Title
Nature-based adaptation in San Francisco Bay: Social and economic benefits of nature-based adaptation solutions to protect San Mateo County from storms and sea level rise

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Social and economic benefits of nature-based adaptation solutions to protect San Mateo County from storms and sea level rise

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Contents

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Introduction

California's coastline is a vital asset, deeply intertwined with the state's economy, home to diverse ecosystems, and cherished for its cultural and recreational significance. Although the 19 coastal counties make up only 22% of California's land, they are home to 68% of the population and generate 80% of the state's wages and GDP[1,2]. The large and increasing concentration of people, critical infrastructure, and high-value real estate further underscores the coast's economic importance[2]. However, California's coast faces growing threats from burgeoning coastal hazards such as large swells, atmospheric rivers, El Nino events, and rising sea levels, which lead to erosion and flooding impacts that jeopardize coastal ecosystems and communities. As a result, the Ocean Protection Council, the Coastal Commission and other State agencies have identified coastal hazard adaptation as one of California's highest priorities[3–5].

Among coastal communities in California, those bordering low-lying estuarine environments, including San Francisco Bay, are highly vulnerable to flooding[7] creating significant economic, humanitarian, and national-security challenges. However, the majority of previous efforts to characterize potential coastal impacts of climate change have focused primarily on long-term SLR with a static tide level, and have not comprehensively accounted for dynamic physical drivers such as tidal non-linearity, storms, short-term climate variability, erosion response and consequent flooding responses. Here we present a dynamic modeling approach that estimates climate-driven changes in flood-hazard exposure by integrating the effects of SLR, tides, waves, and storms.

A 100-year storm event, combined with 2 meters of sea level rise (SLR), could impact 675,000 people throughout the State, and two-thirds of that flooding risk is concentrated in the San Francisco Bay Area[7]. Addressing these hazards is challenging and costly—raising coastal defenses to prepare for 2 meters of SLR could cost up to $450 billion for the region[8]. San Mateo County is projected to experience the greatest flood exposure in the State, with over $50 billion in infrastructure at risk by the end of the century[9]. Key assets exposed to climate hazards, including San Francisco International Airport and Silicon Valley, are already feeling the effects of rising seas and increased storm activity, and these risks are expected to intensify as climate change progresses.

At present, San Francisco Bay relies heavily on gray infrastructure, like levees and pumps, for flood protection. However, the region is increasingly moving away from traditional approaches and exploring various pathways to integrate nature-based shorelines, such as wetland restoration[10,11]. The 2016 passage of Measure AA by Bay Area Voters to support wetland restoration for risk mitigation illustrates this increasing momentum for more sustainable, nature-based approaches to climate adaptation. Wetlands provide effective coastal protection, flood mitigation capabilities, and valuable co-benefits, including wildlife habitat and carbon sequestration[12–15]. Historically, coastal development has eliminated or altered up to 90% of the Bay's historical tidal wetlands, leading to significant habitat loss and increased vulnerability to sea level rise and coastal encroachment[16,17].

In San Mateo County, marshes were diked, drained and, in some cases, developed into communities, leading to significant loss and alterations of historical marshes along the Bay's coast[18]. In their current condition, the remaining marshes now struggle to support diverse vegetation and adapt to rising sea levels[19]. Because of San Mateo County's flood risk and the state of its wetlands, the conservation and restoration of its marshes are highly prioritized[20]. Recent efforts have focused on restoring legacy salt ponds through levee breaching to restore historical tidal flow and enable natural inundation, sedimentation, and revegetation[21–23]. To manage increasing risks, the region has begun to plan how to effectively leverage nature-based solutions like wetland restoration[16,17]. In areas that are urbanized and developed, a smaller and more localized adaptation and resilience strategy involves the use of horizontal levees (or ecotone levees) that integrate vegetation with traditional levees to retrofit the levee itself. The vegetation reduces wave-driven action and provides a natural buffer against coastal flooding. This approach complements the restoration of marshes, offering a solution where large-scale habitat restoration is not feasible, while still promoting resilience and flood protection[10].

However, key limiting factors for the implementation of nature-based adaptation to date have included the lack of quantitative demonstrations of cost-effectiveness and access to financing. This study focused on rigorously evaluating the risk reduction benefits of previously proposed nature-based adaptation strategies for the county of Santa Mateo by combining coastal hazards, flood processes, and the socioeconomic impacts across multiple storm and sea level rise conditions. The results provide a comprehensive assessment of (i) risks now and in the future, and (ii) the spatially explicit benefits of nature-based climate adaptation measures. The study also covers the distribution of impacts and benefits in disadvantaged communities. To address the funding challenges of nature-based solutions, financing mechanisms that could support these solutions were also reviewed and discussed. Our aim is that this granular, multi-scenario study can inform about the risks and challenges posed by sea level rise and point to cost-effective strategies to adapt to the effects of climate change in the Bay Area.

This summary report provides an overview of the methodology, key results and findings. It is also accompanied by a more extended technical report and the spatial dataset.

Executive Summary

California's coast faces growing threats from burgeoning coastal hazards such as large swells, atmospheric rivers, El Nino events, and rising sea levels, which lead to erosion and flooding impacts that jeopardize coastal ecosystems, infrastructure, and communities. San Mateo County is projected to experience the greatest coastal flood exposure in California, with over $50 billion in infrastructure at risk by the end of the century.

In San Mateo County, marshes were diked, drained and developed leading to significant marsh loss across the Bay's foreshores. There is growing interest and investment in the conservation and restoration of San Mateo's marshes for flood risk management and adaptation.

This study rigorously evaluates the risk reduction benefits of marsh restoration and horizontal levees as nature-based solutions (NBS) for climate adaptation for Santa Mateo county. We assessed risks and NBS benefits by developing models of coastal hazards, flood exposure, and the socioeconomic impacts across multiple storm and sea level rise conditions. The study considers two types of adaptation strategies: (1) wetland restoration and (2) horizontal levees that use marshes in front of the artificial levee to reduce wave impacts. These adaptation scenarios are rigorously assessed in a variety of storm conditions and sea level scenarios.

- Presently, flood risk in San Mateo County is estimated at $477.6 million per year and for the 100-year flood, flood damages reach up to $1.8 billion.

- In the future, increases in storms and sea levels will significantly increase the risk of flooding across the county. Considering future storms and 0.5 m of sea level rise scenario, the annual flood damages in 2050 would increase by more than 3x to $1.6 billion; with storms and 1 m of SLR flood risk would increase 20x to $9.6 billion annually.

- Increases in risk will be even larger in disadvantaged communities, where annual flood risk estimates increase 17x under a 0.5 m SLR scenario and >750x with a 1 m SLR scenario.

- Potential marsh restoration of up to 7200 acres throughout the county could reduce present flood risk by $9.6 million per year. With 1 m SLR, the risk reduction from marshes increases to $50 million per year. Most of today's protection benefits from marsh restoration would be concentrated in Ingold-Milldale, but future benefits are distributed throughout the county's shoreline driven by the widespread flooding caused by SLR. Disadvantaged communities in the county would receive $6.8 million in annual protection benefits from salt marsh restoration.

- Horizontal marsh levees would reduce economic risk by 6% across the bayshores of San Mateo County. Under current conditions, horizontal levees could reduce risks by $4.6 million in extreme storms. In the future with increases in storms and 1 m of SLR, the benefits of horizontal levees could increase by 10x to $46.6 million. Redwood Shores and the area south of the San Francisco International Airport (SFO) receive the largest benefits against flood hazards, with benefits exceeding $10 million of avoided damage per census tract in a strong storm. Horizontal levees would not provide many direct benefits to disadvantaged communities.

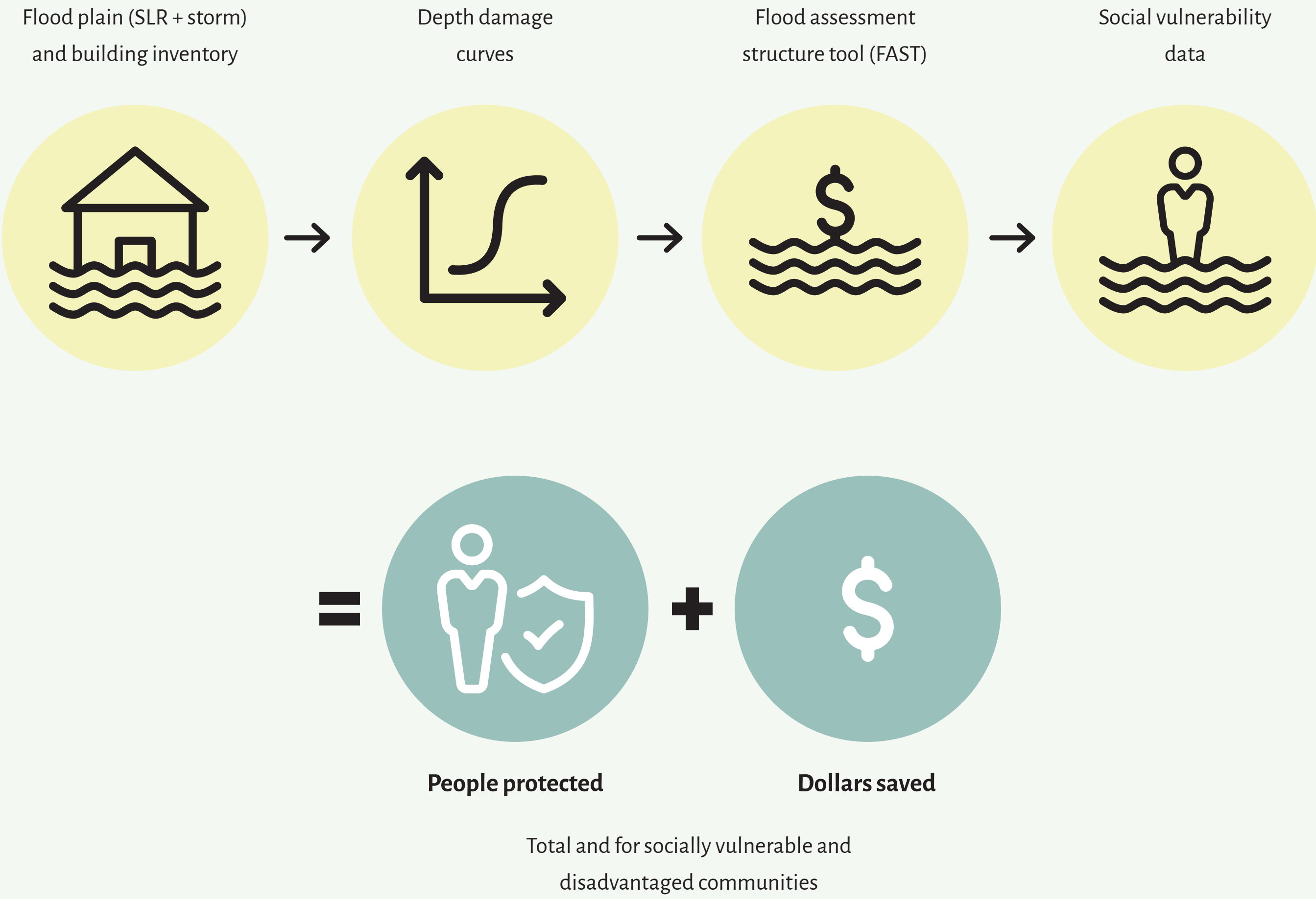
The study also explores opportunities for risk financing for these nature-based solutions . Identifying where marsh restoration and levees have the greatest economic benefits opens opportunities to support projects with funds for hazard mitigation, disaster recovery and/or climate adaptation. These values can be used in benefit-cost analyses to bolster applications for public investments, such as through Regional Measure AA funding, which provides approximately $500 million for marsh restoration throughout the San Francisco Bay, supported by a regional parcel tax. Other potential finance mechanisms include bond funding, such as Proposition 4 which was passed to support climate and water projects, California's Green and Infrastructure Banks, and the development of blue carbon credits following examples in the California Delta.

Methods in brief

The quantification of flood risks and benefits of nature-based adaptation projects followed a quantitative risk-based approach that integrates high-resolution elevation data, ecosystem presence, and adaptation projects into hydrodynamic models to define flood zones. Flood damages were calculated by evaluating the buildings and population affected by flooding for different storm probabilities. Economic damages were derived from building value and classifications using depth damage curves. The models are run for present climate conditions, future climate conditions that factor in sea level rise, and scenarios with adaptation options. The main steps of the methodology are summarized below and in Figure 1.

Figure 1.

Summary of methodological steps for assessing risk reduction benefits of nature-based adaptation.



Flood Risk Modeling

Hydrodynamic models were used to develop flood hazard maps, and considered high-resolution bathymetry, elevation data, and the distribution of wetlands, ponds, and levees[A]. These models accounted for coastal dynamics (tides, storm surge, river discharge, wave setup, and sea level rise), as well as existing ecosystems and flood protection systems. Marsh habitats were identified using the Bay Area Aquatic Resources Inventory (BAARI)[27], and flood control infrastructure from the SFEI's Bay Shore Inventory[28], which includes features such as levees, embankments, wetlands, and natural shorelines, among others. The model was driven by storm water levels, wind, and a pressure time series and creek discharge[7] for different storm return periods. In this way, the model accounts for flooding influenced by both the bay and the two gauged creeks in the region, San Mateo and San Francisquito[29]. Sea level rise was considered in the models assuming a 0.5 m and 1.0 m future SLR scenarios, as a static rise in mean water level. These scenarios are aligned with the most recent guidelines for California[2,30].

A Numerical models: Delft3D Flexible Mesh[24] for tides and storm surge and Simulating Waves Nearshore model (SWAN)[25] for wave simulation and propagation. The models were calibrated and validated with observations from NOAA tide gauges and water logger data collected from Laumeister marsh[26].

Modeling the Effects of Nature-Based Adaptation Strategies

The study considered two types of nature-based adaptation projects that were identified by stakeholders and previous studies in the county: marsh restoration and horizontal levees. Their possible locations and configurations were defined based on consultation with stakeholders and the San Francisco Bay Shoreline Adaptation Atlas[10]. The two types of adaptation options required different modeling approaches, and therefore, were modeled independently of each other.

Marsh Restoration

The locations of modeled marsh restoration projects were developed in collaboration with local flood managers and other stakeholders from San Mateo County and the Bay Area over a series of workshops. Insights informed the development of plausible scenarios of marsh restoration to assess its effects on flood risk in the study region. These scenarios resulted in wetland restoration areas and configurations along the county's shoreline, as represented in Figure 2.

Figure 2.

Location of the study area and details of the simulated restorations. (2A) and (2B) Location of this study, shown by the purple dot in (2A) and the black boxes in (2B) which show the extent of the maps in (2C-2F). (2C) Vertical offset applied to the restoration sites to simulate sediment accretion/nourishment, bringing each site to +1 m relative to mean sea level. These values range from 0.05 to 1.1 m. (2D) Levee breaches across historical marsh channels to facilitate tidal connectivity in salt ponds are shown in orange. (2E) Current and (2F) restored marsh habitat types, determined by elevation relative to tidal datum, as shown in equation 1. The three shades of green, from dark to light, denote low, transition, and high marsh habitat.

Figure 2A.

Figure 2B.

Figures 2C-2D.

(2C) Vertical offset applied to the restoration sites to simulate sediment accretion/nourishment, bringing each site to +1 m relative to mean sea level. These values range from 0.05 to 1.1 m. (2D) Levee breaches across historical marsh channels to facilitate tidal connectivity in salt ponds are shown in orange.

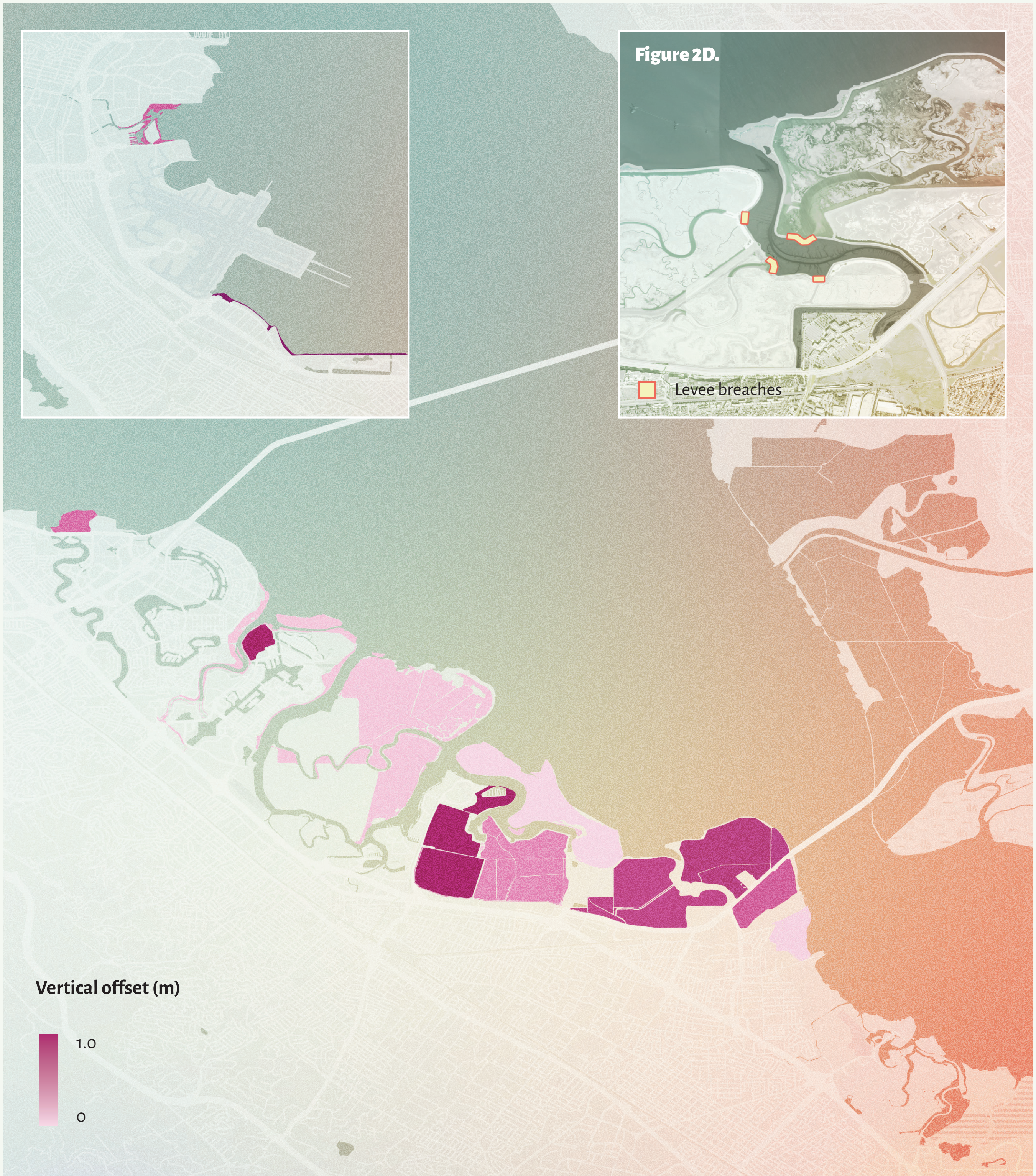


Figure 2E.

Current marsh habitat types, determined by elevation relative to tidal datum, as shown in equation 1. The three shades of green, from dark to light, denote low, transition, and high marsh habitat.

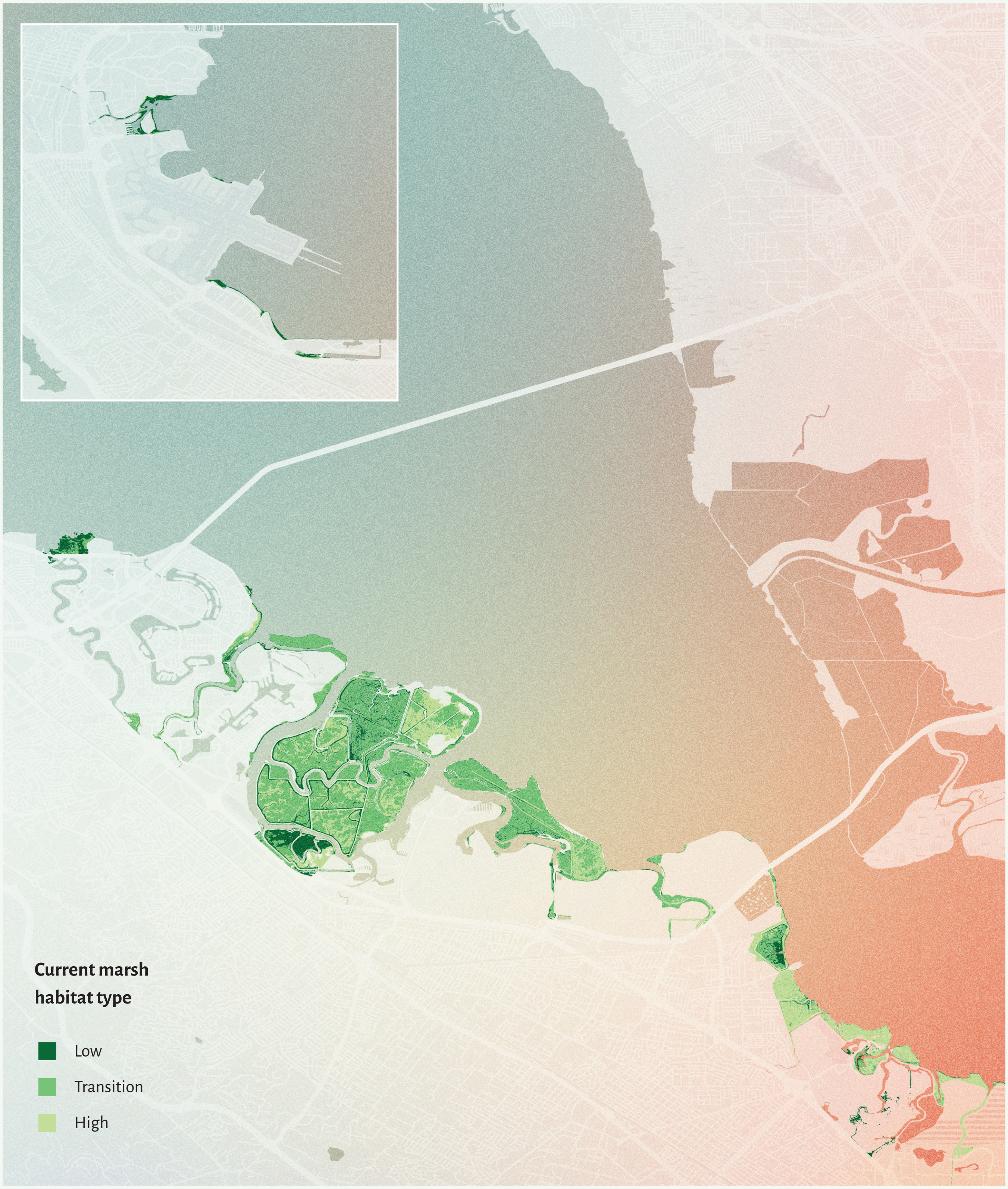
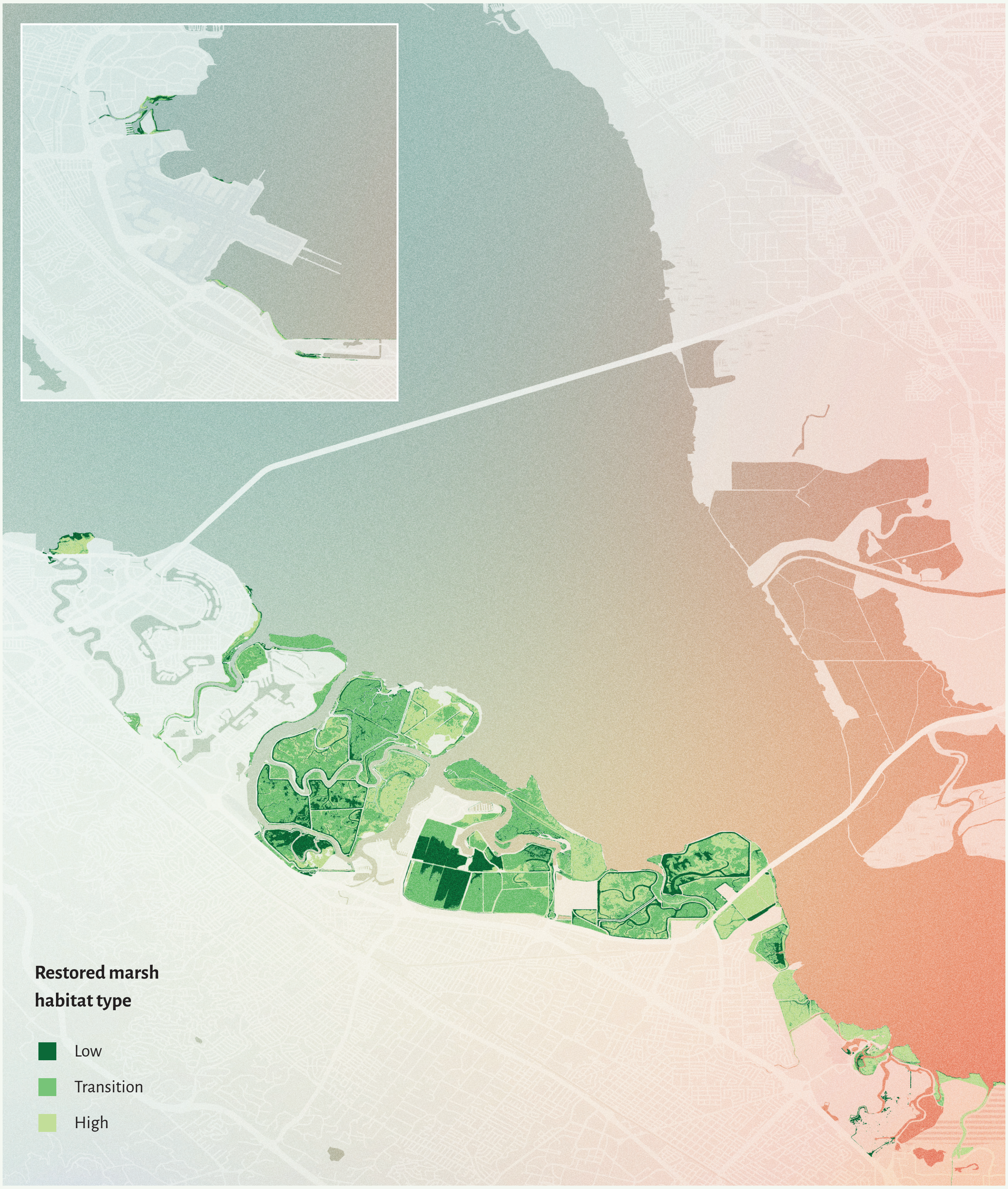


Figure 2F.

Restored marsh habitat types, determined by elevation relative to tidal datum, as shown in equation 1. The three shades of green, from dark to light, denote low, transition, and high marsh habitat.



Marsh restoration effects, including sediment nourishment and re-vegetation, were included in the hydrodynamic models by changes in elevation and bottom friction. Restoration sites were assumed to have an average elevation of 1 meter above mean sea level, a representative height for healthy regional marshes (see vertical offset in Figure 2-C)[31,32]. This vertical adjustment was applied across all restoration sites and types: low, transition, and high marsh vegetation. The zones with vegetation were also adjusted to reflect the upslope shift of marsh areas due to elevation changes and rising sea levels (Figure 2-E and 2-F). The model also included the breaching levees around salt ponds. The breach locations were determined via satellite imagery and historical photography to identify natural openings (Figure 2-D). While the model used the most recent marsh distribution data, marshes are dynamic and manual changes to sites were incorporated based on stakeholder input with respect to the original datasets.

Horizontal Levees

Horizontal, or ecotone, levees are hybrid nature-based adaptation options that combine traditional levees (gray infrastructure) with restored marsh vegetation (green infrastructure) to enhance flood protection (Figure 3-A). In between the levee and the water's edge, marsh plants distributed on a wide and gently sloping expanse of vegetated habitat attenuate waves and reduce the probability of wave-driven levee overtopping. Wave attenuation depends on plant characteristics and wave and water level conditions.

This analysis analyzed levee slopes for specific shoreline sections to determine optimal designs for reducing the risk of levee overtopping across the county's shoreline. The locations for potential horizontal levees were identified using the San Francisco Adaptation Atlas (Figure 3-C). Flooding was simulated with a numerical model that considered vegetation factors like stem density, height, diameter and drag, and determined overtopping flows and optimal levee slopes for improved flood protection[B,38].

Since overtopping events can result from various combinations of wave and water levels, a joint probability analysis using Multivariate Copula Analysis[39] was conducted to assess the likelihood of different wave heights and storm surge levels in producing overtopping. The resulting probability curves were recalculated for sea-level rise (SLR) scenarios as they will influence the probability of a certain wave height and extreme water level to drive overtopping more frequently in the future.

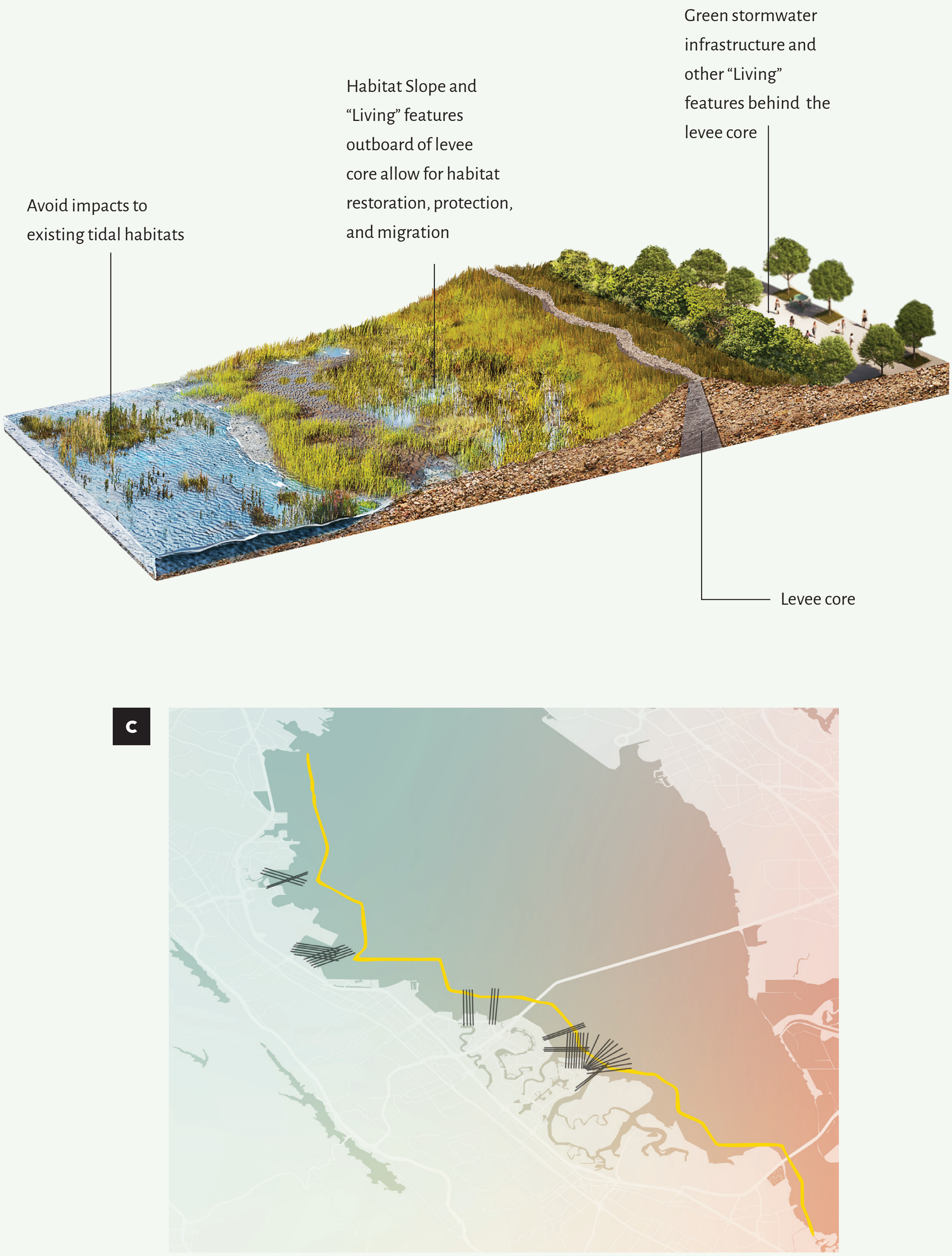
B Wave overtopping was simulated with the numerical model XBeach, a non-hydrostatic wave model that resolves nearshore wave transformation with the presence of vegetation and has been recently validated for overtopping problems[33-37]. The model was applied in 120m cross-shore sections along the levee length. The model captured differences in slopes, levee heights, and fringing marsh configurations while assuming perpendicular wave action against the shore. Slopes ranged from 1:20 to 1:100 ratios.

Figure 3.

Depiction of a horizontal levee (A) and study location (B and C). Transects used in the hydrodynamic simulations are shown by the black lines in (C).

A

C



Flooding in the lee of the levees was quantified with another hydrodynamic model using the overtopping rates to produce flood maps[C].

Flood Damage Calculations

Economic damages were calculated using the distribution of buildings from the National Structure Inventory (NSI) buildings dataset[40]. Flood depths and vulnerability curves, from the FEMA FAST damage estimation tool[41], were used to infer damages to buildings. These spatially explicit damages were integrated across different storm probabilities to determine Expected Annual Damages (EAD), which is a risk metric that represents the average damage expected every year. EADs were calculated by integrating each storm probability, sea-level rise (SLR) scenario, and the two adaptation scenarios: without adaptation (baseline) and with adaptation options (marsh restoration or horizontal levee). The risk reduction benefits of adaptation options, or Expected Annual Benefit (EAB), was determined by comparing EADs between the two adaptation scenarios. In this way, the comparison of future-present damages and the with- and without- adaptation options provides direct quantification of the future changes in risk from sea level rise and the risk reduction of adaptation strategies, respectively. The final damages and benefits were spatially aggregated and measured using multiple metrics, including the number of flooded buildings, economic damages, and affected people.

Risks and Adaptation Benefits for Disadvantaged Communities

In general, low-income and socially vulnerable groups disproportionately shoulder the burden of flood damages. Disadvantaged populations are also projected to be more vulnerable to the impacts of climate change and sea level rise. This assessment sought to further understand implications for disadvantaged communities by utilizing social vulnerability data at the census block group level, alongside building-level damage estimates, to more precisely assess the social and economic benefits of restoration options for disadvantaged and vulnerable populations. This methodology was applied using multiple datasets, including BCDC[42] and CalEnviroScreen[43] to compare how total damages and risk reduction benefits vary depending on the scale and rank methodology of the data.

C Flooding behind levees was simulated with the numerical model Delft3D using 6-hour storms with different combinations of water levels and wave heights, based on the joint probability analysis and the overtopping rates from XBeach.

Results

Flood Risk and Effects of Sea Level Rise

At present, the estimated county-wide cost from flood damages caused by **a single 100-year storm is $1.8 billion** (Table 1)**.** Flood risk in San Mateo County is estimated at **$477.6 million per year**. However, sea level rise (SLR) will significantly increase the risk of flooding across the county. With a **0.5 m** SLR scenario, which could be reached before the mid-century according to the latest SLR guidance for California[D], annual flood damages to infrastructure would increase to **$1.6 billion,** a 3.3-fold increase. Meanwhile, 1 m of SLR would increase flood risk **20x** and cost up to **$9.6 billion per year.** A SLR of 1 m could be reached by 2060 according to an intermediate scenario for California[4].

A **single 100-year storm**, combined with **1 m** of SLR, could generate **$47.3 billion** in damages, a **26x increase** from risk at present (Figure 4). I Throughout the Bay Area, the **largest risks** from flooding and SLR are present in the northern areas of **Redwood City**, **Foster City**, **Redwood Shores**, and **Ingold-Milldale,** where damages associated with the **1-in-100-year** event, could exceed **$1 billion per census tract**. Risk will also increase significantly in other communities along the coast, such as areas around **Downtown San Mateo** and **East Palo Alto**.

In disadvantaged communities, annual flood risk estimates increase **17x** under a **0.5 m** SLR scenario and **754x** with a **1 m** SLR scenario. This significant rise in risk is largely due to the fact that, as sea levels rise, more inland areas, many of which are disadvantaged communities, become vulnerable to coastal flooding. Currently, these areas are better protected from coastal flood event. For instance, under a combined 1-in-100-year storm event and 1m SLR scenario, estimated flood damages in these communities could rise from the current estimate of $0.2 billion to $8.7 billion. Even with moderate SLR values, such as a **0.5 m** SLR, damages from **a single 100-year storm** could increase to **$1 billion** in **disadvantaged communities alone.**

D

Figure 4.

Economic flood damages with 1 m sea level rise and a 100-year return period storm and no nature-based adaptation. Values represent USD. Areas outlined in blue and red denote disadvantaged communities identified by the BCDC and the CES4 criteria, respectively.

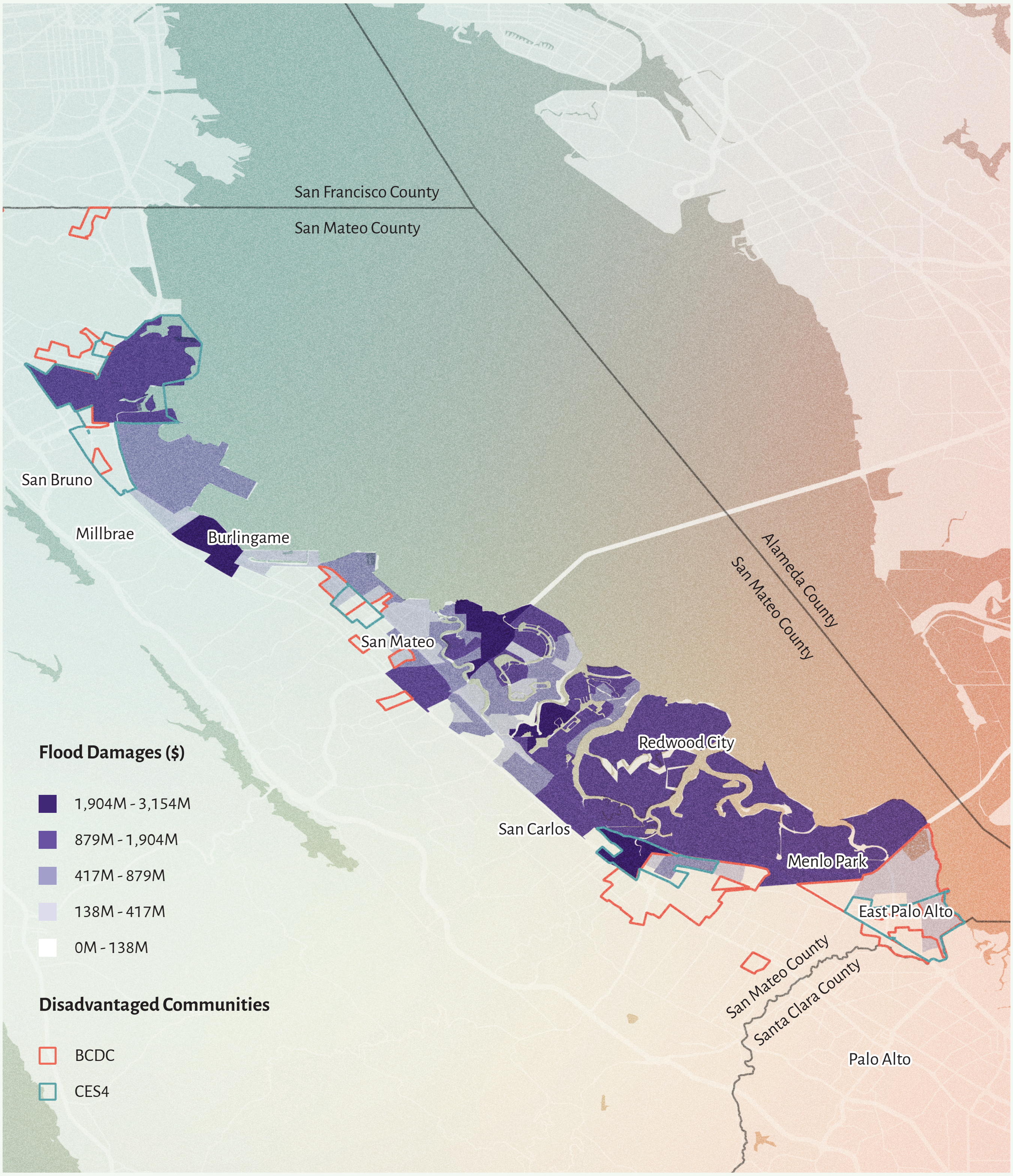


Table 1.

Flood risks totals across the county of San Mateo. Expected Annual Damages, EAD ($/year) are shown at the top, followed by economic damage associated with the storm of the 100-year return period.

EAD	SLR = 0	SLR = 0.5	SLR = 1
Total	$ 477,640,348	$ 1,578,031,602	$ 9,592,405,827
Total in top-5 tracts at risk	$ 99,925,248	$ 175,508,600	$ 2,162,931,668
Total in disadvantaged communities (BCDC)	$ 2,213,505	$ 38,282,499	$ 1,670,833,205

100-year	SLR = 0	SLR = 0.5	SLR = 1
Total	$ 1,820,064,765	$ 7,994,739,078	$ 47,342,492,708
Total in top-5 tracts at risk	$ 744,692,184	$ 2,896,134,818	$ 18,009,836,099
Total in disadvantaged communities (BCDC)	$ 229,708,239	$ 1,045,144,660	$ 8,681,846,855

Adaptation Options

Marsh Restoration

Potential marsh restoration of 7200 acres throughout the county could reduce present flood risk by **$9.6 million per year** across the county. With 1 m SLR, the risk reduction from marshes increases to **$50 million per year** across the county**. For a single 100-year storm** event, marsh restoration throughout San Mateo County would prevent **$115.5 million** in damages **and $150 million** with 1m SLR**. The comparison of the value of marshes for risk reduction in annualized terms versus an extreme storm indicates that marshes can provide a larger effect in mitigating smaller floods that would become increasingly frequent as sea levels rise along the Bay.** Most of today's protection benefits from marsh restoration would be concentrated in **Ingold-Milldale** (census tract 6081605100), but future benefits are distributed throughout the county's shoreline driven by the widespread effect of SLR that would create flooding atop the levee structures.

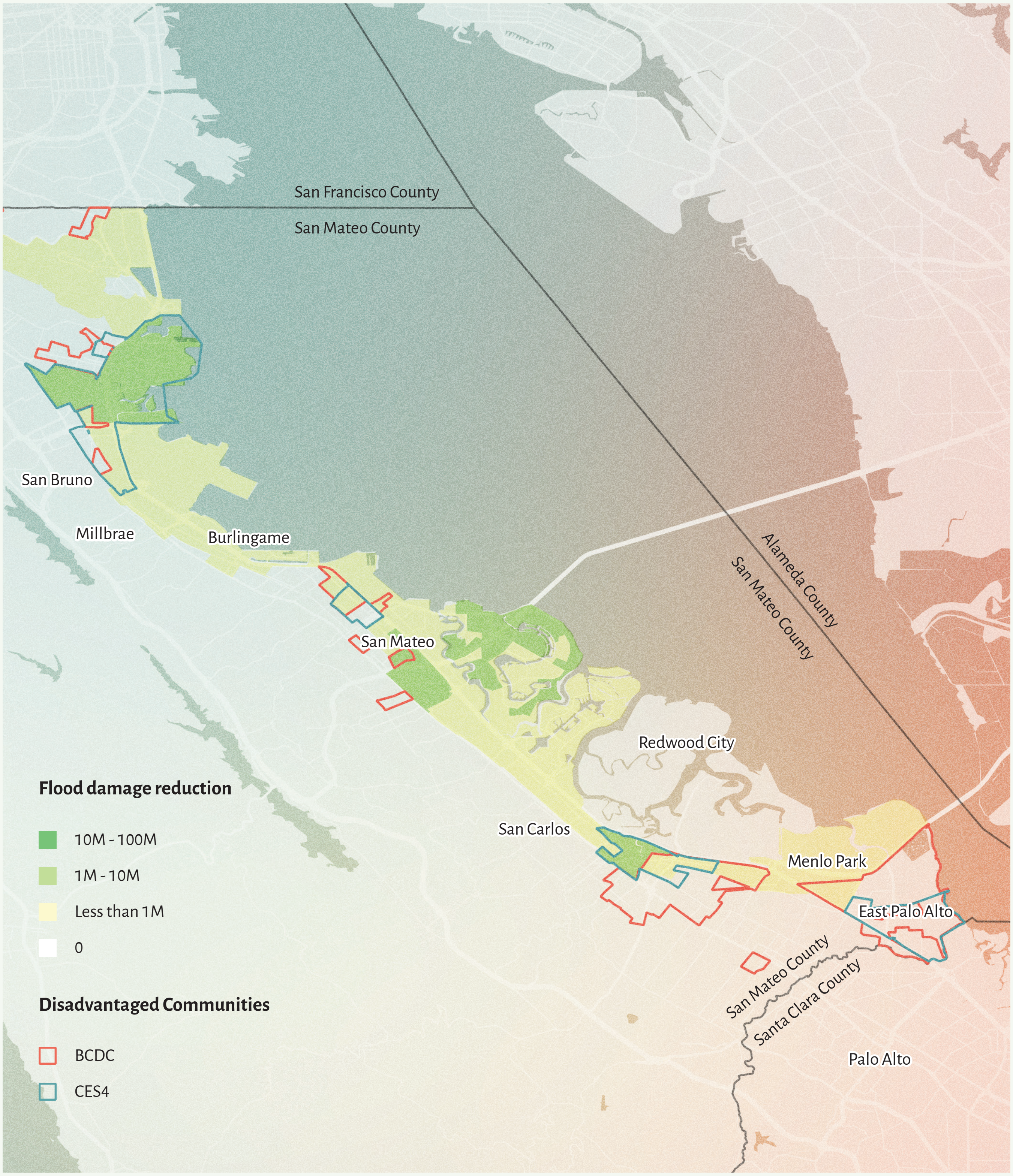
Overall, these results indicate that marsh restoration can be an effective strategy against SLR in many areas of the county. However, marsh restoration would not be able to protect areas totally from the added risks of SLR, which would be widespread across the county and they should be combined with retrofitting of levees and other measures, particularly in key census tracts where SLR will increase flood risks most.

The high-resolution hydrodynamic simulations also indicate another important factor to consider in marsh restoration. The configuration of the restored wetlands should be carefully assessed as it may modify storm surge propagation compared to the existing open pond areas and could increase flood potential in some areas, particularly for intermediate SLR scenarios (0.5 m). This is explained by the effects of the restoration configuration on the storm tide propagation through the wetlands. This effect was observed in the Cargill Ponds where marsh restoration would allow surge levels to reach the levee system faster than with the existing pond areas. For intermediate SLR scenarios, ponds function as flood regulation features that slow down the storm tide. However, this amplification is a highly local feature in south sections of the Cargill Ponds where the tipping point occurs for a SLR scenario of 0.5 m. Across the region, and for larger increases in sea levels, the marsh restoration reduces flooding.

Marshes also provide important benefits to mitigate the large increases in risk to disadvantaged communities. Disadvantaged communities in the county would receive **$6.8 million** in **annual protection benefits** from implemented salt marsh restoration. **Hayward Park**, a disadvantaged community, would receive the majority of these benefits, around **$6.5 million (Figure 4)**. Disadvantaged communities are often located further inland from the waterfront and will be protected from SLR if marshes are restored by the waterfront across storm conditions.

Figure 5.

Flood damage reduction due to restoration of salt marshes with a 100-year return period storm and 1 m SLR. Values represent USD. Areas outlined in blue and red denote disadvantaged communities identified by the BCDC and the CES4 criteria, respectively.



Horizontal Levees

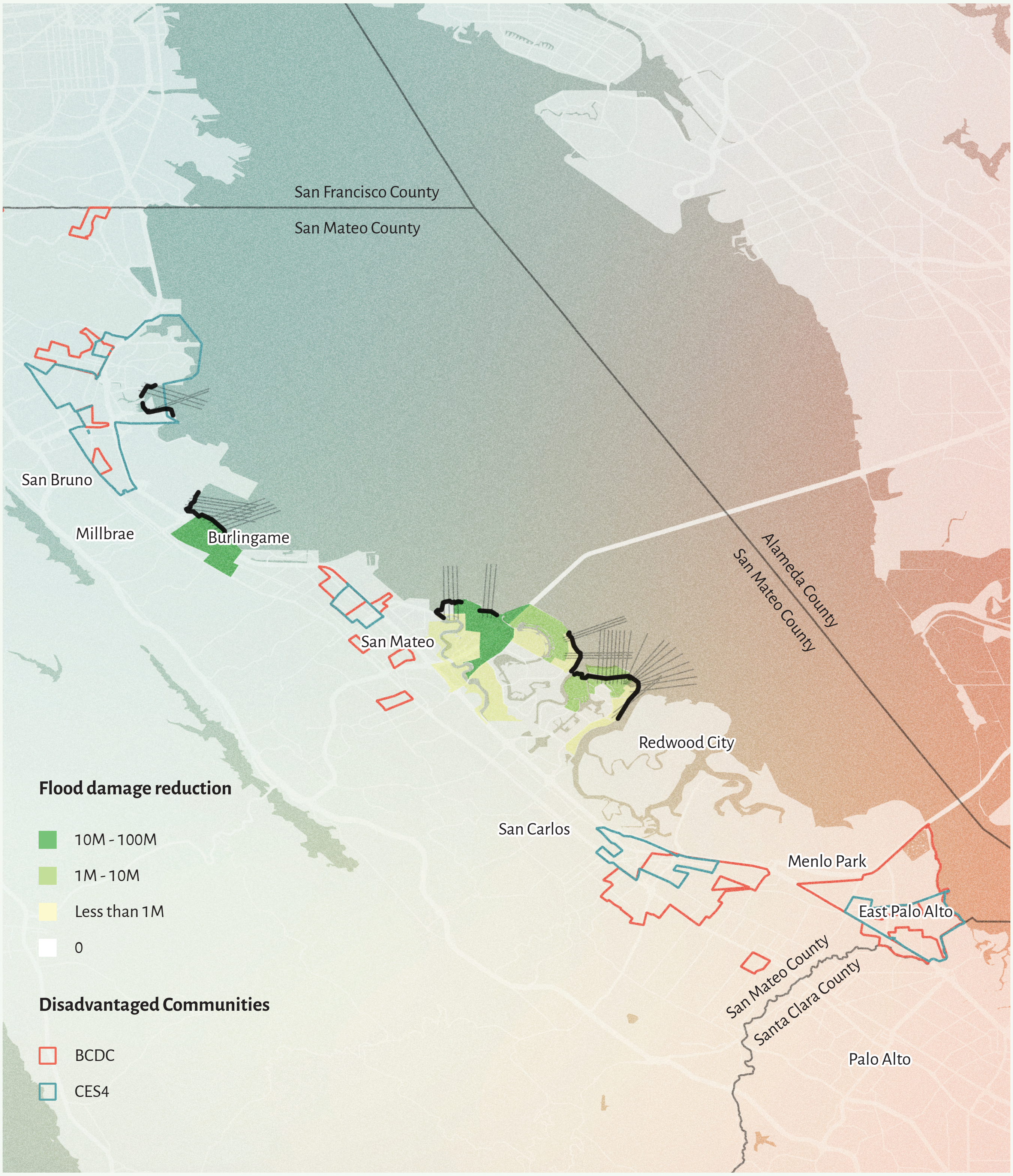
Adapting the levee system with **horizontal levees** would reduce economic risk by **6% countywide**. At present, the implementation of horizontal levees could provide $4.6 million in protection benefits in an extreme storm. In the future, with 1 m of SLR, horizontal levees could reduce **$46.6 million** in damage from an extreme storm resulting in a promising strategy for many vulnerable sections behind existing levees.

Further, more than **86%** of the **flood mitigation benefits** would be offered by only **three tracts** along the county's shoreline, including the eastern coast of **Redwood Shores**, the area **South of SFO**, and **Foster City**. **Redwood Shores** and the area **South of SFO** receive the largest benefits against flood hazards, with benefits exceeding **$10 million per census tract**.

However, in contrast with marsh restoration strategies, horizontal levees will not provide protection from SLR to disadvantaged communities. This is because horizontal levees would reinforce and upgrade traditional levee sections previously selected for horizontal levee emplacement by the SFEI Adaptation Atlas. However, these restoration scenarios were not located throughout the county, or necessarily in areas to protect disadvantaged communities. Thus, implementation of horizontal levees did not show benefits in disadvantaged communities, as compared to marsh restoration.

Figure 6

Flood damage reduction due to horizontal levees with a 100-year return period storm and 1 m SLR. Values represent USD. Areas outlined in blue and red denote disadvantaged communities identified by the BCDC and the CES4 criteria, respectively.



Climate risk financing options for nature-based adaptation

The term “risk financing” is relatively new and refers to financial mechanisms and structures that have the potential to fund activities that reduce the risk of natural hazards and climate change. Here we explore opportunities for risk financing for nature-based solutions (NBS) to reduce coastal flooding, specifically those suitable for estuarine, urban waterfront areas like the San Francisco Bay. The additional potential ecosystem benefits beyond flood risk reduction, such as biodiversity conservation, enhanced cultural value, and climate change mitigation only further reinforce the foundation and integrity of potential market-based mechanisms that could help channel funding toward nature-based adaptation projects in the San Francisco Bay area and beyond. Some of the main mechanisms identified are summarized below (more details are provided in the technical report).

Insurance policies that consider nature-based solutions

The world’s first insurance policy for a natural asset was developed in 2018 by The Nature Conservancy and partners for a part of the Mesoamerican Reef in Quintana Roo, Mexico[44,45]. This **parametric insurance** policy in Mexico provided coverage for the coral reef in the event of a storm that met a specified high wind trigger, with the payout funding reef restoration after the storm. Similar coverages for coral reefs in other locations have been developed since then.

Parametric insurance policies for coral reefs have inspired the development of other insurance products that also aim to leverage the risk reduction benefits of natural ecosystems. **Resilience insurance** is one such product[46]—here, the coastal ecosystem itself is not insured, but rather provides insurance benefits to policyholders by reducing property insurance premiums or expanding insurance availability for property owners who could not otherwise obtain insurance. Because resilience insurance would require a single aggregated buyer, it may be compatible with **community-based insurance**, an emerging concept which aggregates homeowners and identifies a single buyer who can purchase private flood insurance. Because nature-based risk reduction occurs on a landscape scale as opposed to an individual property scale, it may be particularly compatible with community-based insurance.

Additionally, private insurance policies can be written to incentivize rebuilding damaged infrastructure with NBS after a disaster. **Green building enhancements** are optional modifications to existing insurance policies, providing policyholders with additional funds if they rebuild more sustainably, including investing in marsh or other habitat restoration for risk mitigation purposes.

Credits

Carbon sequestration is central to many financing instruments and would, therefore, allow using carbon-related financing mechanisms to bring resources for salt marsh restoration aiming at decreasing flood risks. **Blue carbon markets** operate by quantifying and valuing the carbon sequestration capacity of coastal and marine ecosystems and integrating it into carbon trading schemes. They involve selling and buying emission reduction credits (offsets) driven by voluntary demand from companies looking to reduce emissions beyond their legal obligations. Currently there is a need for a larger global supply of blue carbon credits to fulfill the existing demand from the corporate sector[47]. **Resilience credits** are another mechanism currently under development[48], which seek to expand upon the idea of blue carbon credits and issue credits associated for flood risk reduction achieved by coastal wetland restoration.

Bonds

Bonds are a fixed income investment, where bond investors become creditors to the issuing entity. Bond investors are paid a fixed interest rate (coupon) on a fixed schedule and will be returned their initial investment (principal) upon maturity of the bond. Ecosystem restoration can be financed by **green bonds**[49], a rapidly growing debt-finance tool that provides a flexible and upfront source of capital[49,50]. Following a similar model to green bonds, **blue bonds** specifically fund projects that benefit coasts and oceans. In 2021, The Nature Conservancy (TNC) and the Government of Belize developed the Belize Blue Bond, a $364 million debt conversion for marine conservation. This innovative initiative reduced Belize's debt by 12% of its GDP, generated $180 million in sustainable financing for conservation, and secured a commitment to protect 30% of Belize's ocean, alongside a range of additional conservation measures. The transaction was the world's largest debt refinancing for ocean conservation, a process often referred to as a **debt-for-nature-swap**. In debt-for-nature-swaps, a portion of a developing nation's foreign debt is forgiven in exchange for investments in environmental conservation measures. Debt-for-nature swaps have been restricted to countries where the risk of default on debt payments is high. In these circumstances, the funder can purchase the debt at well below its face value. While such a transaction has not yet occurred domestically, it may be possible with participation from local governments with high debt burdens.

Other debt-based (pay-for-performance) financing tools to mobilize funds for large-scale wetland restoration include **resilience and environmental impact bonds**[50,51]. Resilience bonds, a sub-set of green bonds, seek to raise capital specifically for climate resilient investment. Environmental Impact Bonds function similarly to other bonds, except they must be used to fund an environmental project and are often designed so the amount investors are repaid is dependent on the success of the project[52-54]. This transfers some of the risk of the project to investors, thereby de-risking the project for the municipality or other issuer of the bonds, helping encourage NBS which are often less proved than other options.

Payments for ecosystem services

Payments for Ecosystem Services (PES) are another way to fund NBS projects in coastal areas[55] and in urban waterfronts. PES mechanisms incentivize ecosystem management practices that provide economic benefits aligned with ecological sustainability. The basic idea behind PES is that ecosystem services should be paid for by the beneficiary of the services as opposed to the 'polluter pays principle'. This shift can help accomplish broader environmental goals. An example for saltmarshes is found in Scotland, where agri-environmental schemes and PES are proposed to compensate landowners for lost livestock revenue when grazing regimes are reduced in salt marsh areas, thus working as an incentive for their restoration[56]. This example incentivizes farmers and landowners to adopt environmentally sensible practices to provide ecosystem services, including flood defense and climate regulation, and use payments for carbon sequestration and other ecosystem services to reduce grazing pressure where opportunity costs are higher.

Building also on the different benefits that ecosystems (natural capital) and NBS can produce, and that private property regimes and markets alone are ineffective and inappropriate to manage sustainably, these systems could also be managed as **Common Asset Trusts (CATs)**[56–58]. Trusts are widely used and well-developed legal mechanisms designed to protect and manage assets on behalf of specific beneficiaries, with funds provided by investors and/or donors. Applying this idea to coastal ecosystems is an extension of the concept. In the case of using a CAT to fund wetland restoration, the investors and/or donors would receive ecosystem service benefits, such as flood risk reduction, in return for their contribution to the trust. CATs can also enhance the financial viability of PES wetland restoration schemes[55], creating diversified investment portfolios that reduce complexity and administrative costs while increasing the credibility of service flows and confidence in returns.

Auctions have also been used to sustainably manage wetlands. For example, in Victoria (Australia), the Corangamite Catchment Management Authority (CMA) and the West Gippsland CMA utilized single-bid auctions to determine the costs for landholders to manage salt marshes according to a pre-existing management plan. Bids were used to identify and select the most cost-efficient and feasible alternatives, and winning landholders were invited to enter five-year contracts to undertake activities to protect coastal salt marshes. This approach allowed the CMAs to efficiently allocate resources to projects that provided the best value for money regarding conservation outcomes, covering significant areas of native vegetation with specific management objectives[59]. Such an approach may be viable for coastal wetlands as well.

Financial exemptions

Taxes or exemptions can also be used to fund nature-based adaptation. An example is found in the South Bay Salt Ponds Restoration Project in the San Francisco Bay Area. In 2003, 15,000 acres of salt ponds owned by Cargill Salt were purchased by the California State Coastal Conservancy, the U.S. Fish and Wildlife Service, and the California Dept. of Fish and Wildlife. The land was acquired for $100 million, plus $143 million in federal tax write-offs to the company.

Partnerships with the Federal Emergency Management Agency (FEMA) could also create additional opportunities for nature-based risk reduction. In the **FEMA Community Rating System**[59,60], FEMA provides discounts on insurance premiums (4 – 5%) on properties insured by the National Flood Insurance Program in communities that take some combination of specified risk-reducing actions. Some examples of the specified actions include construction of flood barriers, adoption of local policies encouraging retreat from the flood zone and using natural areas and open space for reducing flood risks. Natural infrastructure could be incorporated into the list of qualified actions. With appropriate agreement by communities and FEMA, a portion of premium savings could be used to support funding of a natural infrastructure project.

Public sector finance

Public sector finance can also support nature-based adaptation through disaster risk management programs such as FEMA's **Hazard Mitigation Assistance Grants**. Recognition of habitats as **Natural National Infrastructure,** as exemplified by coral reefs, facilitates the issuance of HMAG funds to NBS. In 2020, Puerto Rico recognized coral reefs as essential protection structures, and in 2023 the state of Hawaii and the U.S. Virgin Islands also made the designation of coral reefs as Natural National Infrastructure, followed by American Samoa in 2024. This type of designation enabled FEMA's Hazard Mitigation Program to provide funding for San Juan, Puerto Rico to restore coral reefs and create artificial reefs in 2022. With further study and engagement, such a path may be possible for wetlands like mangrove and marsh habitats. If marshes are designated as Natural National Infrastructure, they too could be more easily supported by FEMA's Hazard Mitigation Program after a disaster. FEMA also administers the **Building Resilient Infrastructure and Communities (BRIC) Grant Program**[61], which is a pre-disaster grant providing funds for hazard mitigation projects and capability and capacity-building activities that expand or improve the administration of mitigation assistance. Funding from this grant reduces reliance on reactive spending and increases proactive investments in science-based community resilience projects, including nature-based adaptation.

Two other key public sector climate finance tools are **infrastructure banks** and **green banks**[51]. Different states have versions of an infrastructure bank, which is a fund established to issue bonds for transportation improvements for highways, railways, and other transit capital. However, given the appropriate legal authority, these banks could fund other types of infrastructure as well. The flexibility of creating financing packages for a project from both public and private sources is a strength of these mechanisms, and while these banks have not historically funded natural infrastructure yet, they may plan an important role with this in the future. Like infrastructure banks, green banks can be public or nonprofit financing entities that combine public and private finance, but with a focus on funding projects that reduce emissions, including clean energy projects. Green banks tend to focus on funding projects that are not fundable by other financial mechanisms and that deliver public benefit or economic development goals. Green banks often focus on making funding available to underserved markets, through loan subsidies, modified credit requirements, or support to other lenders.

Another opportunity born from California legislation is the development of **climate resilience districts**. Senate Bill 852, passed in 2022, authorizes local cities, counties, and special districts, either alone or in combination, to establish climate resilience districts, which can then raise and allocate funding for projects that address climate threats including sea level rise and flooding. Funding for such projects can be raised through tax funding, voter approved supplementary property taxes, and other fees. These districts can then use the funds to plan and implement projects that are focused on climate mitigation and adaptation. Establishment of such a district in San Francisco Bay could enable funding to be allocated to support marsh restoration and horizontal levee development for flood risk reduction. While some funding avenues require voter support (e.g. supplementary property taxes), voters in the Bay Area have historically been supportive of such measures.

Figure 7.

Feasibility and impact of a range of disaster risk financing mechanisms for marsh restoration in San Francisco Bay. Position along the axes represent the qualitative degree of feasibility and impact (capacity to fund nature-based adaptation).

Funding type

Private · State · Public and NGO · NGO · Public · Public and private · Federal · State and private

Moving forward

This report summarizes work developed to support adaptation to sea level rise and climate change through nature-based solutions in the San Francisco Bay Area. The study quantified the socio-economic benefits of salt marshes for flood risk reduction in San Mateo County to inform innovative implementation and financing of nature-based adaptation. The project specifically focused on the risk reduction services of two specific nature-based adaptation projects that were identified by the San Francisco Adaptation Atlas and stakeholders: salt marsh restoration projects, and marsh-levee designs. These two solutions, identified as promising strategies to adapt to sea level rise, remained to be evaluated in quantitative risk terms, which this study aimed to address. The analyses provide a rigorous assessment of the value of these nature-based projects for risk reduction through detailed modeling of present and future flood risks and both economic considerations and prioritization of where adaptation strategies could offer the greatest benefits to socially vulnerable communities. The project also explored new financing mechanisms that could support these and other nature-based and sea level rise adaptation strategies.

While restoration can meaningfully reduce flood risk to people and property in San Mateo County and the San Francisco Bay Area, it is only part of a set of hybrid solutions needed to provide sufficient flood protection. Furthermore, flood protection is only one of many benefits that salt marshes, horizontal levees and other nature-based solutions provide in the Bay. Other co-benefits include carbon sequestration, fish and wildlife habitat, improved water and air quality, and recreation. This first-of-its-kind valuation of nature-based adaptation benefits has the potential to advance the protection and restoration of important natural infrastructure in San Mateo County, the California county with the greatest exposure to sea level rise, via the following pathways:

1. **Restoration project design.** Marsh restoration and horizontal levees do not reduce flood risk evenly across the landscape—some locations in San Mateo County would benefit more than others. The detailed flood model developed in this study evaluates the risk of flooding with and without nature-based adaptation at a local scale, a tool that can be highly useful for the planning and design phases of nature-based climate adaptation projects in San Mateo County. It also informs pre-feasibility designs (e.g. which slopes and locations) would be most effective and under what scenarios.

2. **Investment in marsh restoration for flood protection.** Monetizing the flood risk reduction benefits of salt marshes and horizontal levees has the potential to help identify where funds for hazard mitigation, disaster recovery and/or climate adaptation would be most cost-effective. The additional quantification of benefits may focus greater investments in restoration projects throughout San Mateo County by further building the case that

project benefits outweigh the costs. Such benefit-cost analyses may be used to bolster applications for public investments, such as through FEMA's BRIC grant program or Regional Measure AA, which provides approximately $500 million for marsh restoration throughout the San Francisco Bay. Private property owners along the Bay may be motivated to invest in salt marshes if they directly benefit from reduced flood risk, in addition to co-benefits such as recreation and habitat protection.

3. **Flood insurance and climate adaptation finance**. A key barrier to incorporating risk reduction benefits of marshes into insurance pricing is the lack of available science that quantifies the risk reduction of marshes across the landscape. This study has taken a first step to fill this data gap, and future work can continue to build the case. A potential next step could be to explore applications in both the risk industry and FEMA's National Flood Insurance Program (NFIP). For example, this science could be integrated into FEMA's Community Rating System, where community investments in flood risk reduction, such as preserving open spaces, could lead to discounted premiums for policyholders. There is also the potential to incorporate the modeling of salt marshes into industry risk models used for pricing private flood insurance products, providing a more detailed assessment of the flood risk reduction benefits of salt marshes and potentially, premium reductions.

Going forward the UCSC Center for Coastal Climate Resilience aims to continue building the evidence base for flood risk mitigation by salt marshes and other nature-based solutions in California, with the goal of unlocking additional investments for climate adaptation and natural infrastructure. This policy brief focuses on quantifying the benefits of salt marshes and horizontal levees in reducing flood risk and levee overtopping in San Mateo County. Future advancement of this work will explore other nature-based adaptation approaches that may be effective across the state of California and how leveraging nature can be a solution to adapt to coastal hazards in the decades ahead.

4. **Replication in other areas.** As climate change progresses and sea level rise and flooding put communities at increasing risk, as spatially quantified in this study, protecting and restoring wetlands can ameliorate the social and economic impacts to coastal communities in San Mateo County and beyond. While this study was focused on a single county, and site-specific conditions, the approach can be replicated and expanded to the rest of the Bay area with all the projects identified in the San Francisco Adaptation Atlas. The approach can also be applied to a diverse array of communities in urban estuaries worldwide.

A primary goal going forward will be to investigate these pathways and determine the opportunities for leveraging the value of salt marshes as a natural infrastructure system to expand their protection and restoration in San Mateo County and the San Francisco Bay more broadly, which has historically relied on gray infrastructure, such as levees. Wetlands play a valuable role in reducing flood risk, and marsh restoration can, therefore, be an important tool for increasing community resilience through nature-based flood defense. Quantifying the benefits of nature-based solutions such as salt marsh restoration will allow for greater opportunities for incorporating them into a holistic set of climate resilience strategies.

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