cost efficient in many cases, which is a signal for other coastal megacities, underpinning the necessity of early adaptation in highly exposed and economically important areas. In terms of the adaptation pathways we evaluated, we found that higher economic efficiency can be reached by first investing in a strategy that focuses on beach nourishment and floodproofing of buildings, and later in time transitioning to a different strategy that underscores engineered protective measures such as sluices and dikes underneath beaches. Some of the measures of the initial strategy will not be fully effective for the duration of their lifespan, which could be viewed as a loss of investments, but still the benefits of an adaptation pathway outweigh these losses. For the case of Long Beach, under a 200 cm sea level rise scenario, economic efficiency can increase up to 10% using an adaptation pathway compared to implementing a single strategy. In addition to the increase in economic efficiency, adaptation pathways hold flexibility over time, allowing for the further development of transition strategies while still early adaptation is implemented.

However, caution should be taken to identify 'investment tipping points' before transitioning to a different strategy. The concept of tipping points was first introduced by Gunderson (2000) as an irreversible shift from one state to another. Although originally developed as an ecological concept, it is later widely applied in many other disciplines including socio-economic systems (e.g., Ahmed et al., 2018; Folke, 2006). In this study, we define investment tipping points as a moment in time where a transition to a different strategy will never reach pre-



**Fig. 6.** The optimal economic efficiencies per area under 200 cm of sea level rise; The NPV in million \$ for the delayed investments (CBA-II, blue) and adaptation pathways (CBA-III, orange) are shown for all strategies and areas. The implementation year or transition year for which these economic efficiencies are reached are displayed.

tipping point economic efficiency. In our case this was caused by investments in time of the initial strategy that were not economically beneficial for a pathway. Hence, after those investments, a pathway transition would result in lower economic returns than if a transition would have been made sooner in time. In a decision maker context, large investments in time that are part of a strategy should be reevaluated by exploring potential pathways before committing to the investments. Alternatively, Gunderson (2000) state that after a tipping point '[...] the only strategy is to adapt to the new, altered system.' (p. 432). Although not explored in our study, a redesign of the transition strategy after an investment tipping point might result in different outcomes.

It should be noted that we assessed economic efficiency triggers for an initial adaptation strategy and a possible transition to another. However, sea level rise is not expected to stop beyond 2100. Hence, when considering the far future, even the DCE strategies are likely only temporary adaptation strategies. While we assumed a lifespan of 100 years for floodproofing and structural measures, this could be modified to a shorter lifespan for different applications of the framework (e.g., when considering a second or third transition), or increase the total time horizon to extend beyond 2100. Other types of adaptation, such as managed retreat, could also be included in such an analysis, but was excluded from this study as it does not fit the current needs of the local stakeholders. However, this could be an interesting addition for future research.

In addition, we have not explicitly considered implementation time of a strategy or transition. Monitoring and re-evaluation of the adaptation strategies should be an ongoing process, and identification of investment tipping points should be identified in time to transition or make changes to the adaptation strategies accordingly.

## 5.2. Co-benefits from nature-based solutions

Similar to King et al. (2011), our results also reveal that climate adaptation strategies with nature-based adaptation strategies at their

core (restoring dunes, strengthening sandy beaches) (Cohen-Shacham et al., 2016; Temmerman et al., 2013) are economically attractive for reducing the risks of sea level rise. For Santa Monica, we find that the co-benefits of such measures for enhancing tourism and reducing beach erosion represent approximately 21–24% of the total benefits for all strategies under a 75 cm sea level rise scenario, and roughly 11% for a DC strategy under a 200 cm sea level rise scenario. For Long Beach, the co-benefits represent only between 0.8 and 1.5% of the total benefits for all strategies and sea level rise scenarios; Long Beach has a relatively high exposure of assets, outweighing the co-benefits of adaptation in beaches. These estimated co-benefits are probably conservative estimates, indicating the need to further develop methods for appraising the value of ecosystem services for coastal areas, especially where beaches play such a dominant role in coastal management.

## 5.3. Over- and under-investments

Sea level rise projections are still uncertain (DeConato and Pollard, 2016; IPCC, 2014), potentially leading to inefficient choices when committing adaptation investments to a single sea level rise projection. We explored for the Long Beach DC strategy the potential economic inefficiencies due to under- or over-investments, representing the hypothetical future situations in which policy makers realize that too much or too little has been invested in adaptation and that an acceleration or delay in adaptation investments is required (See Fig. 7 and the electronic supplementary information SI1.2 for a background). We found that for both under- and over-investments only minor inefficiencies are found over time. For under-adaptation economic inefficiencies primarily occur because the mandatory floodproof or elevation extent does not increase over time, leaving many structures vulnerable. For over-adaptation, a similar investment tipping point occurred, where an investment is made to increase the extent of the mandatory floodproof or elevation extent, while these properties are not yet at risk due to a slower rising sea level than anticipated. Again, this shows the importance of

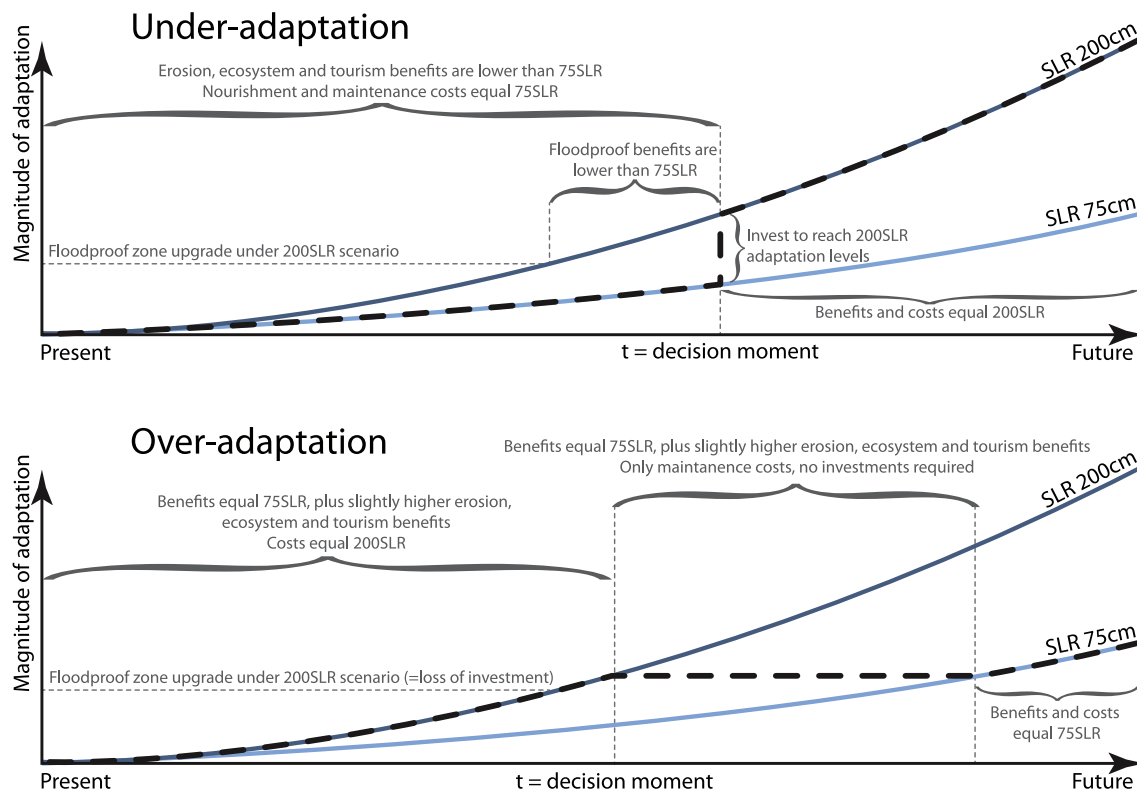


Fig. 7. Conceptualized overview of under- and over-adaptation. The graphs indicate the changes in costs and benefits of adaptation as a result of under-adaptation (upper graph) and over-adaptation (lower graph).

reevaluating the economic return of future investments by making use of learning about climate change.

## 6. Conclusion

While climate change and socio-economic development are expected to exacerbate the impacts of flooding, future uncertainty requires the improvement of evaluation tools to support adaptation decisions. Adaptation pathways are defined as a sequence of adaptation actions or strategies over time, which anticipate uncertain and changing risk conditions such as sea level rise. This study presents a comparative CBA framework which combines scenario-based methods with adaptation pathways, to allow a transition from one strategy to another over time. The adaptation pathways are compared to a more conventional evaluation of delay in investments, where adaptation measures are implemented later in time to improve economic efficiency.

We applied our method to an illustrative example of a major metropolitan area: Los Angeles County (LAC). To account for the geographical diverse characteristics of the LAC coast, the evaluated adaptation strategies were tailored to six main coastal segments: Malibu, Santa Monica & Venice Beach, South Bay, the Ports of Los Angeles and Long Beach (LA & LB), the residential back area of the ports (Wilmington/West Side), and Long Beach. Long Beach was used as the primary focus, but the results of all areas are found in the supplementary materials. The scenario-based CBA showed that economically desirable adaptation measures can be implemented in 2020, highlighting the necessity of early adaptation. However, we found that adaptation pathways have the potential to improve economic efficiency up to 10% in net-present values, compared to implementing a single adaptation strategy. Besides the increase in economic efficiency, the adaptation pathway CBA-III shows the benefits of early implementation of the initial strategy, while the transition strategy can be further optimized by learning about the pace of sea level rise. However, caution should be taken with ‘investment tipping points’, a point in time after which a transition of strategies will only lead to lower economic efficiencies than if the transition was made before the tipping point.

Overall, we recommend that studies evaluating adaptation strategies should integrate scenario-based cost–benefit analyses (or delayed investment CBAs) with adaptation pathways into their frameworks. This approach can better inform decision makers about the robustness and economic desirability of their investment choices. The flexibility of adaptation pathways presents the possibility of making early investments in adaptation and keeping options open to increase protection standards in the future, while maintaining economic efficiency.

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## Author contributions

Lars de Ruig: Conceptualization, Methodology, Formal Analysis, Investigation, Writing – Original Draft and Review & Editing, Visualization; Patrick Barnard: Resources, Data Curation, Writing – Review & Editing; Wouter Botzen: Conceptualization, Methodology, Writing – Review & Editing, Supervision; Phyllis Grifman: Conceptualization, Writing – Review & Editing, Funding Acquisition; Juliette Finzi Hart: Conceptualization, Methodology, Resources, Writing – Review & Editing; Hans de Moel: Conceptualization, Methodology, Writing – Review & Editing, Supervision; Nick Sadrpour: Conceptualization, Resources, Writing – Review & Editing; Jeroen Aerts: Conceptualization, Methodology, Writing – Review & Editing, Visualization Supervision, Funding Acquisition.

## Competing interests

The authors declare no competing interests.

## Data availability

Datasets used during this study are publicly available: CoSMoS 3.0 (Barnard et al., 2017), HAZUS MH (FEMA, 2013), USC SSI parcel data (USC SSI, 2016), LAR-IAC building level data (Greninger, 2014), and strategy cost estimates (Aerts et al., 2018a, 2018b). All data generated or analyzed during this study are included in this article (and its supplementary information files).

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2019.04.308>.

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