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Can California coastal managers plan for sea-level rise in a cost-effective way?

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This paper examines five representative sites on the California coast to illustrate a cost-effective methodology using tools and data that local decision makers can apply to analyse the economics of sea level rise (SLR) adaptation. We estimate the costs/benefits of selected responses (e.g. no action, nourishment, seawalls) to future flooding and erosion risks exacerbated by SLR. We estimate the economic value of changes to public/private property, recreational and habitat value, and beach related spending/tax revenues. Our findings indicate that the costs of SLR are significant but uneven across communities, and there is no single best strategy for adaptation. For example, Los Angeles's Venice Beach could lose $450 million in tourism revenue by 2100 with a 1.4 m SLR scenario while San Francisco's Ocean Beach would lose $80 million, but the impacts to structures could total nearly $560 million at Ocean Beach compared to $50 million at Venice Beach.

Keywords: economics; sea level rise; adaptation; benefit/cost

1. Introduction

California's coast faces increasing risks from sea-level rise (SLR), which is expected to exacerbate the impacts of high tides, storm surges and erosion (Revell et al. 2011). Later in this century, SLR will significantly exacerbate damage caused by flooding and storm surges, placing valuable infrastructure, recreational areas, and critical habitats at increased risk. In the near future, coastal managers and elected officials must make critical policy choices about how to address the impacts of SLR – these decisions may reflect sound planning or be *ad hoc* responses after a significant event such as an El Nino storm. However, the cost of adaptation, while expensive, may be less costly over the long run than these *ad hoc* responses.

Previous studies estimating the economic losses from SLR have been primarily "macro" in form – often relying on highly aggregated data sets and/or simplifying assumptions for evaluating damages over large spatial scales (e.g. county, state). While macro-scale damage assessments provide valuable information for higher-level policymakers, these studies fail to provide local jurisdictions with a clear understanding of the site-specific risks they face (e.g. Nicholls and Cazenave 2010). To plan for these effects at the local level, decision-makers must have proper, cost-effective tools at their disposal.

This paper is based on a study funded by the State of California. It outlines methodologies that can help local communities make first-order evaluations of the

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*Corresponding author. Email: pgking@sfsu.edu economic impacts of SLR. This study incorporates publically available data and generally employs standard methods that have been tested and used by other natural resource management agencies (e.g. Federal Emergency Management Agency (FEMA)). While more sophisticated methods have been developed to identify the economic costs of SLR impacts and adaptation responses, such methods often rely on expensive surveys (e.g. by the U.S. Army Corps of Engineers) which are cost-prohibitive for many local governments. Further, in many cases a first order cost/benefit analysis may be sufficient to rule out some options, saving local jurisdictions the cost of more elaborate studies.

This study employed a more granular, "micro" level methodology, which we illustrate through several case studies that highlight the diverse built and natural assets and services at risk to SLR on the California coast. We evaluated the relative economic costs of a 1.0, 1.4 and 2.0 m SLR following an extreme event (i.e. 100-year flood, which has a 1 percent chance of occurring in any given year) in the year 2050 and 2100 at Ocean Beach, San Francisco; Carpinteria City and Carpinteria State Beach, Carpinteria; Zuma Beach and Broad Beach, Malibu; Venice Beach, Los Angeles; and Torrey Pines Beach, San Diego (see Figure 1). Due to space limitations, we only present detailed results from the latter two sites here. Planning for SLR demands a comprehensive assessment of potential impacts to the wide variety of services provided by coastal environments. To this end, we include impacts not only to property and structures, but to sandy beach recreation value, beach related spending and habitats as well.

2. Background

2.1. Sea-level rise and extreme events

There is consensus among scientists that climate change is unequivocal and substantially influenced by human activity (IPCC 2013). The effects of a warming climate, detailed in many reports, for example the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (2013), are wide reaching, and consideration of these effects are increasingly pertinent to long-range planning efforts. One aspect of climate change is SLR, caused by thermal expansion of the world's oceans and increased glacial melting in high-latitude regions (Lombard et al. 2005). Global sea level rose by an upwards of 20 cm over the past century and could rise by nearly 2.0 m this century (Pfeffer, Harper, and O'Neel 2008), though projections generally fall below this number (Vermeer and Rahmstorf 2009; NRC 2012; IPCC 2013).

California's coastal communities already face risks from storms in the form of flooding, erosion and shoreline retreat and SLR will generally exacerbate these conditions. The most significant impacts to the coast occur in the form of extreme (storm or other) events caused by the superimposition of multiple factors, including, but not limited to, low barometric pressure, high runoff, wind, and waves (Wang et al. 1999; Cayan et al. 2008). For example, in the winter of 1982–1983, the California coast experienced the damaging impacts from the confluence of these factors when coastal flooding and shoreline erosion resulted in over $200 million in damages (NRC 2012).

2.2. Economic sea-level rise studies

Yohe et al. pioneered some of the earliest work evaluating the potential costs of SLR with a cost-benefit model that weighed the cost of protecting (e.g. armouring) a property

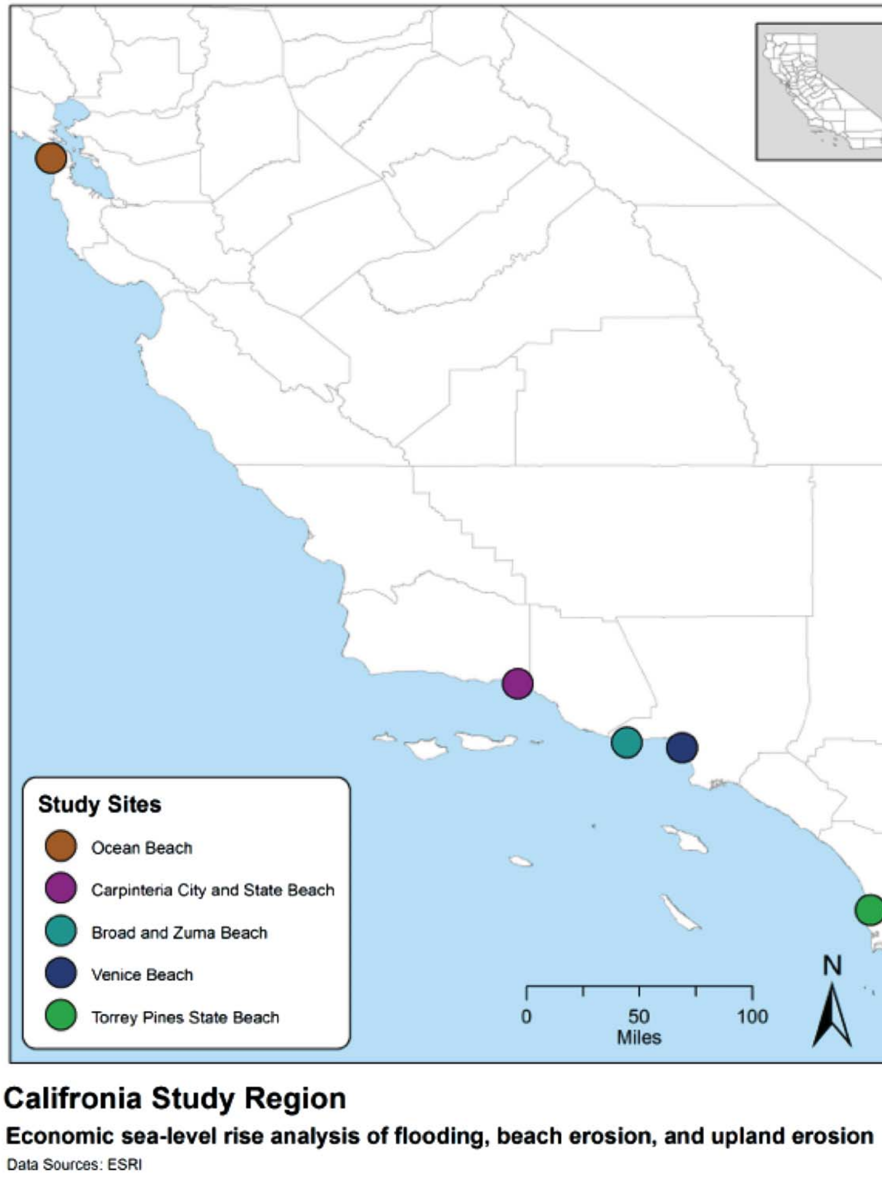

Figure 1. Study sites. (See online colour version for full interpretation.)

against the property's value at the time of inundation (Yohe 1989; Yohe *et al*. 1996; Yohe and Schlesinger 1998). This approach holds that property will be protected if the value of property exceeds the cost of protection at the time of inundation, and will be abandoned if protection costs outweigh property value. A number of restrictive assumptions follow from this approach. First, only damages from changes in sea level are modelled, ignoring potential extreme storm events and erosion that rising sea level exacerbates. Second, it assumes property owners and decision-makers have perfect foresight and will build protective structures in anticipation of a rise in sea level; history argues otherwise. Third, this approach only examines the net social cost of property values, ignoring other economic impacts (e.g. business interruptions) from SLR (Hanemann 2008; Heberger *et al*. 2009). More recent studies have accounted for the economic impact of storm events in the context of rising seas (Michael 2007; Kirshen, Knee, and Ruth 2008) and evaluated other adaptation responses such as nourishment (e.g. Neuman and Hudgens 2006).

In California, the Pacific Institute (PI) conducted an examination of impacts from a one-meter rise in sea level, including an elevated 100-year high tide elevation in the San Francisco Bay (Gleick and Maurer 1990). While the report did address the construction and maintenance costs for protective measures to safeguard existing high-value development, it did not quantify the costs of protecting or restoring marshes, wetlands, or groundwater aquifers. In 2009, the PI expanded the scope of the 1990 analysis, covering the entire 1100-mile California coast (Heberger *et al*. 2009). The 2009 update represents one of the most comprehensive regional planning-level studies to date. The authors used more comprehensive data, improved assessment methods and modern analytical tools (e.g. Geographic Information Systems) than previous studies. They estimate 480,000 people, 875,000 hectares of wetlands, and nearly \$100 billion (in 2000 dollars) of property are at risk in the event of a 100-year coastal storm event following an SLR of 1.4 m. Reinforcing and building new protective structures was estimated at \$14 billion, with \$1.4 billion per year in maintenance costs.

3. Methods

Most planning-level studies evaluate property and habitat at risk for only a single SLR scenario at one point in time (e.g. 1.0 m SLR in the year 2100). These single-scenario assessments do not allow for a comparative evaluation of potential losses for a range of potential sea level futures. Given the uncertainty in future SLR, it is important to consider a range of scenarios at different points in time. To this end, we evaluated losses following a 1.0, 1.4 and 2.0 m rise in sea level (2100) in the years 2050 and 2100. We evaluate damages using a 2010 socioeconomic baseline. Although providing multiple scenarios can be confusing, and policy makers often want one conclusion, we believe that given the current uncertainty one must analyse multiple scenarios.

This study adopts the following three SLR scenarios: 1.0 m by 2100 (Cayan B1), 1.4 m by 2100 (Cayan A2), and 2.0 m by 2100 (Pfeffer). Intermediate (year 2050) sea level estimates are adopted directly from Cayan *et al*. (2008) for the low and medium scenarios, and calculated for the high scenario by an NRC function outlined by the U.S. Army Corps of Engineers (USACE) (2009) (see Figure 3). We estimate damages for the following categories: (1) temporary flooding from a 100-year coastal storm; (2) sandy beach erosion from the berm to the backbeach; and (3) upland erosion landward from the backbeach where cliffs or dunes are present.

In order to accurately model damages, one must recognize that the total value of an asset (e.g. land, structures, contents) will not necessarily be lost if that property intersects a hazard zone. For instance, low levels of flooding (e.g. one foot) are unlikely to result in complete loss of property value. Similarly, if only a portion of a property is eroded it is likely that not all of the property's assets are lost. While previous studies have aggregated all asset value at risk, we aim to increase the accuracy of economic damage estimates by employing damage functions that account for these dynamics.

3.1. Upland damage assessment

3.1.1. Flooding

Similar to Heberger *et al.* (2009), we add SLR projections to water levels from a current 100-year coastal flood (i.e. base flood) event in order to estimate future flooding impacts; a parameter often used in coastal hazard assessments. This technique allows us to model how a rise in sea level increases the base flood elevation and extends the area of the flood's reach, thereby threatening more assets. We model these changes using digital elevation and base flood elevation models with GIS.

We account for damages from increasing flood depth associated with a rise in sea level by applying U.S. Army Corps of Engineers (USACE) depth-damage curves (see Figure 2). The USACE has published these curves that relate flood depth to damage estimates for various types of structures (e.g. residential, commercial and governmental). This particular application is widely used, not only by the USACE, but also by FEMA. The USACE has a number of memos/papers describing the application of flood damage curves (e.g. see USACE 2003a, 2003b and references contained within). In our application, we linked the depth-damage curves to the mean depth of flooding values at each threatened parcel, allowing us to estimate damages as a percentage of the structure value (similar to Kirshen *et al.* (2012)). Although these depth damage curves have their limitations (e.g. damages also depend on the duration of the flooding, the velocity of floodwaters) they do provide policymakers with a reasonable approximation of expected damages and are the standard now used by many government agencies (e.g. see FEMA 2006).

To estimate structure value, we linked building characteristics data (e.g. size, type, number of stories, year built) to mean cost-per-square-foot replacement values identified

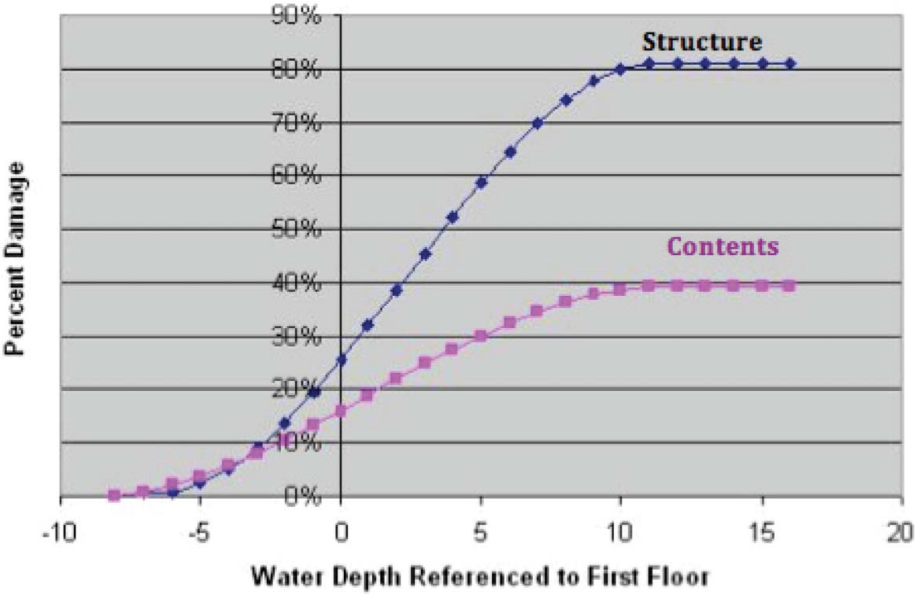

Figure 2. Generic example, USACE depth-damage functions. Source: USACE 2010. Note: The blue curve (top) references the relationship between the depth (ft) of water and damages as a percentage of the structure's value. The pink curve (bottom) represents content damages, also as a percentage of structure value. (See online colour version for full interpretation.)

by the National Institute of Building Sciences (NIBS) (FEMA 2006). In order to estimate the damages to structures and their contents, we used the depreciated replacement value - the estimated cost of replacing an asset with a substitute of similar kind, utility, and condition. For building characteristics data, we used (pre-existing) secondary property data from county assessor offices. These data are publicly available at varying levels of detail depending on the county and parcel of interest. We also took the NIBS average cost-per-square-foot construction estimates and adjusted them using the appropriate region-specific building-cost indices maintained by Engineering News Report (ENR) (ENR 2010). These values were further adjusted for inflation. In order to estimate content damages, we used USACE content-to-structure value ratios for various building types, which represent content value as a percentage of the depreciated structure value.

3.1.2. Upland erosion

California does not have a consistent statewide dataset delineating coastal upland areas at risk to erosion from a rise in sea level. For our study site in northern California (Ocean Beach) we used GIS erosion hazard zones developed by Philip Williams and Associates. This dataset (Revell *et al*. 2011) evaluates future erosion by considering changes to total water level (TWL), historic rates of shoreline change, and a 100-year storm event (Revell *et al*. 2011; Ruggiero *et al*. 1996, 2001). In southern California, where no similar dataset exists for our study sites, we approximated the acceleration of long-term shoreline erosion. According to the California Climate Adaptation Strategy (CNRA 2009), by 2100, southern California cliff erosion rates are expected to accelerate by 20 percent for a 1.0 m rise in sea level. Applying this rate of change parameter proportionally to sea level equations derived by the NRC (USACE 2009) (see Figure 3), we modelled an exponential integration of shoreline movement for each respective sea-level rise scenario in 2050 and 2100. These values were then modelled in GIS to produce erosion hazard zones.

Estimating upland erosion damages to land and structures requires valuation methods that are distinct from those used to assess flood damages; land and structures literally fall into the ocean, and cannot be replaced. We estimated the market value of land and property in areas zoned for residential use as opposed to the assessed value, which is typically provided in parcel level data (see Figure 3). This distinction between the market value and the assessed value of land and property is critical since the increase in assessed

$$\Delta E = E(t_2) - E(t_1) = 0.0017(t_2 - t_1) + b(t_2^2 - t_1^2)$$

$E(t)$ = mean sea level at year t

t_1 = starting date – 1986

t_2 = future date – 1986

b is a linear coefficient

Figure 3. National Research Council sea-level rise quadratic approximation function. Source: USACE 2009.

value in California is capped at an annual inflation factor of 2 percent (CABOE 1978) by Proposition 13 – thus a property purchased many years ago may have an assessed value much lower than its market value. In the case of open-space parcels (which represented a large majority of the property at risk) we used recent sales data and estimated an average sale price per hectare – likely lower than the market value of the land if it was zoned for other uses. For all other land uses at risk to erosion (e.g. commercial) we made use of assessor parcel values that were readily available. The value of structures were estimated using similar methods and data as referenced in the above "flooding" assessment discussion.

We estimated losses according to the following assumptions, which were developed in response to the call from Heberger *et al*. (2009) for more micro-level analysis of erosion damages at the parcels level:

(1) Developed parcels less than or equal to 5,000 square feet (464 square m) with a structure-to-lot size ratio of 0.5 or greater face a complete loss of structure and land value.
(2) Developed parcels greater than 5,000 square ft (464 square m) are evaluated on a case-by case basis. Structure and land losses are evaluated separately. If a structure intersects with the erosion hazard zone, the structure faces a complete loss of depreciated value. If a structure does not intersect with a hazard zone, then only land losses are included as a function of the percent surface area of the parcel within that hazard zone. To estimate the land component of a parcel's value, we use a hybrid "extraction" technique, where depreciated structure value is subtracted from the expected market price of a property.
(3) Undeveloped (vacant) parcel damage is a function of the percent of parcel (surface area) within the erosion hazard zone, regardless of parcel size.

3.2. Sandy beach erosion

Higher sea level generally leads to narrowing of sandy beaches unless the backbeach is allowed to retreat. We use the Bruun Rule (1962) to estimate the area of beach eroded away passively due to SLR (Schwartz 1965; Dubois 1992; Davidson-Arnott 2005). This method models beach recession as a function of increases in sea level, producing a linear, landward shoreline movement estimate that is multiplied by the length of the beach. The result is in an estimate of beach area lost to SLR, assuming that the shoreline reach is impacted uniformly. While the Bruun Rule is used frequently in SLR assessments, it has been criticized due to restrictive assumptions, specifically the model's two-dimensionality and the fact that it does not account for longshore currents (Pilkey and Cooper 2004). Our methods for calculating economic losses can easily be adapted in the event that the resources for a more sophisticated model become available. Many governmental and academic sources (e.g. California Coastal Sediment Master Plans; Maalouf *et al*. 2001; Lippman, Brookins, and Thornton 1996; Revell *et al*. 2011) were used to collect the best available data inputs (e.g. beach width, beach berm[1] elevation, foreshore slope[2], depth of closure[3]) to model the Bruun Rule at each study site.

3.2.1. Recreational value and economic impact

Coastal recreation generates two important economic contributions to the economy: direct economic impacts and non-market value. Economic impacts measure the flow of money through an economy and the associated jobs, wages, salaries and taxes associated with these flows. Non-market value, in contrast, is the net value added to society that the resource provides (often not included in standard measures of economic output such as GDP). Since California's beaches are open to the public, there is no market price for a day at the beach, but the trip still has value, typically measured by a consumer's willingness to pay for the trip, if they had to pay. This non-market value can be measured in a number of ways (e.g. see Pendleton *et al*. 2011a). From the perspective of the coastal user as well as a professional economist, economic value should be the primary driver of policy, although many stakeholders (e.g. politicians, city planners, developers) are often more concerned with economic and tax impacts. Our analysis estimates both.

For beaches, the most significant economic direct use value is usually recreation. Although estimating a concrete value for non-market activities like beach recreation is more challenging than measuring the value of market goods, there are a number of standard techniques that can be applied, and general agreement exists among economists (within a reasonable range) of what the appropriate value is for a day at the beach (USACE 2003b; King 2001; Pendleton *et al*. 2011a). To date, the most comprehensive examination of consumers' valuation of beach visitation was the Southern California Beach Valuation (SCBV) study (Hanemann, Pendleton, and Mohn 2005), which used a random utility model (RUM) to examine beach visitation in Orange and Los Angeles counties. Their results are consistent with an earlier valuation made for the American Trader case (Chapman and Hanemann 2001), and not inconsistent with the day use valuations employed by the USACE (2004). None of these models, however, consider impacts to valuation stemming from changes in beach width.

Pendleton *et al*. (2011a) estimate welfare benefits of enhanced beach width in a RUM based on data from the SCBV project. They find significant welfare benefits from enhanced beach width. Further, they find that water users (e.g. swimmers and surfers) as well as people on the pavement also benefit from increased beach width, though, after a point, the marginal benefit of increased beach width diminishes. In a related paper, Pendleton *et al*. (2011b) use the same dataset to estimate welfare losses at southern California beaches when beach width decreases due to erosion. A number of studies also examine the welfare benefits of increased beach width at beaches on the east coast of the United States. Huang and Poor (2004) examine the value of protecting against beach loss in the states of Maine and New Hampshire. Landry, Keeler, and Kreisel (2003) examine a Georgia island community, using a hedonic model to quantify benefits to property owners, and stated preference techniques to determine the benefits of beach preservation and enhancement strategies. They find that, in general, people prefer wider beaches and also dislike armouring strategies. Parsons, Massey, and Tomasi (2000) examine beaches in New Jersey and Delaware. They find that people prefer wider beaches, but only up to a point (about 250 ft, or ~75 m). Whitehead *et al*. (2006) also use a random effects Poisson model – combining revealed preference and stated preference data – and find that people prefer wider beaches.

To estimate losses in recreational value due to beach erosion, we use a standard model that is reasonably tractable – a benefit transfer (BT) approach, which allows one to apply estimates from previously analysed sites to similar beaches. In practice, BT is much cheaper than other methods and also has the advantage of consistency. This study used the Coastal Sediment Benefits Analysis Tool (CSBAT), developed for the US Army Corps of Engineers and the State of California, to value beach recreation (per user per day). CSBAT uses the following six criteria to assess the recreational value of California beaches:

1. Weather
2. Water quality and surf
3. Beach width and quality
4. Overcrowding
5. Beach facilities and services and
6. Availability of substitutes.

The functional form used in the CSBAT analysis is a Cobb-Douglas utility function, of the general form:

$$\text{Value of a Beach Day} = M * A^{a} * A_2^{b} * A_3^{c} * A_4^{d} * A_5^{e} * A_6^{f}$$

Where:

M is the maximum value for a beach day
$A_1 \ldots A_n$ represent each beach amenity (rated on a scale of 0 to 1)
$a \ldots f$ are the weighting of each amenity value
$a + b + c + d + e + f = 1$.

The CSBAT model has been calibrated with data from existing studies. The Cobb-Douglas function exhibits diminishing marginal utility with respect to beach width. In addition, the model employed in this study caps beach width benefits at 300 ft (~90 m). This is consistent with a number of studies indicating that beaches can, in fact, be too wide (e.g. Landry, Keeler, and Kreisel 2003, Pendelton *et al*. 2011b). However, wider beaches also diminish crowding, the benefits of which are taken into account in the model.

Coastal erosion, and in particular beach erosion, threatens communities in California which rely on beach tourism. To address these potential losses, we use estimates of economic value based on the CSBAT model (King 2001) and spending estimates from King and Symes (2003) updated for inflation using the Consumer Price Index (CPI). The key variable in estimating spending and revenue is the percentage of day-trip visitors versus out-of-town visitors (who spend more). We assume that spending per visitor does not change as beach width changes – thus, all of the economic and tax revenue impacts estimated in this study are a result of estimated changes in beach attendance. It is possible that changes in beach width could affect the composition of overnight/day-trip visitors, which would affect spending/tax estimates, but this impact was considered secondary and is not estimated in this study. Tax revenue impacts are based on spending estimates combined with data from the California Statistical Abstract, a collection of social, economic, and physical data for the State of California Department of Finance (2009).

3.2.2. Habitat value

Although beaches are best known for their recreational value, other values may be just as important. Beaches provide important storm-buffering services. Wider beaches protect upland property from wave attack and reduce upland erosion. California's beaches provide habitat for a number of threatened species (e.g. Least Tern, Snowy Plover), and spawning opportunities in the intertidal zone for grunion and others. Reducing the size of beaches diminishes this habitat and potentially reduces biodiversity. Schlacher *et al.*

(2007) find that human activity on beach habitats has already significantly reduced their capacity to provide ecological services.

Although studies of these non-recreational benefits are few in number, these studies should not be ignored. The dollar-value estimation of the habitat services of beaches is in its infancy, and few studies have been conducted to this end. Costanza *et al*. (2006) estimated that beaches in New Jersey produce a flow of disturbance regulation benefits (i.e. buffering of floods, storm surges and erosion) totalling $10,000 per hectare per year. This value is an output of hedonic analyses that related the value of the beach to the specific home and community attributes in the study area.

Wetland ecological services have been studied in greater detail and, at minimum, provide a range for the ecological value for beaches.[4] Brander, Florax, and Vermaat (2006) conducted the most comprehensive study of wetland valuation to date, examining over 200 studies of the economic value of wetlands and found that the average biodiversity value of a wetland is about $17,000 per hectare and habitat value is about $5,000 per hectare. They also estimate that wetlands provide $4000 per hectare per year in flood relief.

To estimate habitat service losses, we aggregate beach lost due to erosion following SLR. In line with our earlier discussion, we adopt a value of $4000 per hectare per year in economic benefits in the form of flood preventions (Brander, Florax, and Vermaat 2006). We consider this estimate to be somewhat conservative since it does not explicitly account for other types of ecosystem service values such as biodiversity value, and could be considered conservative.

3.3. *Coastal adaptation measures*

The increasing vulnerability of coastal communities has inspired a number of proposed adaptation measures; these are often categorized as: soft solutions (e.g. beach nourishment); hard solutions, (e.g. seawalls and revetments); and passive solutions (e.g. managed retreat). Decisions on which measure to implement are typically left in the hands of local and state certified coastal programmes.

3.3.1. *Soft solutions*

Beach nourishment is the primary soft solution for shoreline management. Some beaches, particularly in tourist-rich southern California, are periodically nourished with sand, to either replace eroded sand, increase a storm buffer, or both. Beach nourishment projects are sometimes viewed as short-term, unsustainable solutions as they are vulnerable to wave energy, primarily in that it displaces sediment both offcoast and downshore. Under accelerated beach erosion from SLR, nourishment requirements will likely increase. This has also prompted discussion about the long-term availability of sufficient sand from inland, nearshore and offshore sources to keep pace with increased erosion (Runyan and Griggs 2003). While nourishment can create wider dry sand zones, the ecological value of nourished shorelines is not likely to scale with natural dry beach width (Speybroeck *et al*. 2006; Peterson *et al*. 2006)

We project the volume of future sand loss at each site and following Flick and Ewing (2009), assuming that the cost of nourishment is $10 per cubic meter. It should be noted that the Bruun Rule does not account for longshore drift. Large wave events can pull sand offshore to depths of 30 m or more, which is beyond the normal closure depth for many beaches in California (Flick and Ewing 2009). These events can restart coastal conditions, and, similar to Flick and Ewing (2009), we assume that each large event strips offshore all past nourishment added to maintain beaches. For illustrative purposes, three storm events were modelled in 2025, 2050 and 2075. The dates of these storm events are hypothetical. The time when a storm event occurs directly influences the volume of sand needed for replenishment. For example, a storm event in the early part of the century would require less volume and have a smaller replenishment cost than a storm event occurring later in the century.

3.3.2. Hard solutions

The most common coastal hazard response in California is the construction of seawalls, near-vertical shoreline structures to protect against storm waves, and revetments, a sloped profile that extends horizontally onto the beach profile to prevent backbeach erosion from storm waves (USACE 1984). While these structures can assist in protecting landward areas from high tides and storm surge, there is concern about the impacts of these structures (see Figure 4). The footprint of seawalls and revetments result in the placement

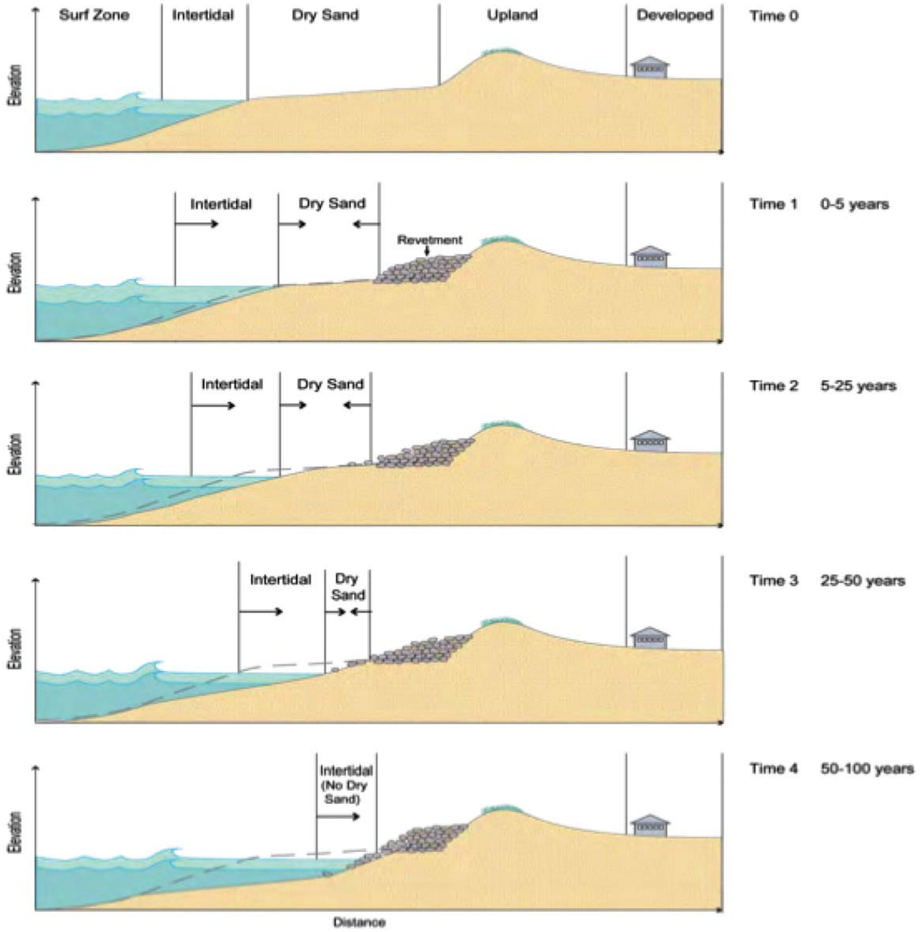

Figure 4. Conceptual model accounting for changes to beach width from a rise in sea level at shorelines fixes by hard structures. Source: ESA-PWA 2012. (See online colour version for full interpretation.)

loss of beach; the quantity of loss being a function of the seaward placement of the structure and its alongshore reach (Griggs 2005). Seawalls and revetments can also cause passive erosion; a rise in sea level may result in the gradual loss of the beach fronting such structures (Griggs 2005). These structures have the capacity to result in the ultimate disappearance of certain beaches as sea levels rise. Coastal armouring can also have negative ecological impacts (i.e. reduced diversity and abundance of seabirds; Dugan *et al*. 2008) beyond simply reducing the size of beaches.

To identify the cost of protecting landward development along our study reaches, we made use of a state GIS dataset that contained information on existing coastal armouring along the California coastline. This dataset allowed us to identify the placement and type (e.g. revetment, seawall) of existing armouring. However, data on the height, condition and life expectancy of these protective structures was not available. These data inputs are necessary for determining the need to strengthen and/or raise existing structures to account for a rise in sea level. Therefore, we assume existing revetments and seawalls are sufficient to protect landward development from a rise in sea level. We use Heberger *et al*. (2009) northern California and southern California regional cost profiles, updating these costs to year 2010 dollars with USACE (2009) civil works construction cost indices. When seawall costs are adjusted for inflation and location, the cost per linear meter is approximately $2,100 in northern California and $1,900 in southern California. Annual maintenance costs are 3 and 2.5 percent of the capital cost of construction for revetments and seawalls, respectively.

3.3.3. Passive solutions

The need for sustainable and cost-effective shoreline responses has directed attention to the practice of “managed retreat” whereby threatened structures and facilities are removed so the shoreline can erode unimpeded (NOAA 2007). Managed retreat requires that nearshore development be guided by land-use policies such as setbacks or rolling easements. Practicing managed retreat can reduce the risk of storm flooding, minimize erosion maintenance costs and assist in preserving land for open space uses (see Figure 5). Yet, it can also lower the economic value of shoreline development that is planned for future relocation and/or abandonment (i.e. risk capitalization). Managed retreat is not widely practiced today, especially in the United States. However, there are an increasing number of sites, particularly in areas vulnerable to hurricanes and excessive wave energy, where managed retreat may be the only feasible option (Griggs 2005). Modelling the adaptation costs for managed retreat strategies was beyond the scope of this project, and was not estimated.

4. Results

Given space limitations of this journal, this discussion will focus on damages from a 1.4 m SLR at the study sites, assessed in years 2050 and 2100. Unless otherwise stated, economic effects are presented in 2010 dollars.

4.1. Flood effects

Our results indicate that absent SLR, the study sites are vulnerable to a range of economic damages from a 100-year coastal flood. SLR exacerbates these flood damages by expanding the floodplain and increasing flood depth. Closer analysis of the results

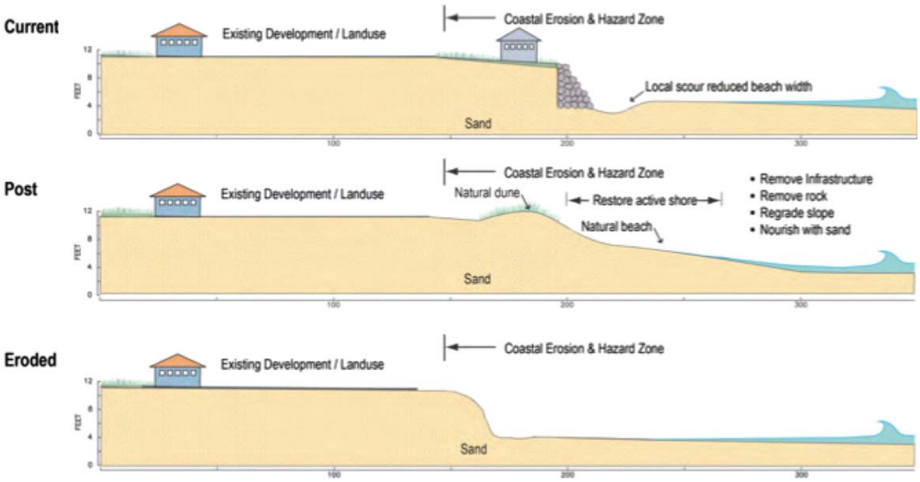

Figure 5. Conceptual model of a managed retreat scenario. Source: ESA-PWA 2012. (See online colour version for full interpretation.)

indicates that there is a non-linear relationship between the rate of SLR and expected damages. Land elevation and the development beyond the year 2000 base flood plain vary greatly by site. These factors, among others, result in “tipping points” or “thresholds” where an increase in the rate of SLR (e.g. from 1.0 m to 1.4 m) results in non-linear increases in damages. For example, at Venice Beach, the first meter of SLR increases damages to $25 million above base flood damage, while the next 0.4 m of SLR causes an additional $20 million in damages.

4.2. Upland effects

Similar to our flood damage results, our study sites are vulnerable to a range of economic damages from erosion at present, which will only be exacerbated as rises in sea level accelerate the rate of shoreline erosion. Damage thresholds and/or tipping points are observed when modelling coastal erosion following a rise in sea level. For instance, the LOSSAN rail corridor runs upland of Torrey Pines State Beach. This is the only rail connector between San Diego and the rest of the United States for passenger, freight and military operations, and is second in passenger traffic to the Boston to Washington DC corridor in respect to Amtrak train ridership (USACE 2007). If historical erosion rates continued to the end of the century, $4 million of track would be at risk (plus the added damages caused by reduced access before the track could be repaired). However, an acceleration of historical erosion rates from a 1.0 m, 1.4 m and 2.0 m SLR increases the amount of railway at risk by approximately $334, $349 and $374 million (see Tables 1 and 2).

4.3. Sandy beach effects

Sandy beaches at our study sites experience varying amounts of erosion; influenced by the existing width of the beach and beach profile characteristics such as berm elevation, depth of closure and foreshore slop. For example, at Ocean Beach, over 90 percent of the

Table 1. 100-year coastal flood impacts (2010 millons of dollars).

	Baseline	1.0 m sea-level rise		1.4 m sea-level rise		2.0 m sea-level rise	
Scenario	*Year 2000*	*Year 2050*	*Year 2100*	*Year 2050*	*Year 2100*	*Year 2050*	*Year 2100*
Ocean Beach	6.5	9.1	14.6	9.8	19.6	11.4	36.4
Carpinteria	1.5	2.4	6.9	4.0	10.7	4.6	19.5
Zuma	12.6	17.1	24.6	18.2	28.5	20.8	37.1
Venice	7.0	12.6	31.6	15.1	51.6	19.4	96.2
Torrey Pines	3.0	3.4	3.9	3.4	5.0	3.7	6.7

Note: Damages (in millions of 2010 dollars) from a 100-year coastal flood in year 2000 followed by three respective sea-level rise scenarios (1.0, 1.4, and 2.0 m by 2100) in 2050 and 2100.

original sandy beach area could passively erode by 2100 following a 1.4 m SLR. At Zuma Beach, approximately 30 percent of beach area erodes under this scenario.

Recreational value losses occur as reductions in beach width decrease visitors' willingness to pay for a day at the beach. Following a 1.4 m SLR, aggregate recreational losses total $15 million at Ocean Beach (Net Present Value (NPV) at 3% discount rate), compared to $102 million at Zuma Beach (NPV at 3% discount rate). Higher damages occur at Zuma Beach due to higher attendance; on average, there are one-half million annual visitors to Ocean Beach, and over seven million annual visitors at Zuma Beach.

As beaches erode, habitat losses occur in the form of reduced biodiversity value, ecological services and storm damage prevention benefits. Damages, a function of total beach area at risk to erosion, are most significant at Ocean Beach, where a 1.4 m SLR by 2100 results in 133 hectares of beach loss and aggregate habitat losses (which in this case only account for reductions in storm damage benefits) amounting to $17 million (NPV at 3% discount rate).

A number of studies (e.g. King 2001; King and Symes 2003) indicate that spending and tax losses will occur as reductions in beach width limit the carrying capacity of beaches and reduce annual attendance loads. Similar to recreational losses, the most significant impacts are experienced at beaches that experience high levels of beach loss and host large numbers of annual visitors. Aggregate local and state spending losses amount to $396 million (NPV at 3% discount rate) at Zuma Beach following a 1.4 m SLR by 2100. Corresponding local and state tax losses amount to $11 million (NPV at 3% discount rate) (see Table 3).

Table 2. Upland erosion impacts (2010 millions of dollars).

	1.0 m sea-level rise		1.4 m sea-level rise	
Scenario	*Year 2050*	*Year 2100*	*Year 2050*	*Year 2100*
Ocean Beach	49.5	177.1	99.5	540.3
Carpinteria	0.1	0.3	0.1	0.3
Torrey Pines	4.0	338.9	4.0	353.3

Note: Damages (in millions of 2010 dollars) from upland erosion (landward from the backbeach) under two sea-level rise scenarios (1.0 and 1.4 m by 2100) in 2050 and 2100. To avoid inconsistencies, the more extreme 2.0 m sea-level rise scenario was not modelled at all sites. Upland erosion damages are not presented at each site due to varying backbeach profile. These results do not net out the potential impacts from historical erosion projected over time.

Table 3 Annual benefits 1.4 m sea-level rise (2010 millions of dollars).

Site	Category	Year 2000	Year 2050	Year 2100
Ocean Beach	% beach area	100%	69%	7%
	Recreational value	3.4	2.6	0
	Habitat value	0.09	0.06	0.01
	Spending	22.3	18.4	0
	Tax revenue	1.7	1.4	0
Carpinteria	% beach area	100%	85%	65%
	Recreational value	15.7	14	10
	Habitat value	0.06	0.05	0.03
	Spending	114	105.3	81.7
	Tax revenue	9.7	9	6.9
Zuma	% beach area	100%	89%	67%
	Recreational value	71	65.4	52.7
	Habitat value	0.01	0.09	0.07
	Spending	390.6	369	315
	Tax revenue	29.3	27.7	23.6
Venice	% beach area	100%	95%	83%
	Recreational value	78.2	76.1	71.4
	Habitat value	0.33	0.31	0.28
	Spending	884.5	860.9	808
	Tax revenue	66.3	64.6	60.6
Torrey Pines	% beach area	100%	75%	23%
	Recreational value	5.6	4.6	1.3
	Habitat value	0.01	0.01	0
	Spending	35.5	30.6	10.6
	Tax revenue	2.7	2.3	0.8

Note: Annual snapshots of economic value (in millions of 2010 dollars) of recreation, habitat, beach-related spending and tax revenue in 2000, 2050, and 2100 under a sea-level rise scenario of 1.4 m by 2100. As sea level rises and beaches erode more rapidly, the annual economic benefits of each beach face reductions. Results represent a hold the line strategy where the backbeach is fixed.

4.4. Adaptation costs

The initial capital costs of armouring currently unprotected reaches of shoreline at each study site with seawalls, total upward of $93 million at Zuma Beach. Seawalls also require annual maintenance, which, for four study sites, would cost more than $2 million per year (see Table 4).

Table 4. Coastal armouring (2010 millions of dollars).

Site	Capital costs	Annual maintenance costs
Ocean Beach	56	2.8
Carpinteria	28	1.0
Zuma	93	2.3
Venice	68	2.1
Torrey Pines	69	2.1

Table 5 Beach nourishment costs (2010 millions of dollars, NPV 3% discount rate).

Scenario	1.0 m sea-level rise		1.4 m sea-level rise		2.0 m sea-level rise	
	Year 2050	*Year 2100*	*Year 2050*	*Year 2100*	*Year 2050*	*Year 2100*
Ocean Beach	7.8	12.3	9.7	16.5	13.6	23.6
Carpinteria	0.9	1.4	1.1	1.9	1.6	2.7
Zuma	2.1	3.3	2.7	4.4	3.7	6.4
Venice	3.4	5.2	4.2	7.1	5.8	10.1
Torrey Pines	4.8	7.6	6.0	10.2	8.4	14.6

Note: Net present value of the cost of annual nourishment to mitigate beach erosion losses in respective sea-level rise scenarios (1.0, 1.4, and 2.0 m) in 2050 and 2100. For illustrative purposes, three storm events were modelled in 2025, 2050 and 2075. The additional sand volume and corresponding costs to restore the pre-storm profiles is included in the total costs.

The additional sand volume and corresponding costs to restore the pre-storm profiles of beaches in our study were tabulated. Carpinteria requires the least amount of nourishment at $2 million (NPV at 3% discount rate) to keep pace with a 1.4 m rise in sea level, while Torrey Pines, a similarly sized beach would require $10 million (NPV at 3% discount rate) in nourishment for the same SLR scenario (see Tables 4 and 5).

4.5. Results discussion

Below we provide some additional context to the results at two of our study sites: Venice Beach, Los Angeles, and Torrey Pines Beach, San Diego.

4.5.1. Venice Beach, Los Angeles

At Venice Beach, a 100-year storm following a 1.4 m rise in sea level could result in approximately $15 million and $52 million in damages to structures and their contents in 2050 and 2100, respectively. To evaluate various adaptation approaches, we assume that unarmoured reaches of the backbeach that host structures, parking lots and dedicated open-space will be armoured. The capital cost of armouring is estimated to be $70 million, with annual maintenance infusions of at least $2 million. Capital costs could change depending on the year of placement, and maintenance costs could increase as the beach erodes and its ability to dissipate wave energy is diminished.

The cost of armouring the shoreline at Venice Beach outweighs the associated benefits of flood reduction. However, if one fixes the shoreline with armouring, SLR will passively swallow the beach. By 2100, the coastal erosion following a 1.4 m SLR could result in losses to recreational and habitat value reaching $39 million, (NPV at 3% discount rate) lost state and local spending totalling nearly $428 million (NPV at 3% discount rate), and lost state and local sales tax totalling nearly $12 million (NPV at 3% discount rate). Using nourishment projects to maintain the existing beach width would require over $7 million (NPV at 3% discount rate). While nourishment presents an economically feasible way to counteract losses related to recreational value, spending, and taxes, nourishment could also result in reductions to habitat value not estimated.

Venice Beach is an iconic destination for many California visitors. Due to large nourishment projects in the past, along with the placement of groins, this stretch of shoreline provides sufficient beach width to continue hosting millions of visitors per year as a rise in sea level passively reduces beach width. Additional nourishment projects could help minimize recreational losses due to SLR; the placement of winter berms could also help reduce the impacts of flooding following large winter storms. Both of these adaptation responses have environmental and ecological consequences that should be further evaluated.

4.5.2. Torrey Pines Beach, San Diego

At Torrey Pines, a 100-year storm following a 1.4 m rise in sea level could result in approximately $3 million and $5 million in damages to structures and their contents in 2050 and 2100, respectively. If a 1.4 m SLR is realized, accelerated landward erosion at unarmoured reaches of the backbeach could result in approximately $4 million and $353 million in damages in 2050 and 2100, respectively.

These damage estimates demonstrate that in the context of SLR, backbeach erosion at Torrey Pines is of a greater economic concern than flooding in the coming century. There are various adaptation strategies that can assist in minimizing flood and upland erosion damage, including armouring the shoreline and nourishing the beach. We estimate that the shoreline at Torrey Pines State Beach could be armoured at a capital cost of $69 million, with annual maintenance infusions of $2 million. Capital costs could change substantially depending on the year of placement, and maintenance costs could increase as the beach erodes and its ability to dissipate wave energy is diminished.

Our analysis indicates that in the coming decades, armouring the shoreline in its entirety is not an economically feasible solution to address flood and backbeach erosion risks. If one fixes the shoreline, a 1.4 m SLR will passively reduce a quarter of the existing beach by 2050, which could result in losses to recreational and habitat value reaching $8 million (NPV at 3% discount rate), lost state and local spending totalling $36 million (NPV at 3% discount rate) and lost state and local sales tax totalling $1 million (NPV at 3% discount rate). Using nourishment projects to maintain the existing beach width would require $6 million (NPV at 3% discount rate). While nourishment could help to minimize losses related to recreational value, spending, and taxes, nourishment could also result in reductions to habitat value not modelled in this report. Allowing the beach to retreat landward unimpeded can help support the existing beach width without the added costs of nourishment, safeguarding the recreational and habitat services that are threatened when the backbeach is armoured.

Upland erosion damages increase from $4 million at mid-century to $353 million in 2100. Ninety-five percent of this exponential increase in damages is directly tied to structural adjustment costs to ensure the continued operation of the LOSSAN railway north of the Los Peñasquitos Lagoon. If armouring is introduced along the entire stretch of shoreline, over 75 percent of the beach could erode following a 1.4 m SLR, resulting in significant losses to recreational and habitat services. Promoting natural beach processes where the beach is allowed to migrate landward unimpeded could result in significant economic benefits between now and 2050.

5. Data limitations

As with any economic analysis, the results depend on the quality of the data. The science of climate change and SLR is constantly evolving. Consequently, any analysis must either provide multiple scenarios (as this study did) or some sort of sensitivity analysis. Our knowledge of coastal flooding and erosion, while much better developed, is still rather basic in many of the scenarios provided here. Further refinement and more detailed studies of coastal geomorphology and flood damages are essential.

In terms of the key economic estimates, there is now a reasonable consensus among economists about the (non-market) value of coastal recreation. However, our knowledge of beach attendance and other recreational uses on the coast is surprisingly limited, despite the existence of many official counts at major beaches. Our knowledge of ecosystem services and the economic valuation of these services are far more limited and likely to remain so in the near future. Despite this limitation, it would be a mistake to completely ignore ecosystem services, in our opinion, since providing no value often implies that ecosystems are valued at zero.

Finally, our estimates of the costs of nourishment largely reflect current scarcity, but it is quite likely that, as coastal erosion increases, the demand for beach compatible sand will increase, raising the cost of nourishment.

6. Conclusions and recommendations

This study intends to increase the relevance of coastal economic impact studies to local planners and policymakers. The risks that rising sea levels present to coastal California communities are real and significant, extending beyond physical threats to beaches and coasts, and reverberating throughout local and State economies.

In this report, we do not implicitly or explicitly recommend implementation of particular coastal adaptation response strategies. The site-specific consequences, positive and negative, of implementing these strategies vary too greatly on a case-by-case basis for a study of this scope to sufficiently address. Rather, these results indicate the scale and nature of the economic risks that coastal California communities will face in the coming century and beyond.

Our six study sites encompass only about 15 of the more than 2000 miles of open coast and bays of the California coastline. Sea-level rise poses unique threats to every coastal community in California. We recommend more studies of this type to identify and assess distinct, site-specific economic risks for the consideration of local policymakers.

While this study was conducted on a more granular scale than previous economic studies, our current knowledge of the physical and biological impacts of SLR are still limited. Improvement in our knowledge of coastal erosion, storm impacts, habitat changes and other changes associated with SLR will need to be brought into a model of the type we propose. Despite these limitations, communities must start planning now for future SLR and the corresponding increased coastal erosion and flood damages. Policy makers will need to weigh the costs and benefits of various responses to SLR based on the best available data, revising these conclusions as better data becomes available. This study outlines a cost-effective method to examine different adaptation scenarios that can be implemented on a local level in a manner that is responsive to local stakeholders.

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Notes

1. A berm is a horizontal build-up of sediment on the back of the beach that results from wave action or human action (e.g. tractor) (CIRIA 1996).
2. The foreshore is the section of beach that is wet under normal tide and wave conditions, extending to the mean high water line (Mangor 2001).
3. Depth of closure for a given or characteristic time interval is the most landward depth seaward of which there is no significant change in bottom elevation and no significant net sediment transport between the nearshore and the offshore (Kraus, Larson, and Wise 1998).
4. Wetlands and beaches have a number of similar ecological functions, e.g. see Center for Coastal Resources Management (2009).

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