Comments on the
Modernization of Army Civil Works Policy Priorities
Docket ID No. COE-2022-0006

Submitted by

The National Wildlife Federation
and
American Rivers

August 2, 2022

Submitted through the Federal eRulemaking Portal at https://www.regulations.gov/

Table of Contents

Attachment A:
Suggested Language for Incorporating PR&G Agency-Specific Recommendations Into Corps Planning

Attachment B:
A. D. Guerry, Silver J., Beagle J., et al, npj Urban Sustainability (2022), Protection and restoration of coastal habitats yield multiple benefits for urban residents as sea levels rise, https://doi.org/10.1038/s42949-022-00056-y.

Attachment C:
Michelle Hummel, Griffin R., Arkema K., Guerry A., PNAS 2021 Vol. 118 No. 29 e2025961118, Economic evaluation of sea-level rise adaptation strongly influenced by hydrodynamic feedbacks, https://doi.org/10.1073/pnas.2025961118.

On behalf of our millions of members and supporters across the country, the National Wildlife Federation and American Rivers appreciate the opportunity to comment on the U.S. Army Corps of Engineers' (Corps) efforts to modernize the Army Civil Works Policy Priorities. Our organizations call on the Corps to use this opportunity to infuse this Administration's ecosystem resilience, community protection, and equity considerations into water resources planning.

Our organizations appreciate the Administration's commitment to institutionalizing "a new way of Corps planning and decision making."[1] We urge the Corps to adopt the recommendations provided in these comments to ensure that this much-needed new way of planning will produce projects that increase community and ecosystem resilience, redress pervasive environmental injustices, respect the rights and sovereignty of Tribes, and protect and restore the health of the nation's waters and the wildlife that relies on those vital resources. We also urge the Corps to obtain additional input into the agency's Environmental Justice and Tribal policies through intensive and direct outreach to communities and Tribes.

General Comments

The changing climate, combined with historic and ongoing destruction and degradation of vast swaths of habitat, have increased flood and storm risks for communities, with economically disadvantaged communities and communities of color often bearing the brunt of the impacts.

The nation has suffered more billion-dollar inland flood disasters in the last decade than in the prior three decades combined. We have endured more billion-dollar hurricane disasters in the last five years than in the decade before.[2] The human suffering caused by these and many smaller disasters is unfathomable, and the ever-mounting toll of human suffering and economic loss from natural disasters shows no sign of abating and every sign that it will continue to grow.

Research shows that both the intensity and number of extreme storms will continue to increase appreciably as our climate warms. In some locations, future extreme events could be twice as intense as historical averages.[3] By 2100, previously rare extreme rainstorms could happen every two years.[4] By 2050, high tides could cause "sunny day" flooding in coastal communities 25 to 75 days a year.[5] By the

[1] Modernize Civil Works Federal Register Notice Overview Virtual Meeting June 22, 2022, Slide 54.
[2] NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2021) (https://www.ncdc.noaa.gov/billions/), DOI: 10.25921/stkw-7w73 (inland flooding "caused by billion-dollar hurricanes (i.e., Harvey, Florence, Matthew) has also increased").
[3] E&E News, Anne C. Mulkern, Climate drives rise in global damage from storms — study, July 12, 2021; Madakumbura, G.D., Thackeray, C.W., Norris, J. et al. Anthropogenic influence on extreme precipitation over global land areas seen in multiple observational datasets. Nat Commun 12, 3944 (2021). https://doi.org/10.1038/s41467-021-24262-x.
[4] Inside Climate News, New Study Shows Global Warming Intensifying Extreme Rainstorms Over North America, June 2, 2020; Megan C. Kirchmeier-Young, Xuebin Zhang, Human influence has intensified extreme precipitation in North America, Proceedings of the National Academy of Sciences Jun 2020, 117 (24) 13308-13313; DOI:10.1073/pnas.1921628117.
[5] NOAA High Tide Flooding Report, 2021 State of High Tide Flooding and Annual Outlook.

end of the century, homes and commercial properties currently worth more than $1 trillion could be at risk of chronic flood inundation.[6]

Storms and floods in the U.S. disproportionately harm Black, Latinx, Indigenous, low-income, and frontline communities. For example, the neighborhood that suffered the worst flood damage during Hurricane Harvey was in an area of southwest Houston where 49 percent of the residents are people of color. Damage from Hurricane Katrina was most extensive in the region's Black neighborhoods. In four of the seven ZIP codes that suffered the costliest flood damages from Hurricane Katrina at least 75 percent of residents were Black.[7] Over the next 30 years, the "risk of coastal floods damaging or destroying low-income homes will triple" resulting in the flooding of more than 25,000 affordable housing units each year.[8]

In addition, "while severe storms fall on the rich and poor alike, the capacity to respond to and recover from flooding is much lower in socially vulnerable populations that even in the best of times are struggling to function."[9] Even low levels of flooding can wreak havoc on buildings and the residents who live in them, damaging belongings, disrupting electrical equipment, contaminating water sources and septic systems, and generating mold. These impacts can "cause profound disruptions to families already struggling to make ends meet" and can be particularly challenging to remedy in affordable housing units, which are often in poor repair to begin with.[10]

The extensive use of structural projects has not stemmed the nation's skyrocketing flood and storm damages—and indeed, damages are increasing at least in part due to the false sense of security that such structures can create. In just the last 5 years (2017-2021), there have been 7 inland flood events that caused more than one billion dollars each in damages. Collectively those floods caused $29.4 billion in damages and 44 deaths. In 2019 alone, the three largest floods caused a total of $22.9 billion in damages and 12 deaths (Mississippi River, Midwest and Southern Flooding; Arkansas River Flooding; and Missouri River and North Central Flooding). Coastal storms caused even more harm. The 18 largest hurricanes between 2017 and 2021 caused $512.5 billion in damages and 3,474 deaths. Hurricanes Harvey (2017), Maria (2017) and Ida (2021) alone caused $334.6 billion in damages and 3,166 deaths.[11]

The nation's wildlife has also been pushed into crisis, helping to drive the planet's ongoing 6th Mass Extinction of species.[12] As many as one-third of America's plant and wildlife species are vulnerable, with

---

[6] Union of Concerned Scientists. Underwater: Rising Seas, Chronic Floods, and the Implications for US Coastal Real Estate (2018).

[7] Thomas Frank, Flooding Disproportionately Harms Black Neighborhoods, Scientific American (June 2, 2020).

[8] Maya K Buchanan *et al,* Sea level rise and coastal flooding threaten affordable housing, *Environ. Res. Lett.,* 15 124020/ (2020).

[9] National Academies of Sciences, Engineering, and Medicine 2019. Framing the Challenge of Urban Flooding in the United States. Washington, DC: The National Academies Press. https://doi.org/10.17226/25381.

[10] Buchanan *et al,* Sea level rise and coastal flooding threaten affordable housing (see footnote 8).

[11] NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2022). https://www.ncei.noaa.gov/access/billions/, DOI: 10.25921/stkw-7w73 (providing the source of all data in this paragraph).

[12] Gerardo Ceballos, Ehrlich Paul, Raven Peter, Vertebrates on the brink as indicators of biological annihilation and the sixth mass extinction. Proceedings of the National Academy of Sciences Jun 2020, 117 (24) 13596-13602; DOI: 10.1073/pnas.1922686117 ("The ongoing sixth mass extinction may be the most serious environmental threat to the persistence of civilization, because it is irreversible. . . . the sixth mass extinction is human caused and accelerating. . . . species are links in ecosystems, and, as they fall out, the species they interact with are likely to go

one in five imperiled and at high risk of extinction.[13] State fish and wildlife agencies have identified more than 12,000 species nationwide in need of conservation action, and fully one-third of North America's bird species require urgent conservation attention.[14]

America's freshwater species, which are most affected by water resources projects, have been particularly hard hit. Freshwater species are the most at risk species per unit area on earth due primarily to habitat loss and degradation that is caused by agriculture, urbanization, infrastructure such as dams and levees, and logging.[15] Approximately 40 percent of the nation's freshwater fish species are now rare or imperiled.[16] Nearly 60 percent of the nation's globally significant freshwater mussel species are imperiled or vulnerable, and an additional 10 percent are already extinct.[17] All medium to large size rivers in the United States rank as having the highest categories of imperiled biodiversity in the nation.[18]

The historic loss and degradation of flood-buffering wildlife habitat across the country makes each additional acre of wetland lost or natural stream segment channelized even more consequential for community safety and well-being and the long-term viability of our nation's fish and wildlife. At least ten states have lost more than 70 percent of their wetlands, which provide essential fish and wildlife habitat, while 22 states have lost 50 percent or more of their original wetland acreage.[19] The construction of levees to reduce the frequency and duration of flooding in the lower Mississippi River

---

also. . . . Our results reemphasize the extreme urgency of taking massive global actions to save humanity's crucial life-support systems.")

[18] U.S. Geological Survey, Ecological Health in the Nation's Streams, Fact Sheet 2013-3033 (July 2013); Carlisle, D.M., Meador, M.R., Short, T.M., Tate, C.M., Gurtz, M.E., Bryant, W.L., Falcone, J.A., and Woodside, M.D., 2013, The quality of our Nation's waters—Ecological health in the Nation's streams, 1993–2005: U.S. Geological Survey Circular 1391 (120 pp).

[13] Stein, B. A., L. S. Kutner, J. S. Adams eds. 2000. Precious Heritage: The Status of Biodiversity in the United States. New York: Oxford University Press.

[14] Stein, B. A., N. Edelson, L. Anderson, J. Kanter, and J. Stemler. 2018. Reversing America's Wildlife Crisis: Securing the Future of Our Fish and Wildlife. Washington, DC: National Wildlife Federation.

[15] Pimm, S. L., C. N. Jenkins, R. Abell, T. M. Brooks, J. L. Gittleman, L. N. Joppa, P. H. Raven, C. M. Roberts, J. O. Sexton. 2014. The biodiversity of species and their rates of extinction, distribution, and protection. Science 344, 1246752.

[16] Jelks, H. L., S.J. Walsh, N.M. Burkhead, et al. 2008. Conservation status of imperiled North American freshwater and diadromous fishes. Fisheries. 33: 372-407.

[17] Williams, J. D., M. L. Warren, K. S. Cummings, J. L. Harris, and R. J. Neves. 1993. Conservation status of freshwater mussels of the United States and Canada. Fisheries 18: 6–22; Lydeard, C., R. H. Cowie, W. F. Ponder, et al. 2004. The global decline of nonmarine mollusks. BioScience 54 321-330.

[18] Hamilton, Healy, Regan L. Smyth, Bruce E. Young, Timothy G. Howard, Christopher Tracey, Sean Breyer, D. Richard Cameron, Anne Chazal, Amy K. Conley, Charlie Frye, Carrie Schloss. 2021. Increasing taxonomic diversity and spatial resolution clarifies opportunities for protecting US imperiled species. Ecological Applications. 32:e2534 DOI: 10.1002/eap.2534. See also FAO (2020) The State of World Fisheries and Aquaculture. Sustainability in Action. Rome. https://doi.org/10.4060/ca9229en.

[19] T.E. Dahl and S.M. Stedman. 2013. Status and trends of wetlands in the coastal watersheds of the Conterminous United States 2004 to 2009. U.S. Department of the Interior, Fish and Wildlife Service and National Oceanic and Atmospheric Administration, National Marine Fisheries Service. (46 pp); Dahl, T.E. 2006. Status and trends of wetlands in the conterminous United States 1998 to 2004. U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. (112 pp); Dahl, T.E. 2000. Status and trends of wetlands in the conterminous United States 1986 to 1997. U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. (82 pp); Dahl, T.E., and Johnson, C.E., 1991, Status and trends of wetlands in the conterminous United States, mid-1970's to mid-1980's. U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. (28 pp).

Valley is the single largest contributor to wetland losses in the country, according to the Department of the Interior.[20] Fish and wildlife have also been severely harmed through the pervasive alteration of natural stream flows, including from reservoirs and locks and dams, which have occurred in 86 percent of the almost 3,000 streams assessed by the U. S. Geological Survey.[21]

If our communities, economy, and wildlife are to survive and thrive, we must quickly implement a new approach to managing the nation's water resources. Maintaining the status quo or relying on ambiguous, non-binding suggestions for planners will not change the Corps' entrenched planning processes—relegating our communities to repeated cycles of ever-increasing hardship and loss and continued reliance on disaster response and recovery instead of increasing community resilience before disaster strikes, while continuing to cause the unnecessary and avoidable destruction of vital wildlife habitat.[22] This in turn will lead to calls for more and more water resources projects that will be forced to compete for construction dollars with the Corps' already significant $109 billion backlog of projects.

Corps planning must be modernized to prioritize building resilience into all Corps projects, operations, and planning across each Corps business line, with a fundamental focus on climate change, biodiversity, and community safety. A resilient system can withstand changing conditions and readily recover from extreme floods, storms, and droughts. Building resilience into Corps planning means protecting our wetlands, rivers, streams, and shorelines, along with the hydrologic processes that maintain these systems. It means restoring critical natural systems that have been lost or damaged. It means pre-planning to ensure that disaster response activities will build community resilience for future storms and increase habitat for wildlife.

Critically, building resilience into Corps projects and planning means making the use of natural and nature-based solutions the rule for Corps projects rather than the exception. Working with nature is an indispensable part of resilience because healthy natural systems provide free and self-sustaining protections and benefits, including reducing flood risks, sustaining fish and wildlife, improving water quality, regulating sediment loading, stabilizing soil, sequestering carbon, and providing recreational opportunities.

Protecting and investing in natural and nature-based solutions makes communities safer and more resilient by absorbing floodwaters, buffering storm surges, and giving rivers room to spread out without harming homes and businesses. These solutions reduce the need for new, often expensive structural

---

[20] Report to Congress by the Secretary of the Interior, The Impact of Federal Programs on Wetlands, Volume II, at 145 (1994). Approximately 80 percent of the bottomland hardwood wetlands in the lower Mississippi River basin have already been lost approximately. Report to Congress by the Secretary of the Interior, The Impact of Federal Programs on Wetlands, Volume I at 39.

[21] U.S. Geological Survey, Ecological Health in the Nation's Streams, Fact Sheet 2013-3033 (July 2013); Carlisle, D.M., Meador, M.R., Short, T.M., Tate, C.M., Gurtz, M.E., Bryant, W.L., Falcone, J.A., and Woodside, M.D., 2013, The quality of our Nation's waters—Ecological health in the Nation's streams, 1993–2005: U.S. Geological Survey Circular 1391 (120 pp).

[22] For example, from 2005 to 2016, the Corps received $31. 4 billion in supplemental funding, which amounts to almost half of the agency's annual discretionary appropriations over that same period.[22] Of those supplemental funds, 87 percent ($27.2 billion) was provided to respond to flooding and other disasters. With ever increasing effects from storms, these emergency supplemental appropriations have also dramatically increased over time, with the Corps receiving "$1.1 billion in the 1990s, $19.2 billion in the 2000s, and $29.0 billion in the 2010s."[22] Many of these expenditures could have been avoided, if we had invested in the necessary resilience projects since every $1 we invest in pre-disaster mitigation saves $6 in avoided costs.

flood projects, and provide an important extra line of defense when levees or other structures are required. Natural and nature-based measures also avoid unintended adverse impacts such as diverting floodwaters onto other communities and inducing development in high risk areas. Notably, the diverse environmental benefits provided by sustainable and cost-effective natural and nature-based solutions can be particularly valuable for under-served communities suffering from flooding and other cumulative environmental assaults.

Detailed Comments

The National Wildlife Federation and American Rivers urge the Corps to implement the recommendations outlined below to institutionalize a planning process that places community and ecosystem resilience at the center of Corps planning.

I. Implementing the PR&G through Effective Agency-Specific Guidelines

The PR&G direct a fundamentally different approach to planning federal water resources projects—an approach that recognizes and seeks to protect and utilize the natural environment and the many vital services it provides to people and wildlife. The PR&G, which have adopted the National Water Resources Planning Policy as the Federal Objective for federal water resources projects, require that Corps projects "reflect national priorities," "protect the environment," and "encourage economic development" by "seeking to maximize sustainable economic development."[23] Regardless of the project, unwise use of floodplains are to be avoided and natural hydrologic processes are to be protected and restored. The PR&G also direct the Corps to count the value of ecosystem services lost as a project cost and to count the value of ecosystem services gained as a project benefit.[24]

We note that the Federal Register notice for this comment period does not use the economic development objectives of the PR&G but instead provides an objective that, if followed, would undermine compliance with PR&G. The Federal Register notice states that the "PR&G emphasizes that water resources projects should maximize economic development . . . ."[25] The PR&G, however, do not direct the maximization of economic development. Instead, as directed by Congress in the National Water Resources Planning Policy (42 USC 1962–3), the economic objective of federal water resources projects is to "<u>encourage</u> economic development" by "seeking to maximize <u>sustainable</u> economic development."[26] A focus on "maximizing economic development" would prevent the Congressionally-directed shift away from the historic paradigm, which does not appropriately consider and advance social and ecological project benefits, which Congress recognized could be more effectively advanced through encouraging "sustainable" economic development. The Corps should ensure that it implements the PR&G objective for *sustainable* economic development in the Corps' agency-specific guidelines.

---

[23] National Water Resources Planning Policy (42 USC 1962–3); Principles and Requirements for Federal Investments in Water Resources (March 2013).
[24] PR&G Interagency Guidelines (December 2014) at 21 ("Ecosystems provide services to people. Thus, Federal investment impacts on the environment or ecosystem may be understood in terms of changes in service flows. The process of identifying, evaluating, and comparing these changes provides a useful organizing framework to produce a complete accounting. Reduced service flows over time amount to costs, and increased services flows over time amount to benefits.")
[25] 87 Fed. Reg. 33756 at 33760 (June 3, 2022).
[26] Principles and Requirements for Federal Investments in Water Resources (March 2013) at 3 (emphasis added).

1. Establish New Planning Steps

The Corps' agency-specific guidelines should adopt new planning steps that come into play at the very beginning of the planning process, well before the comparison of alternatives or the assessment of an alternative's costs and benefits. Corps planners should be directed to:

1. First explore solutions that use natural and nature-based features or nonstructural measures to solve a water resources problem, including features and measures outside the Corps' existing authorities. If those solutions exist they should be prioritized. Such measures include those defined at 33 USC 2289a. For flood and storm damage reduction projects, planners should explore the use of such measures both within and outside of the project area, including, for example, protecting and restoring upstream floodplains and wetlands. For navigation projects, non-structural measures would include such things as crew training, use of switch boats, appointment scheduling systems, improved maintenance of existing structures, and use of multimodal transport in lieu of new construction.

2. If natural features, nature-based features, or nonstructural measures (or a combination of such features and measures) would address only a part of the problem, structural solutions could then be incorporated to address the remaining problems.

3. Corps planners should turn to a wholly structural solution <u>only if</u> natural and nature-based features or nonstructural measures (or a combination of such features and measures with structural components) will not work in a given situation.

4. Clarify that only alternatives that are developed through this process can move into the final array of alternatives that will be analyzed in more detail.

2. Account Fully for Project Costs and Benefits

The Corps' agency-specific guidelines should make clear that only alternatives developed through the process outlined in point 1 above can move into the final array of alternatives that will be analyzed in more detail. Critically, for projects requiring a benefit-cost analysis as part of this detailed analysis, the agency guidelines should clarify that the benefit-cost analysis must:

a. Equitably account for project costs and benefits. This includes fully assessing and accounting for the costs of such things as transferring flood risks onto vulnerable communities and landowners the costs of exposing or resuspending toxic pollutants (including resuspending toxic sediments and increasing water or air pollution). The benefits of flood and storm damage reduction projects should not be based only on home or property values in the project area, as this approach can create significant barriers to the approval of flood damage reduction projects for many communities and traditional benefit-cost analysis does not account for the greater financial and social impact that a flood event may have on low-income households compared to higher-income households. The Corps should incorporate social vulnerability into benefit-cost frameworks, as suggested by social economists such as Jarl Kind and Carlos Martin.[27]

b. Account for the value of ecosystem services lost as a project cost, and account for the value of ecosystem services gained as a project benefit, as highlighted in the PR&G.[28] This should include, at a minimum, an assessment of the following ecosystem services: flood risk reduction, wildlife habitat, water quality, groundwater recharge, sediment regulation, soil stabilization, carbon sequestration, and recreation. The value of ecosystem services lost to a project should not be considered to be offset by potential mitigation measures, since such measures have not demonstrated the capacity to offset the full array of ecosystem services lost. The Corps should also identify the values of any ecosystem services lost or gained on federal or state owned conservation lands and lands protected by permanent conservation easements in a separate sub-category to help identify the impacts to lands that have been protected to help preserve the ecosystem services they provide.

c. Account for the full life-cycle costs and benefits, including the costs and benefits associated with long-term operations and maintenance, major rehabilitation, and decommissioning and removal (which may enhance ecosystem services). This should include the value of ecosystem services projected to be lost or gained over time. When assessing life-cycle costs and benefits of project alternatives, the Corps should consider long-term impacts of climate change using the best available predictions for the project location, including accounting for such things as greenhouse gas emissions resulting from a project or the loss of carbon sequestration opportunities caused by ecosystem modifications. A full accounting of life-cycle costs and benefits would provide important information for decision makers and predictability for non-federal sponsors.

d. Base cost estimates on realistic projections of the project's construction start date and likely funding stream, historical cost increases by project type and geographic location, appropriate discount rates, other relevant factors.

3. Define "Unwise Use of Floodplains" and Provide Examples

The Corps' agency-specific guidelines should comprehensively define the term "unwise use of floodplains" in a way that supports the avoidance of impacts to the well-recognized and vitally important values provided by floodplains to people and wildlife. The definition should be consistent with the implementing guidelines for E.O. 11988 (Floodplain Management) and E.O. 13690 (Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering

---

[27] Junod A., Martin C., Marx R., Rogan A, A Review of Benefit-Cost Analysis in Federal Flood Mitigation Infrastructure, 2021, Urban Institute; Kind J., Botzen W.J.W., Aerts J.C.J.H.,Social Vulnerability in Cost-Benefit Analysis for Flood Risk Management, 2020, Environment and Development Economics.

[28] PR&G Interagency Guidelines (December 2014) at 21 ("Ecosystems provide services to people. Thus, Federal investment impacts on the environment or ecosystem may be understood in terms of changes in service flows. The process of identifying, evaluating, and comparing these changes provides a useful organizing framework to produce a complete accounting. Reduced service flows over time amount to costs, and increased services flows over time amount to benefits.")

Stakeholder Input)[29], in defining the floodplain area and natural and beneficial floodplain functions and values. In developing this definition, we recommend consulting with: the Federal Emergency Management Agency, which is anticipated to undertake a rulemaking to update the Floodplain Management Standards for Land Management and Use; and the Federal Interagency Floodplain Management Task Force, which is charged with implementing the Unified National Program for Floodplain Management. To assist Corps planners, the agency-specific guidelines should also provide examples of activities that constitute unwise use of floodplains that should include:

a. Structural projects in floodplain areas when nonstructural measures, natural or nature-based measures, or ecosystem restoration either within the floodplain or within the watershed (either upstream or downstream) could effectively resolve or minimize the problem at hand.

b. New or enlarged levees, floodwalls, and other similar structures to facilitate or encourage the development of currently undeveloped floodplain land.

c. Projects that divert floodwaters onto other communities and landowners (with careful consideration being given to both upstream and downstream impacts).

d. Projects in or affecting floodplain areas that adversely impact important fish or wildlife breeding, spawning, rearing, nesting, foraging, or migratory habitat.

e. Projects that eliminate an opportunity to restore the natural and beneficial floodplain functions, or that undermine or work against other federal or federally-funded efforts to protect and restore floodplain wetlands, streams, and rivers, including authorized Corps restoration projects and programs.

f. Projects in floodplain areas that would result in those projects being unacceptably vulnerable to flood damage.

The agency-specific guidelines should require the Corps to provide a detailed description of the actions taken to ensure the proposed project complies with the requirements of E.O. 11988 to minimize, restore, and preserve the beneficial functions and values of floodplains if a proposed action will result in harm to or within the floodplain. As specified in the implementing guidelines for E.O. 11988 and E.O. 13690, agencies must: (a) minimize "harm" to both lives and property, and to natural and beneficial floodplain values; and (b) "preserve" and "restore" natural and beneficial floodplain values pursuant to the following definitions:

> "Restore means to reestablish a setting or environment in which the natural and beneficial values of floodplains could again function. Where floodplain values have been degraded by past actions, the agency must identify, evaluate, and implement measures to restore the values diminished or lost. The functions of many of the Nation's degraded floodplains can be partially or fully restored through remedial action."

---

[29] Federal Emergency management Administration. "Guidelines for Implementing Executive Order 11988, Floodplain Management, and Executive Order 13690, Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input". Oct 8 2015. FEMA-2015-0006-0358.

> "Preserve means to prevent modification to the natural floodplain environment, or to maintain it as closely as possible to its natural state. This term applies foremost to floodplains showing little or no disruption by man. If an action will result in harm to or within the floodplain, the agency must design or modify the action to assure that it will be carried out in a manner which preserves as much of the natural and beneficial floodplain values as is possible."

Many Corps project proposals provide extremely limited details on impacts to the natural and beneficial functions and values of floodplains in part because the 1983 Principles and Guidelines assume compliance with E.O. 11988 and E.O. 11998.

4. Provide Examples of Activities that Qualify as Natural or Nature-Based Features

The Corps' agency-specific guidelines should provide examples of the types of activities that are consistent with the definition established at 33 USC 2289a, and thus can qualify as natural or nature-based features. These examples should include at least the following:

a. Acquisition of land or easements, including flooding easements;

b. Removal of structures such as dams, levees, and culverts to restore natural hydrology, form, function, or ecological processes;

c. Modification of structures such as dams, levees, and culverts, including through sediment diversions or levee setbacks, to restore natural hydrology, form, function, or ecological processes;

d. Reoperation of dams and reservoirs to restore or better mimic natural hydrology and flow patterns;

e. Restoration efforts designed to reestablish natural hydrology, form, function, or processes of rivers, streams, floodplains, wetlands, shorelines, and source headwaters;

f. Creation or restoration of living shorelines; and/or

g. Reintroduction of native vegetation, including floodplain forests, and/or removal of nonnative vegetation.

5. Establish Clear Criteria for Project Decisions

The Corps' agency-specific guidelines should clearly identify the types of projects that Corps planners may not recommend absent an overriding consideration of national need as determined in writing by the Assistant Secretary of the Army (Civil Works). This should include, but not be limited to, a prohibition against selecting an alternative if:

a. The alternative would increase or transfer flood risk onto another upstream or downstream community in excess of local or state floodplain regulations.

b. The alternative would disproportionately affect people of color, or low-income or vulnerable populations.

c. Another less environmentally damaging alternative that would address the identified water resources problem is available and practicable. Clean Water Act section 404 requires that the Corps select the least environmentally damaging practicable alternative.

d. The alternative would result in environmental impacts that cannot be mitigated pursuant to 33 USC 2283(d).

6. Empower Impacted Communities to Participate in Project Planning

The Corps' agency-specific guidelines should empower impacted communities to participate in project planning, regardless of whether or not they are the non-federal sponsor, including by directing planners to:

a. Authentically engage with potentially affected communities early in the project planning process (before the required National Environmental Policy Act scoping process) to ensure that the underlying problem is accurately defined and that the project scope is appropriate, and to explore potential project approaches and designs that reflect community values and norms and help redress environmental injustices. Ensure procedures to fully address concerns raised by potentially affected communities, including rejecting an alternative that is unacceptable to the community. Apply these requirements to new project studies, studies and planning affecting already authorized but unconstructed projects, and studies and planning affecting ongoing project operations and/or maintenance.

b. Use the most accurate and localized data available to facilitate understanding of the impacts or benefits of project alternatives on specific communities and increase overall access to such information through locally accessible means and languages.

c. Include in every environmental impact statement, an assessment of the potential negative environmental, public safety (including the risks of diverting floodwater), or public health impacts (including evaluation of measures of health inequality) on any communities of color, economically disadvantaged communities, or Tribes or Indigenous communities that may be affected by proposed alternatives.

Suggested language for incorporating these directives into the agency-specific guidelines is provided at Attachment A to these comments.

As highlighted in Section V of these comments, these changes in combination with effective and meaningful engagement with communities and Tribes, will help ensure that Corps projects and programs achieve the Federal Objective adopted by the PR&G and mandated by the National Water Resources Planning Policy (42 USC 1962–3), and the full suite of applicable federal laws and policies. which direct that all water resources projects are to protect and restore the environment.

II. Engaging with Communities Suffering from Environmental Injustices

It is essential that the Corps adopt policies and procedures that will ensure effective and meaningful engagement with communities of color, economically disadvantaged communities, Indigenous communities, and Tribes. To help achieve these goals, the Corps should engage in additional and extensive outreach with such communities from initial planning stages through to finalization of any related guidance, as well as implementation and ongoing opportunities to improve policies and procedures. The Corps should also:

1. Direct Corps planners to invest the time, cultural respect, and regard required to build authentic relationships with communities of color, economically disadvantaged communities, Indigenous communities, and Tribes to facilitate effective consultation, learning, and engagement; and provide Corps staff with the resources, training, and time required to do so.

2. Engage with communities and Tribes up front and at all stages possible, not only after plans are already developed, to ensure that projects—including long-term operations and maintenance—redress instead of exacerbate environmental injustices. Corps planners should visit communities and Tribes that may be affected by a Corps project to meet with community members and see the problems they are facing first hand. Direct Corps planners to change, modify, or adapt project recommendations to address community and Tribal needs and concerns. To engage with communities and Tribes equitably, the Corps should consider impacts of historical disinvestment; procedures that increase overall access to information and decision-making; and procedures for free, prior, and informed consent.

3. Use all Corps programs and projects—including by improving project operations—to advance resilient solutions that will help communities and Tribes thrive and address multiple problems and cumulative burdens by involving communities and Tribes in decision-making to prevent harm at every stage. Prioritize community-identified solutions and the evaluation of self-sustaining natural and nature-based features and nonstructural measures that provide co-benefits to help communities thrive, and incorporate the clean-up of toxic sediments and toxic pollution as part of all Corps projects whenever feasible.

4. Direct Corps planners to account for community and Tribal resource constraints, competing priorities of community members, and the time needed to review and evaluate complex planning data, when developing public hearing schedules and public comment timelines. Corps planning schedules should accommodate requests for additional time to provide comments to the maximum extent allowed by law. Corps public input opportunities and materials should be made accessible in the languages used by potentially impacted communities and Tribes.

5. Consult and coordinate with the National Environmental Justice Advisory Council (NEJAC) to the Environmental Protection Agency, the White House Environmental Justice Advisory Council (WHEJAC), and the Federal Interagency Working Group on Environmental Justice (EJ IWG) on methods and approaches for effectively implementing outreach efforts. Utilize applicable public engagement-related recommendations included in the Environmental Justice for All Act (H.R. 5986), Promising Practices for EJ Methodologies in NEPA Reviews (March 2016) developed by the Federal Interagency Working Group on Environmental Justice & NEPA Committee, and the Model Guidelines for Public Participation (January 2013) developed by the National Environmental Justice Advisory Council.

6. Ensure that Corps procedures and planning comply with—and incorporate applicable recommendations identified through—environmental justice Executive Orders, including but not limited to: Executive Order 12898 ("Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations"), Executive Order 13748 ("Establishing a

Community Solutions Council"), Executive Order 13990 ("Protecting Public Health and the Environment and Restoring Science To Tackle the Climate Crisis"), and Executive Order 14008 ("Tackling the Climate Crisis at Home and Abroad"). Ensure that Corps procedures and planning comply with Title VI of the Civil Rights Act ("Prohibition against exclusion from participation in, denial of benefits of, and discrimination under federally assisted programs on ground of race, color, or national origin").

7. Create a new position of Senior Advisor for Environmental Justice within the Office of the Chief of Engineers and establish a standing Federal Advisory Committee on Environmental Justice to provide recommendations for improving community engagement and increasing the equitable delivery of services, projects, and project benefits through all Corps programs and projects. Establish and maintain community liaisons and environmental justice expertise within each District.

8. Strengthen the Corps' technical assistance and resiliency planning assistance programs for Tribes and Indigenous communities, economically disadvantaged communities, communities of color, and communities facing repetitive flooding. Use existing environmental justice screening and mapping tools and consult with federal agencies and Tribes to help identify communities most in need of such assistance, and set affordable community costs for assistance. Provide assistance to appropriate unelected community leaders (such as religious leaders and leaders in the not-for-profit sector, who can play an important role in shaping community development) in addition to municipal staff and elected officials.

9. Quickly implement the Pilot Programs for Economically Disadvantaged and Rural Communities established by Section 118 of the Water Resources Development Act of 2020. These programs facilitate the study and delivery of flood and storm damage reduction projects to such communities, including through full federal funding for up to 10 studies that evaluate significant use of natural or nature-based features. Provide assistance to help communities apply for the pilot programs.

10. Incorporate into Corps planning, relevant recommendations and principles identified by the: Principles of Environmental Justice developed at the First National People of Color Environmental Leadership Summit (October 24-27, 1991); 10 Essential Public Health Services developed through the Public Health National Center for Innovations and recognized by the Centers for Disease Control; and Community Benefits 101 model developed by the Partnership for Working Families.

III. Consulting and Engaging with Tribes

The Corps should engage in additional, robust and extensive outreach and consultation with Tribes to identify and implement appropriate procedures for ensuring that the Corps' Tribal consultation process respects and fully accounts for the principles of "Tribal sovereignty and self-governance, the Federal trust and treaty responsibilities to Tribal Nations, and regular, meaningful, and robust consultations with Tribal Nations", as recognized in Executive Order 13175 ("Consultation and Coordination With Indian Tribal Governments"), and other issues identified by the Tribes.

To assist in these efforts, we encourage the Corps to also implement the following recommendations:

1. Direct the Corps' Tribal Nations Technical Center of Expertise (TNTCX) to robustly engage with Tribes and Tribal leaders to obtain recommendations for improving the Corps' Tribal consultation process. The TNTCX should ensure robust participation by Corps Divisions and Districts in these engagement efforts. As recognized on the Corps' website, "the TNTCX can engage with each of the 574 Federally recognized Native American Tribes, national and regional organizations representing Native American governments, Native American communities, and the USACE Commands serving those communities." Tribes should drive the development of the Corps' Tribal consultation procedures.

2. Explicitly acknowledge—and develop procedures to ensure—that consultation and coordination with Tribes respect and fully account for:

    a. The principles of "Tribal sovereignty and self-governance, the Federal trust and treaty responsibilities to Tribal Nations, and regular, meaningful, and robust consultations with Tribal Nations", as recognized in Executive Order 13175 ("Consultation and Coordination With Indian Tribal Governments") and reaffirmed in the January 26, 2021 Presidential Memorandum on Tribal Consultation and Strengthening Nation-to-Nation Relationships.

    b. The fact that Tribal Nations are the signatories to, and beneficiaries of, more than 368 treaties with the United States, and the U.S. Government is obligated to comply with treaty requirements, as recently highlighted in the Supreme Court decision *McGirt v. Oklahoma*, 591 U. S.__, 140 S.Ct. 2452 (2020).

    c. The fact that as sovereign and self-governing nations, the 574 Federally recognized Tribes in the United States maintain diverse and wide-ranging approaches to natural resource regulation and development, do not speak with a single voice, and do not share a single culture.

    d. The significant historical and ongoing inequitable impacts of environmental policies and projects on Tribes and Tribal resources and Indigenous communities and resources. The Guidance should clearly state, however, that the Corps' responsibility to account for and redress such environmental injustice is distinct from and in addition to the Corps' responsibilities to engage in Nation-to-Nation relationship with Tribes, to respect and account for Tribal sovereignty and self-governance, and to comply with Federal trust and treaty responsibilities.

3. Incorporate applicable consultation-related recommendations identified through:

    a. The Programmatic consultations carried out in response to the January 26, 2021 Presidential Memorandum on Tribal Consultation and Strengthening Nation-to-Nation Relationships, which seek Tribal input on a number of important aspects of project- and policy-specific Tribal consultation processes, including such things as: (i) what does "consultation" mean; (ii) what actions trigger consultation requirements; and (iii) the appropriate time-period for consultation, including whether consultation should continue throughout the decision-making process.

    b. Previous consultation and evaluation processes as documented in the following reports: Executive Office of the President, *2016 White House Tribal Nations Conference Progress*

Report, A Renewed Era of Federal-Tribal Relations (January 2017); United States Government Accountability Office, *Tribal Consultation, Additional Federal Actions Needed for Infrastructure Projects*, GAO-19-22 (March 2019); and U.S. Army Corps of Engineers, Institute for Water Resources, *Strengthening USACE Collaboration with Tribal Nations for Water Resources Management*, 2020-R-01 27 (October 2020).

4. Prohibit a determination of Tribal consent to a proposed action unless the Tribe provides such consent in writing with free, prior, and informed consent. Corps planners must obtain an official written determination from an affected Tribe and may not assume that a Tribe's failure to respond to a request for consultation or comment constitutes consent to the proposed action.

5. Require the Corps to fully address objections and concerns to project proposals and permits raised by Tribes, including where necessary rejecting the proposed project or permit.

6. Establish a Tribal Liaison in each Corps District and a formal continuity program for Corps Tribal Liaisons and other Corps staff who interact regularly with Tribes to ensure that knowledge about general and specific Tribal issues, policies, and contacts are not lost due to Corps staffing changes.

7. Evaluate Tribal interest in a standing Tribal Advisory Committee to provide long-term input into the Corps' Tribal consultation process, and establish this Committee if requested.

8. Direct Corps planners to account for Tribal Nations' and Indigenous communities' constraints, including limited staffing and budgets and competing priorities, when developing schedules for Corps planning, construction, and operations. Corps planning schedules should accommodate Tribal Nations' and Indigenous communities' requests for additional time to consult and provide comments to the maximum extent allowed by law. Review periods are often too short to accommodate competing Tribal and Indigenous priorities and limited capacity and resources.

9. Direct establishment of processes and procedures to ensure full transparency for Tribes, Tribal governments, and Indigenous communities regarding Corps laws and policies, planning, construction, operations, and permits that may affect Tribes or Tribal resources or Indigenous communities or resources, including by: (a) establishing a single, publicly available website that provides access to all such information along with information on Tribal consultation procedures and contact information for all Corps Tribal and Indigenous Liaisons; (b) providing full project planning schedules to Tribes and Indigenous communities for any study, project construction, or project operations that may affect Tribes, Indigenous communities, and Tribal or Indigenous resources; (c) providing technical assistance to Tribes and Indigenous communities to facilitate their ability to fully evaluate technical planning information developed by the Corps; and (d) identifying all Corps projects, project operations, and project studies that may affect Tribes and Tribal resources or Indigenous communities and resources.

10. Direct Corps planners to invest the time, cultural respect, and regard needed to build authentic relationships with Tribes and Indigenous communities to facilitate effective consultation, learning, and engagement. This should include regular engagement (including in person, when it is safe to do so) outside of project consultations to build relationships. Whenever possible, Corps staff should consult with Tribal and Indigenous leaders through face-to-face meetings carried out in an appropriate location identified by Tribal or Indigenous leaders.

11. Establish mandatory training on consulting with Tribal Nations and engaging with Tribes and Indigenous communities for all Corps employees engaged in project planning and operations; review or approval of permits under Section 10, Section 404, and Section 408; and outreach. Such trainings should address the Federal Trust Responsibility, sovereignty, treaties and their meaning, and guidance for carrying out effective government-to-government consultations.

IV. Defining "Economically Disadvantaged Community"

We urge the Corps to give very careful, additional attention to the definition of an economically disadvantaged community and to engage in robust outreach with communities to develop a more appropriate definition. The proposed definition is highly restrictive and does not account for the often significant differences in economic prosperity that can be found within some communities. The proposed definition does not account for regional variations in the costs of basic necessities including housing, food, healthcare, and transportation. The proposed definition also does not account for historic and ongoing inequities that can impose additional and significant economic burdens on community members. As a result, the currently proposed definition will exclude many communities that warrant the additional protections and services available to economically disadvantaged communities.

As a starting point to address these problems, the Corps should develop a new definition of economically disadvantaged community that, among other things:

1. Is informed by input from the public, with particular attention to input from members of communities that may fall under the definition of an "economically disadvantaged community. This input should be obtained through additional, robust and well-publicized, opportunities to provide input. Materials supporting both the outreach and development of the definition should be made readily available to communities through multiple methods and in languages used by community members. The Corps should engage environmental justice community groups and organizations, Tribes and Tribal organizations, Indigenous communities and organizations, state and local governments, academia, and non-governmental organizations in this process.

2. Relies on census block data, as opposed to community-wide data. The Environmental Justice for All Act (H. R. 2021) defines a low-income community as "any census block group in which 30 percent or more of the population are individuals with an annual household income equal to, or less than, the greater of—(A) an amount equal to 80 percent of the median income of the area in which the household is located, as reported by the Department of Housing and Urban Development; and (B) an amount equal to 200 percent of the Federal poverty line."

3. Accounts for regional differences in salaries and the cost of living, including the costs of basic necessities such as housing, food, healthcare, and transportation.

4. Accounts for historic and ongoing inequities, including environmental injustices and discrimination, that can create additional economic burdens on community members, including: increased health risks and associated healthcare costs (e.g., high levels of toxic air pollution, poor water quality); increased risks from flooding and other natural disasters and associated recovery costs (e.g., living in a floodplain, lack of resources to purchase flood insurance); and lack of ready access to grocery stores, healthcare facilities, public transportation, and other key

infrastructure that can significantly increase the costs associated with accessing essential services (including transportation costs).

5. Accounts for vulnerability to climate change impacts due to a lack of resources required to improve community resilience.

6. Incorporates applicable provisions of similar or related definitions used by other federal agencies.

V. The Recommended Changes Will Improve Project Planning

The changes outlined in Section I above, in combination with effective and meaningful engagement with communities and Tribes, will help ensure that Corps projects and programs achieve the Federal Objective adopted by the PR&G and mandated by the National Water Resources Planning Policy (42 USC 1962–3), and the full suite of applicable federal laws and policies.

1. Complying With Federal Law and Policy

The changes outlined in Section I above will help ensure that Corps projects comply with the broad suite of federal laws and policies that require the Corps to protect and restore the environment and avoid the unwise use of floodplains to the maximum extent possible, including:

- The Water Resources Development Acts (WRDA). Numerous WRDA provisions require and encourage the Corps to carefully consider the use of natural and nature-based features. Section 115 of the Water Resources Development Act (WRDA) of 2020 builds on previous WRDAs to explicitly direct the Corps to consider natural and nature-based features in flood and storm risk reduction studies.[30] The Corps has been required to consider nonstructural alternatives when planning flood damage reduction projects since 1974. 33 U.S.C. § 701b-11.

- The Clean Water Act Section 404(b)(1) Guidelines. The mandatory 404(b)(1) Guidelines prohibit the construction of a federal water project where, among other things, there are practicable alternatives that will cause less harm to the aquatic ecosystem and the agency has not taken "appropriate and practicable" steps to minimize potential adverse impacts. An action is practicable if it is "available and capable of being done after taking into consideration cost, existing technology, and logistics in light of overall project purposes." 40 CFR § 230.10 and 230.3. The substantial resources and opportunities available to the federal government make the use of natural and nature-based features and nonstructural measures highly practicable.

- The Corps' Clean Water Act Section 404 regulations. These regulations prohibit construction of a federal water project that is not in the "public interest." The "unnecessary alteration or destruction of" wetlands is deemed to be "contrary to the public interest" and impacts to floodplains must be avoided whenever practicable alternatives exist outside the floodplain. 33 CFR §§ 320.4 and 323.6.

[30] In 2016, Congress directed the Corps to consider natural and nature-based measures in flood and storm risk reduction and ecosystem restoration studies (33 USC 2289a). In 1997, the Council on Environmental Quality and the Office of Management and Budget issued guidance requiring the Corps to utilize nonstructural measures where appropriate.

- The National Environmental Policy Act (NEPA). NEPA requires a careful evaluation of "a reasonable range of alternatives that are technically and economically feasible, and meet the purpose and need for the proposed action"[31] to help "fulfill the responsibilities of each generation as trustee of the environment for succeeding generations" and ensure that all Americans have "safe, healthful, productive, and esthetically and culturally pleasing surroundings."[32] As established by the U.S. Court of Appeals for the Fifth Circuit decades ago, NEPA requires an "intense consideration of other more ecologically sound courses of action, including shelving the entire project, or of accomplishing the same result by entirely different means" through "a thorough consideration of all appropriate methods of accomplishing the aim of the action, including those without the area of the agency's expertise and regulatory control as well as those within it."[33]

- Executive Order 11990 (Protection of Wetlands). This Executive Order directs each federal agency to provide leadership and take actions to minimize the destruction, loss or degradation of wetlands, and to preserve and enhance the natural and beneficial values of wetlands in carrying out agency policy.

- Executive Order 11988 (Floodplain Management). This Executive Order directs each federal agency to avoid, to the extent possible, the long and short-term adverse impacts associated with the occupancy and modification of floodplains; to avoid direct and indirect support of floodplain development wherever there is a practicable alternative; and "to restore and preserve the natural and beneficial values served by flood plains in carrying out its responsibilities." Guidance issued by the Office of Management and Budget and the Council on Environmental Quality in 1997 requires that Federal agencies consider and utilize nonstructural measures for flood damage reduction where practicable.

- Executive Order 13690 (Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input). This Executive Order[34] directs each federal agency to "avoid, to the extent possible, the long- and short-term adverse impacts associated with the occupancy and modification of floodplains and to avoid direct or indirect support of floodplain development wherever there is a practicable alternative." It establishes a Federal Flood Risk Management Standard to increase resilience against flooding and directs that: "Where possible, an agency shall use natural systems, ecosystem processes, and nature-based approaches when developing alternatives for consideration" to help preserve the natural values of floodplains.

2. Producing Highly Effective, Climate Resilient Water Resources Projects

The value of natural systems for protecting communities is well recognized, as evidenced by the Corps' own findings. In a 1972 study evaluating options to reduce flooding along the Charles River in Massachusetts, the Corps concluded:

---

[31] 87 Fed.Reg. 23453 at 23470 (April 20, 2022) (Reasonable alternatives means a reasonable range of alternatives that are technically and economically feasible, and meet the purpose and need for the proposed action.")
[32] 42 U.S.C. §4331(b).
[33] Environmental Defense Fund, Inc. v. Corps of Engineers, 492 F.2d 1123, 1135 (5th Cir. 1974).
[34] This Executive Order was reinstated by President Biden.

> Nature has already provided the least-cost solution to future flooding in the form of extensive [riverine] wetlands which moderate extreme highs and lows in streamflow. Rather than attempt to improve on this natural protection mechanism, it is both prudent and economical to leave the hydrologic regime established over millennia undisturbed.[35]

As aptly noted by the Reinsurance Association of America: "One cannot overstate the value of preserving our natural systems for the protection of people and property from catastrophic events."[36]

While sometimes necessary and appropriate, large scale structural projects typically cause significant harm to the environment and can have negative secondary effects. For example, such projects often divert floodwaters onto other communities, induce development in high-risk areas, and come with the very real risk of catastrophic failure and over topping that endanger the very communities they are meant to protect.

The divergent costs and benefits of natural and nature-based measures and structural solutions has been clearly documented in two recent studies looking at different solutions for reducing flood risks along the San Francisco Bay in California. A study released just last month found that sea level rise adaptation efforts that include nature-based solutions "deliver up to eight times the benefits of a traditionally engineered baseline as well as additional habitat for key species" for the San Francisco Bay area, while also creating an additional 50 ha (124 acres) of beach. Incorporating additional feasible nature-based solutions could provide up to six times the marsh area, eight times the stormwater pollution reduction, and six times the carbon sequestration of an engineered baseline, along with an additional 170 ha (420 acres) of beach.[37]

By contrast, building just one large seawall in a small portion of California's San Francisco Bay could significantly increase flooding in other areas, causing up to $723 million of flood damages to communities throughout the area after just a single flood event[38]—an estimate that is highly conservative as it "doesn't account for potential damage to ecosystems and fisheries."[39] This 2021 study found that protecting individual segments (5 to 75 km) of the shoreline would divert 36 million cubic meters of flood waters (9.5 billion gallons) onto other communities, and in some cases could "cause regional flood damages that exceed the local damages prevented from protection."[40]

---

[35] American Rivers, Unnatural Disasters, Natural Solutions: Lessons From The Flooding Of New Orleans (2006) (quoting USACE, from Massachusetts Department of Fish and Game, *Functions of Riparian Areas for Flood Control*, http://www.mass.gov/dfwele/river/pdf/riparian_factsheet_1.pdf.)
[36] Restore America's Estuaries, Jobs & Dollars BIG RETURNS from coastal habitat restoration (September 14, 2011).
[37] A. D. Guerry, Silver J., Beagle J., et al, npj Urban Sustainability (2022), Protection and restoration of coastal habitats yield multiple benefits for urban residents as sea levels rise, https://doi.org/10.1038/s42949-022-00056-y. A copy of this study is provided at Attachment B to these comments.
[38] Michelle Hummel, Griffin R., Arkema K., Guerry A., PNAS 2021 Vol. 118 No. 29 e2025961118, Economic evaluation of sea-level rise adaptation strongly influenced by hydrodynamic feedbacks https://doi.org/10.1073/pnas.2025961118 (July 2021). A copy of this study is provided at Attachment C to these comments.
[39] Matt Simon, Be very careful where you build that seawall, WIRED (July 14, 2021).
[40] Michelle Hummel, Griffin R., Arkema K., Guerry A., PNAS 2021 Vol. 118 No. 29 e2025961118, Economic evaluation of sea-level rise adaptation strongly influenced by hydrodynamic feedbacks https://doi.org/10.1073/pnas.2025961118 (July 2021) (documenting that the seawall would divert 36 million cubic

As highlighted in the National Wildlife Federation's report on The Protective Value of Nature[41] and in the examples provided below, there is ample evidence of the effectiveness of natural and nature-based solutions in reducing flood and storm damages:

- During Hurricane Sandy, wetlands prevented $625 million in flood damages in the 12 coastal states that were affected by the hurricane, and reduced damages by 20 to 30 percent in the four states with the greatest wetland coverage.[42]

- In southern California, restoration of 1,800 feet of shoreline with cobble beach and vegetated sand dunes east of the mouth of the Ventura River will "provide resilience and offset risk from sea level rise and storms for 50 years" while maintaining beach access and other coastal resources. Even with only one of two phases of this Surfers' Point Managed Shoreline Retreat Project completed, the restored beach and dunes withstood 2015-2016 winter high wave conditions without damage, while other locations such as the Ventura Pier and promenade were damaged and the Pierpont neighborhood east of the project site was inundated. Since the project began, Surfers' Point has become Ventura County's most visited beach.[24]

- In northern California, the community-developed Napa Valley Flood Control Project "living river" plan replaced the Corps' originally-proposed floodwalls and levees with terraced marshes, wider wetland barriers, and restored riparian zones. The project is restoring more than 650 acres of high-value tidal wetlands of the San Francisco Bay Estuary while protecting 2,700 homes, 350 businesses, and over 50 public properties from 100-year flood levels, saving $26 million annually in flood damage costs.[25] Though only partially completed, the project was credited for lowering flood levels by about 2 to 3 feet during the 2006 New Year's Day flood. Property damage from flooding in Napa County is now approximately $25 million lower per year resulting in $1 billion in flood damage savings over the life of the project.[43]

- In California, wetlands provide an estimated $16.6 billion in benefits each year (in 2013 dollars) by reducing flood damages, recharging groundwater, purifying water supplies, providing recreational opportunities, and supporting healthy populations of fish and wildlife.[44]

- In Florida, the Corps is using wetland restoration in the Upper St. John's River floodplain to provide important flood damage reduction benefits. The backbone of this project is restoration of 200,000 acres of floodplain which will hold more than 500,000 acre-feet of water—enough to

---

meters of flood waters (9.5 billion gallons) onto other communities, and demonstrating the value of natural infrastructure for alleviating flooding and damages along other stretches of the coastline.).

[41] Glick, P., E. Powell, S. Schlesinger, J. Ritter, B.A. Stein, and A. Fuller. 2020. The Protective Value of Nature: A Review of the Effectiveness of Natural Infrastructure for Hazard Risk Reduction. Washington, DC: National Wildlife Federation.

[42] Narayan, S., Beck, M.B., Wilson, P., et al., The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA. Scientific Reports 7, Article number 9463 (2017), doi:10.1038/s41598-017-09269-z (available at https://www.nature.com/articles/s41598-017-09269-z).

[43] Parsons, Brandon, L. Marshall, M. Buckley, and J. Loos. 2020. Economic Outcomes of Urban Floodplain Restoration: Implications for the Puget Sound. Accessed Aug. 26, 2022. https://www.americanrivers.org/wp-content/uploads/2020/06/AR-Economic-Outcomes-Report.pdf

[44] Harold Mooney and Erika Zavalata (editors), Ecosystems of California, University of California Press (2016) at 684.

cover 86 square miles with 10 feet of water—and will accommodate surface water runoff from a more than 2,000 square mile area. The Corps predicts that this $200 million project will reduce flood damages by $215 million during a 100-year flood event, and provide average annual benefits of $14 million. This project was authorized by Congress in 1986 to reduce flood damages along the river.

- In Illinois, wetlands in the seven-county Chicago metropolitan area provide $22,000 in benefits per acre each year in water flow regulation on average, as documented by a 2014 study. This study also found that watersheds with 30 percent wetland or lake areas saw flood peaks that were 60 to 80 percent lower than watersheds without such coverage; that preventing building in floodplain areas could save an average of $900 per acre per year in flood damages; and that natural systems are the least costly and most efficient way to control flooding.[45]

- In central Indiana, wetlands in the Eagle Creek watershed reduce peak flows from rainfall by up to 42 percent, flood area by 55 percent, and maximum stream velocities by 15 percent.[46]

- In Iowa, the purchase of 12,000 acres in easements along the 45-mile Iowa River corridor saved local communities an estimated $7.6 million in flood damages as of 2009. The easement purchase effort began after the historic 1993 floods when river communities in east-central Iowa recognized the need for a more effective approach to reducing flood damages.

- In Louisiana, coastal wetlands reduced Hurricane Katrina's storm surge in some New Orleans neighborhoods by two to three feet, and levees with wetland buffers had a much greater chance of surviving Katrina's fury than levees without wetland buffers.[47]

- In Massachusetts, the 1972 Corps study cited above showed that upstream wetlands were playing a critical role in reducing flooding in the middle and upper reaches of the Charles River by storing millions of gallons of water and preventing $17 million each year in flood damages. This led the Corps to preserve 8,000 floodplain acres to ensure future flood storage, at a cost of just one-tenth of the structural project it had previously planned to build. This approach was sanctioned by Congress in 1974 when it authorized the Charles River Natural Valley Storage Area. These floodplain wetlands are credited with reducing major floods, including in 1979, 1982, and 2006. The Corps estimates that this project has prevented $11.9 million in flood damages while providing recreational benefits valued at between $3.2 and $4.6 million.[48]

---

[45] Will Allen, Ted Weber, and Jazmin Varela, *Green Infrastructure Vision: Version 2.3: Ecosystem Service Valuation.* (The Conservation Fund: 2014), 13-15, https://datahub.cmap.illinois.gov/dataset/c303fd2e-beaf-4a75-a9ec-b27c6da49b69/resource/028c9b69-bb19-425e-bb92-3d33656bea4c/download/tcfcmapgiv23ecosystemservicesfinalreport201412v2.pdf. This study was conducted for the Chicago Wilderness Green Infrastructure Vision.

[46] Javaheri, A., and M. Babbar-Sebens. 2014. On comparison of peak flow reductions, flood inundation maps, and velocity maps in evaluating effects of restored wetlands on channel flooding. Ecological Engineering 73: 132–145.

[47] Bob Marshall, *Studies abound on why the levees failed. But researchers point out that some levees held fast because wetlands worked as buffers during Katrina's storm surge,* The New Orleans Times-Picayune (March 23, 2006).

[48] American Rivers, Unnatural Disasters, Natural Solutions: Lessons From The Flooding Of New Orleans (2006) (Charles River Valley Natural Storage Area case study); and https://www.arcgis.com/apps/MapJournal/index.html?appid=0bf97d033a8642b18c2e8075d4b5ecfe.

- In southern Missouri, the forest and other conservation lands that make up the 28,000 acre Meramec Greenway along the Meramec River contribute about $6,000 per acre in avoided flood damages annually.[49]

- In New York, restoration of wetlands and lands adjacent to 19 stream corridors in Staten Island "successfully removed the scourge of regular flooding from southeastern Staten Island, while saving the City $300 million in costs of constructing stormwater sewers."[28] Some 400 acres of freshwater wetland and riparian stream habitat has been restored along 11 miles of stream corridors that collectively drain about one third of Staten Island's land area. A 2018 study commissioned by the City of New York found that using "hybrid infrastructure" that combines nature, nature-based, and gray infrastructure together could save Howard Beach, Queens $225 million in damages in a 100-year storm while also generating important ecosystem services.[50]

- In Oregon, the Portland Bureau of Environmental Services restored 63 acres of wetland and floodplain habitat, restored 15 miles of Johnson Creek, and moved structures out of high-risk areas to reduce flood damages in the Johnson Creek neighborhood. In January 2012, when heavy rainfall caused Johnson Creek to rise two feet above its historic flood stage, the restored site held the floodwaters, keeping nearby homes dry and local businesses open. An ecosystem services valuation of the restored area found that the project would provide $30 million in benefits (in 2004 dollars) over 100 years through avoided property and utility damages, avoided traffic delays, improved water and air quality, increased recreational opportunities, and healthy fish and wildlife habitat.[51]

- In Vermont, a network of floodplains and wetlands, including those protected by 23 conservation easements protecting 2,148 acres of wetland along Otter Creek, saved Middlebury $1.8 million in flood damages during Tropical Storm Irene, and between $126,000 and $450,000 during each of 10 other flood events. Just 30 miles upstream, in an area without such flood plain and wetland protections, Tropical Storm Irene caused extensive flooding to the city of Rutland.[52]

- In Washington, Floodplains by Design, the innovative and ambitious public-private partnership program working to reduce flood risk and restore habitat along Washington's rivers, has implemented 45 projects on 15 major floodplains, reducing flood risks to 59 communities, improving or protecting more than 9,000 acres of working lands, and restoring habitat for endangered salmon on over 50 miles of rivers. Since 2013, the Washington State Legislature has

---

[49] Kousky, C., M. Walls, and Z. Chu. 2014. Measuring resilience to climate change: The benefits of forest conservation in the floodplain. p 345–360. In: V.A. Sample and R.P. Bixler, eds. Forest Conservation and Management in the Anthropocene: Conference Proceedings. Proceedings RMRS-P-71. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
[50] The Nature Conservancy, *Urban Coastal Resilience: Valuing Nature's Role*. (2015), https://www.nature.org/content/dam/tnc/nature/en/documents/urban-coastal-resilience.pdf.
[51] "Johnson Creek Restoration, Portland, Oregon," Naturally Resilient Communities, accessed November 12, 2019, http://nrcsolutions.org/johnson-creek-restoration-portland-oregon/.
[52] Keri B. Watson, Ricketts T., Galford G., Polasky S., O'Niel-Dunne J., Quantifying flood mitigation services: The economic value of Otter Creek wetlands and floodplains to Middlebury, VT, Ecological Economics, Volume 130: 16-24 (2016), https://doi.org/10.1016/j.ecolecon.2016.05.015.

appropriated $165 million to support large multiple-benefit projects across the state through the Floodplains by Design grant program.[53]

- A single acre of wetland can store one million gallons of floodwaters.[54] Just a 1 percent loss of a watershed's wetlands can increase total flood volume by almost seven percent.[55]

Natural infrastructure is also often more cost-effective than structural measures. A recent study documents that using natural infrastructure solutions for reducing coastal flood risks in Texas, Louisiana, Mississippi, and Florida would have a benefit-cost ratio of 3.5 compared to just 0.26 for levees and dikes. Restoring wetlands in this region could prevent $18.2 billion in losses while costing just $2 billion to carry out.[56] Natural infrastructure also has the significant added benefits of being self-sustaining and avoiding the risk of catastrophic structural failures. Importantly, natural infrastructure can work both alone and in combination with more traditional grey infrastructure to reduce flood and storm risks.

3. Sustaining Wildlife and the Outdoor Economy

By protecting and helping to restore healthy natural systems, natural and nature-based features and non-structural measures help sustain fish and wildlife and outdoor recreation and commercial fishery-based economies. Projects that restore healthy rivers, floodplains, and wetlands are also an important creator of jobs that are by necessity local and cannot be exported.

Healthy rivers, floodplains, and wetlands provide vital fish and wildlife habitat and allow people and wildlife to benefit from natural flood cycles. In a healthy, functioning river system, precipitation events and other natural increases in water flow can deposit nutrients along floodplains creating fertile soil for bottomland hardwood forests. Sediment transported by these increased flows form islands and back channels that are home to fish, birds, and other wildlife. By scouring out river channels and riparian areas, these events prevent rivers from becoming overgrown with vegetation. They also facilitate breeding and migration for a host of fish species, and provide vital connectivity between habitat areas. In the deltas at the mouths of rivers, increased flows release freshwater and sediment, sustaining and renewing wetlands that protect coastal communities from storms and provide nurseries for multibillion dollar fisheries.

Wetlands are some of the most biologically productive natural ecosystems in the world, and support an incredibly diverse and extensive array of fish and wildlife. America's wetlands support millions of migratory birds and waterfowl. Up to one-half of all North American bird species rely on wetlands. Although wetlands account for just about 5 percent of land area in the lower 48 states, those wetlands are the only habitat for more than one third of the nation's threatened and endangered species and

---

[53] Floodplains By Design. "Floodplains By Design: Reducing Risk, Restoring Rivers.", accessed July 26, 2022. https://www.floodplainsbydesign.org/wp-content/uploads/2020/08/847580214NatureorgFloodplainsByDesignInfographic11x14v12.png

[54] Environmental Protection Agency*, "Wetlands: Protecting Life and Property from Flooding." EPA 843-F-06-001.* (2006) (factsheet).

[55] Demissie, M. and Abdul Khan. 1993. "Influence of Wetlands on Streamflow in Illinois." Illinois State Water Survey, Contract Report 561, Champaign, IL, Table 7, pp. 44-45.

[56] Borja G. Reguero et al., "Comparing the Cost Effectiveness of Nature-Based and Coastal Adaptation: A Case Study from the Gulf Coast of the United States," PLoS ONE 13, no. 4 (April 11, 2018), https://doi.org/10.1371/journal.pone.0192132.

support an additional 20 percent of the nation's threatened and endangered at some time in their life. These same wetlands are home to 31 percent of the nation's plant species.[57]

Wetlands are also the economic driver for fish and wildlife associated recreation. Hundreds of species of birds, waterfowl, and wildlife and 90 percent of fish caught by America's recreational anglers are wetland dependent. In 2016, fishing, hunting, and other wildlife-associated recreation contributed $156.3 billion to the national economy. "This equates to 1% of Gross Domestic Product; one out of every one hundred dollars of all goods and services produced in the U.S. is due to wildlife-related recreation." Anglers alone spent "$46.1 billion on trips, equipment, licenses, and other items to support their fishing activities" while people who "fed, photographed, and observed wildlife," spent $75.9 billion on those activities.[58]

Ninety five percent of commercially harvested fish and shellfish are wetland dependent. Healthy coasts "supply key habitat for over 75% of our nation's commercial fish catch and 80-90% of the recreational fish catch."[59] Healthy rivers are equally important to these fisheries and the economic benefits they provide. Commercial fishing in the Apalachicola River and Bay (which relies on river flows to remain healthy) contributes $200 million annually to the regional economy and directly supports up to 85 percent of the local population.

Projects that restore natural systems also create jobs. Restore America's Estuaries reports that coastal restoration "can create more than 30 jobs for each million dollars invested" which is "more than twice as many jobs as the oil and gas and road construction industries combined."[60]

In Louisiana, a proposed $72 million project to restore a 30,000-acre expanse of degraded marsh near downtown New Orleans known as the Central Wetlands Unit would create 689 jobs (280 direct jobs and 400 indirect and induced jobs) over the project's life.[61] Implementation of the entire $25 billion dollars of restoration in Louisiana's Master Plan over the next fifty years would multiply those jobs hundreds of times over. In Florida, restoration of the Everglades will produce more than 442,000 jobs over the next 50 years and almost 23,000 short- to mid-term jobs for the actual restoration work. Restoring the Everglades is also predicted to produce a return of four dollars for each dollar invested.[62]

Coastal restoration projects carried out under the U.S. Fish and Wildlife Service's Partners for Fish and Wildlife Program and Coastal Program in FY2011 returned $1.90 in economic activity for every dollar spent on restoration. In California, the rate of return was $2.10 for every dollar spent.[63] The Department of the Interior's FY2010 investment of $156 million for ecosystem restoration activities in

---

[57] Environmental Protection Agency, Economic Benefits of Wetlands, EPA843-F-06-004 (May, 2006) (factsheet).
[58] U.S. Fish and Wildlife Service, *2016 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation: National Overview*, Issued August 2017. This study is the source for all quotes and data in this paragraph.
[59] Restore America's Estuaries, *Jobs & Dollars BIG RETURNS from coastal habitat restoration* (September 14, 2011) (http://www.estuaries.org/images/81103-RAE_17_FINAL_web.pdf).
[60] *Id*.
[61] Environmental Defense Fund, Profiles in Restoration: The Central Wetlands Unit, Part VI (May 3, 2010) (http://blogs.edf.org/restorationandresilience/category/central-wetlands-unit/).
[62] Everglades Foundation, Everglades Restoration a 4-to1-Investment (http://everglades.3cdn.net/79a5b78182741ae87f_wvm6b3vhn.pdf).
[63] U.S. Fish and Wildlife Service, *Restoration Returns—The Contribution of Partners for Fish and Wildlife Program (PFW) and Coastal Program Restoration Projects to Local US Economies*, February 2014 (http://www.sfbayjv.org/resourcedocs/usfws-restoration-returns.pdf).

the Chesapeake Bay, Great Lakes, and Everglades supported more than 3,200 jobs and contributed more than $427 million in economic outputs.[64] The Department of the Interior supported 12 to 30 jobs for every million dollars spent on restoration in FY2018.[65]

In Oregon, a $411 million investment in restoration from 2001 to 2010 generated an estimated $752 to $977 million in economic output. The 6,740 restorations projects completed during that time supported an estimated 4,600 to 6,500 jobs, including jobs in construction, engineering, wildlife biology, and in supporting local businesses such as plant nurseries and heavy equipment companies. On average, $0.80 of every $1 spent on a restoration project in Oregon stays in the county where the project is located and $0.90 stays in the state.[66]

VI. Conclusion

Full and effective implementation of the PR&G combined with robust engagement with communities and Tribes will help ensure that Corps planning can address the nation's most pressing water resources needs while protecting and restoring the environment and redressing long-standing environmental injustices. We urge the Corps to adopt the recommendations outlined in this letter to help make that happen.

Sincerely,

Melissa Samet
National Wildlife Federation
Senior Water Resources Counsel
sametm@nwf.org
415-762-8264

Eileen Shader
American Rivers
Director, River Restoration
eshader@americanrivers.org
570-856-1128

[64] The Department of the Interior's Economic Contributions (Department of the Interior, 2011) at 5, 106 (http://www.doi.gov/news/pressreleases/upload/DOI-Econ-Report-6-21-2011.pdf).
[65] U.S. Department of the Interior Economic Report FY2018 (Department of the Interior, 2019) at 4 (https://doi.sciencebase.gov/doidv/files/2018/pdf/FY%202018%20Econ%20Report.pdf).
[66] Whole Watershed Restoration Initiative, Oregon's Restoration Economy, Investing in natural assets for the benefit of communities and salmon (2012)(http://www.ecotrust.org/wwri/downloads/WWRI_OR_brochure.pdf).

Attachment A

National Wildlife Federation and American Rivers Comments
Modernization of Army Civil Works Policy Priorities
Docket ID No. COE-2022-0006

Suggested Language for Incorporating the PR&G Agency Specific Guideline Recommendations Into the Planning Process Documented in ER 1105-2-100 (Planning Guidance Notebook)

The language below illustrates one way that the recommendations provided in Section I of the comments submitted by the National Wildlife Federation and American Rivers could be integrated into the ER 1105-2-100 (Planning Guidance Notebook). While we have proposed language for inclusion in the context of the Corps' current Six-Step Planning Process,[1] we believe that the proposed language could—and should—be utilized in the much more comprehensive rewriting of that planning process called for by the PR&G.

Recommendations for Corps Planning Step 3—Formulating Alternative Plans

Planning Step 3—Formulating Alternative Plans. Planning Design Teams (PDTs) shall follow and provided detailed documentation of compliance with the following requirements to formulate a range of alternative plans that comply with the Federal Objective, the PR&G, and federal law.

A. Identifying Solutions

(1) **Phase 1—Identifying natural and nature-based features and nonstructural measures.** PDTs shall first identify and evaluate natural and nature-based features and nonstructural measures to determine the extent to which such measures or a combination of such measures can address the defined water resources problem or a portion of the defined water resources problem. Such measures are presumed to be available and practicable unless clearly demonstrated otherwise. Examples of such measures are provided in Subsection C (Definitions) below.

(2) **Phase 2—Identifying structural measures.** PDTs shall use the following criteria to ensure appropriate evaluation of structural measures:

i. If Phase 1 identifies features or measures (either alone or in combination) that can fully address the defined water resources problem, PDTs shall move directly to Planning Step 4—Evaluating Alternative Plans.

ii. If Phase 1 identifies features or measures (either alone or in combination) that can partially address the defined water resources problem, PDTs shall identify and evaluate structural measures to address the remaining aspects of the water resources problem that cannot be addressed through the measures identified in Phase 1.

[1] As documented in the Planning Guidance Notebook, "[t]he Corps planning process follows the six-step process defined in the P&G. This process is a structured approach to problem solving which provides a rational framework for sound decision making. The six-step process shall be used for all planning studies conducted by the Corps of Engineers. The process is also applicable for many other types of studies and its wide use is encouraged. The six steps are: Step 1 - Identifying problems and opportunities; Step 2 - Inventorying and forecasting conditions; Step 3 - Formulating alternative plans; Step 4 - Evaluating alternative plans; Step 5 - Comparing alternative plans; Step 6 - Selecting a plan." Each of these steps involves an iterative process. ER 1105-2-100 (Planning Guidance Notebook), 22 April 2000, at paragraph 2-3, page 2-2.

iii. If Phase 1 does not identify any features or measures (alone or in combination) that can assist in solving the defined water resources problem, PDTs shall identify and evaluate structural measures for addressing the identified water resources problem.

B. Selecting Alternatives for Step 4—Evaluation of Alternatives

(1) To avoid the unwise use of floodplains, PDTs shall not include any of the following features or measures in an alternative advanced to the final array of alternatives reviewed in detail under Planning Process Step 4—Evaluation of Alternatives and the National Environmental Policy Act:

i. New or enlarged levees, floodwalls, and other similar structures designed to facilitate or encourage the development of currently undeveloped floodplain land.

ii. Measures or features that divert floodwaters onto other communities and landowners (with careful consideration being given to both upstream and downstream impacts).

iii. Measures or features in or affecting floodplain areas that adversely impact important fish or wildlife breeding, spawning, rearing, nesting, foraging, or migratory habitat.

iv. Measures or features that eliminate an opportunity to restore the natural and beneficial floodplain functions, or that undermine or work against other federal or federally-funded efforts to protect and restore floodplain wetlands, streams, and rivers, including Congressionally authorized restoration projects and programs.

v. Measures or features in floodplain areas that would result in those measures or features being unacceptably vulnerable to flood damage.

(2) To protect communities, redress environmental injustices, and fully account for the sovereignty of Tribes, PDTs shall not advance an alternative to the final array of alternatives reviewed in detail under Planning Process Step 4—Evaluation of Alternatives and the National Environmental Policy Act:

i. If the alternative would increase or transfer flood risk onto another upstream or downstream community in excess of local or state floodplain regulations; or

ii. If the alternative would disproportionately negatively affect people of color, low-income, or vulnerable populations; or

iii. Unless the alternative has been vetted with potentially affected communities through robust and authentic outreach to such communities

iv. For alternatives on or affecting Tribal lands, PDTs shall ensure that only those alternatives fully vetted and approved by the affected Tribe(s) through robust formal consultation that respects and fully accounts for the sovereignty of the Tribe(s) shall advance to Planning Process Step 4—Evaluation of Alternatives.

C. Definitions

(1) **Natural and Nature-Based Features**. A "natural feature" is "a feature that is created through the action of physical, geological, biological, and chemical processes over time." 33 USC 2289a. A "nature-based feature" is "a feature that is created by human design, engineering, and construction to provide risk reduction by acting in concert with natural processes." 33 USC 2289a. Natural features and nature-based features are types of nonstructural measures for the purposes of Corps planning. 33 701b-11(a).

Natural and Nature-Based features include such things as:

i. Acquisition of land or easements, including flooding easements;

ii. Removal of structures such as dams, levees, and culverts to restore natural hydrology, form, function, or ecological processes;

iii. Modification of structures such as dams, levees, and culverts, including through sediment diversions or levee setbacks, to restore natural hydrology, form, function, or ecological processes;

iv. Reoperation of dams and reservoirs to restore or better mimic natural hydrology and flow patterns;

v. Restoration efforts designed to reestablish natural hydrology, form, function, or processes of rivers, streams, floodplains, wetlands, shorelines, and source headwaters;

vi. Creation or restoration of living shorelines; and/or

vii. Reintroduction of native vegetation, including floodplain forests, and/or removal of nonnative vegetation.

(2) **Nonstructural measures.** For flood and storm damage reduction projects, nonstructural measures include such things as: floodproofing of structures, including through elevation; acquisition of floodplain land for recreational, fish and wildlife, and other public purposes; relocations; and floodplain regulation. For navigation projects, nonstructural measures include such things as: crew training, use of switch boats, appointment scheduling systems, improved maintenance of existing structures, and use of multimodal transport in lieu of new construction. For water supply or water storage projects, nonstructural measures include such things as headwaters protection, groundwater protection, and water efficiency measures.

Recommendation for Planning Step 4—Evaluation of Alternatives

A. **Fully Accounting for Project Costs and Benefits.** In developing assessments of project costs and benefits, PDTs shall:

   i. Equitably account for project costs and benefits. This includes fully assessing and accounting for the costs of such things as transferring flood risks onto vulnerable communities and landowners the costs of exposing or resuspending toxic pollutants (including resuspending toxic sediments and increasing water or air pollution). (Note that the Corps' agency-specific guidelines should also detail key approaches for ensuring this critically important equitable accounting, including addressing the benefit-cost assessment items identified in our comments)

   ii. Account for the value of ecosystem services lost as a project cost, and account for the value of ecosystem services gained as a project benefit. This should include, at a minimum, an assessment of the following ecosystem services: flood risk reduction, wildlife habitat, water quality, groundwater recharge, sediment regulation, soil stabilization, carbon sequestration, and recreation. PDTs shall not offset the value of ecosystem services lost to a project by potential benefits that might accrue through mitigation measures, given the inherent difficulties in fully replacing lost ecosystem services through mitigation measures. The values of any ecosystem services lost or gained on federal or state owned conservation lands and lands protected by permanent conservation easements are to be included in a separate sub-category to help identify the impacts to lands that have been protected to help preserve the ecosystem services they provide.

   iii. Account for the full life-cycle costs and benefits, including the costs and benefits associated with long-term operations and maintenance, major rehabilitation, and decommissioning and removal (which may enhance ecosystem services). This is to include the value of ecosystem services projected to be lost or gained over time. When assessing life-cycle costs and benefits of project alternatives, PDTs are to consider the long-term impacts of climate change using the best available predictions for the project location.

   iv. Base cost estimates on realistic projections of the project's construction start date and likely funding stream, historical cost increases by project type and geographic location, and other relevant factors.

B. **Evaluating Project Impacts and Benefits.** PDTs shall provide the detailed evaluation of the full suite of project impacts required by the National Environmental Policy Act. As part of this analysis, PDTS also shall provide detailed documentation of the following:

   i. The potential negative environmental, public safety (including the risks of diverting floodwater), or public health impacts (including evaluation of measures of health inequality) on any communities of color, economically disadvantaged communities, or Tribes or Indigenous communities that may be affected by proposed alternatives. PDTs are to utilize the most accurate and localized data available to facilitate the understanding of the impacts or benefits of project alternatives on specific communities.

ii. The actions taken to ensure the proposed project complies with the requirements of E.O. 11988 and E.O. 13690, which require all federal agencies to minimize, restore, and preserve if a proposed action will result in harm to or within the floodplain. As specified in the implementing guidelines for these Executive Orders, federal agencies must minimize "harm" to both lives and property, and natural and beneficial floodplain values and must also "restore" and "preserve" natural and beneficial values of floodplains, which are defined as follows:

> "Restore means to reestablish a setting or environment in which the natural and beneficial values of floodplains could again function. Where floodplain values have been degraded by past actions, the agency must identify, evaluate, and implement measures to restore the values diminished or lost. The functions of many of the Nation's degraded floodplains can be partially or fully restored through remedial action."
>
> "Preserve means to prevent modification to the natural floodplain environment, or to maintain it as closely as possible to its natural state. This term applies foremost to floodplains showing little or no disruption by man. If an action will result in harm to or within the floodplain, the agency must design or modify the action to assure that it will be carried out in a manner which preserves as much of the natural and beneficial floodplain values as is possible."

iii. The steps taken: to first avoid adverse impacts to wetlands and other waters; to then minimize adverse impacts to wetlands and other waters that cannot be avoided; and to then ensure that any impacts that cannot be avoided will be mitigated (including the steps taken to ensure that required mitigation will be carried out and will be ecologically successful). These descriptions are in addition to the mitigation plan and other mitigation requirements established in the Water Resources Development Acts and the Clean Water Act and its implementing regulations. PDTs shall provide this information, and comply with all Water Resources Development Act and Clean Water Act mitigation requirements, in all project studies including in studies evaluating the operations and maintenance of already authorized civil works projects.

Recommendation for Planning Step 6—Selecting a Plan

Add a New Provision Providing Plan Selection Criteria:

A. **Plan Selection Criteria:** PDTs shall not recommend an alternative as the Tentatively Selected Plan or the Recommended Plan:

   i. If the alternative would increase or transfer flood risk onto another upstream or downstream community in excess of local or state floodplain regulations; or

ii. If the alternative would disproportionately affect people of color, low-income, or vulnerable populations; or

iii. For alternatives on or affecting Tribal lands, if the affected Tribe(s) has not provided its consent in writing; or

iv. If another less environmentally damaging alternative that would address the identified water resources problem is available and practicable, as required by the Clean Water Act; or

v. The alternative would result in unacceptable adverse impacts to the nation’s rivers, streams, floodplains, wetlands, or shorelines and the fish and wildlife that rely on those resources; or

vi. The alternative would result in environmental impacts that cannot be mitigated as required by 33 USC 2283(d).

Attachment B

National Wildlife Federation and American Rivers Comments
Modernization of Army Civil Works Policy Priorities
Docket ID No. COE-2022-0006

ARTICLE OPEN

Check for updates

Protection and restoration of coastal habitats yield multiple benefits for urban residents as sea levels rise

A. D. Guerry[1,2✉], J. Silver[1,2], J. Beagle[3,4], K. Wyatt[1,2,5], K. Arkema[1,2,6], J. Lowe[3], P. Hamel[1,7], R. Griffin[1,8], S. Wolny[1], E. Plane[3], M. Griswold[9], H. Papendick[9] and J. Sharma[9,10]

Globally, rising seas threaten massive numbers of people and significant infrastructure. Adaptation strategies increasingly incorporate nature-based solutions. New science can illuminate where these solutions are appropriate in urban environments and what benefits they provide to people. Together with stakeholders in San Mateo County, California, USA, we co-developed nature-based solutions to support adaptation planning. We created six guiding principles to shape planning, summarized vulnerability to sea-level rise and opportunities for nature-based solutions, created three adaptation scenarios, and compared multiple benefits provided by each scenario. Adaptation scenarios that included investments in nature-based solutions deliver up to eight times the benefits of a traditionally engineered baseline as well as additional habitat for key species. The magnitude and distribution of benefits varied at subregional scales along the coastline. Our results demonstrate practical tools and engagement approaches to assessing the multiple benefits of nature-based solutions in an urban estuary that can be replicated in other regions.

npj Urban Sustainability (2022)2:13 ; https://doi.org/10.1038/s42949-022-00056-y

INTRODUCTION

As the climate warms, cities will continue to experience increases in stressors from sea-level rise[1,2]. Sixty-five percent of the world's megacities are within 100 km and 50 m elevation of the coast[3] and one billion people live less than 10 m above current high tide lines[3]. Despite global forcing, the impacts of sea-level rise are experienced locally, putting local governments on the frontlines of planning and implementing adaptation[4]. Sea-level rise offers local and municipal governments opportunities for proactive planning, though it brings challenges related to prioritizing amongst myriad, immediate concerns[5,6].

One solution is to draw on approaches that both address sea-level rise and deliver diverse benefits to people, improving the livability of urban regions. Nature-based solutions are 'actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human wellbeing and biodiversity benefits'[7]. Ecosystem-based adaptation is a form of nature-based solution that specifically refers to the 'use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change'[8,9]. Such nature-based solutions include the use of existing natural systems (e.g., protecting a marsh), managing or restoring those systems (e.g., restoring a marsh), or creating new systems (e.g., combining mud flats, marshes, and concrete levees to create a horizontal levee)[7]. All of these types of nature-based solutions can support coastal resilience and risk reduction by using natural processes and landforms to provide protection for both ecosystems and the built environment[10,11]. They can provide not only protection from sea-level rise and storms[12–14], but also climate change mitigation through carbon sequestration, opportunities for recreation, habitat for key species, and other benefits[15–20]. These benefits–ecosystem services or nature's contributions to people–help connect healthy, functioning ecosystems to human wellbeing[21,22].

Implementing nature-based solutions in urban environments can bring unique challenges. Some stem from biophysical constraints and their interaction with the built environment. For example, in urban environments, space is often at a premium, and coastal habitats are at risk of coastal squeeze, in which there isn't space for them to migrate upslope as sea-level rises[23–25]. Also, sediment supply in urban environments is often dramatically reduced from more natural conditions, starving marshes of sediment, preventing accretion, and thus making it difficult, if not impossible, for them to keep up with sea-level rise[26–28]. Other challenges relate to ownership, governance, regulations, and funding. In urban areas, patchy ownership of real estate along the shoreline complicates coordinated action. Similarly, governmental jurisdictions are often complex and overlapping. Meeting joint objectives requires integration among various levels of government, extensive stakeholder engagement, agreement about the risks faced and feasibility of solutions, and policies that enable desired actions[29]. Regulatory challenges exist too—for example, regulations designed to prevent the filling of wetlands can prevent the 'beneficial use' of sediments for such purposes[30,31]. Finally, coastal adaptation strategies can be expensive; finding the revenue to devote to future challenges can be difficult for already stressed communities[32].

There are also significant concerns related to environmental justice. The growing interest in nature-based solutions, especially in urban contexts, has sparked critiques calling attention to the unintended consequences associated with green infrastructure projects. These effects are primarily displacement associated with increased property values and other forms of 'eco-

[1]Natural Capital Project, Stanford University, Stanford, CA 94305, USA. [2]School of Environmental and Forest Sciences, University of Washington, Seattle, WA 98195, USA. [3]San Francisco Estuary Institute, Aquatic Science Center, Richmond, CA 94804, USA. [4]US Army Corps of Engineers, San Francisco District, San Francisco, CA 94102, USA. [5]Puget Sound Partnership, Olympia, WA 98501, USA. [6]Pacific Northwest National Laboratory, Seattle, WA 98109, USA. [7]Asian School of the Environment, Nanyang Technological University, Singapore 639798, Singapore. [8]School for Marine Science and Technology, University of Massachusetts Dartmouth, Dartmouth, MA 02747, USA. [9]County of San Mateo Office of Sustainability, Redwood City, CA 94063, USA. [10]County of Santa Clara Office of Sustainability, San Jose, CA 95131, USA. ✉email: anne.guerry@stanford.edu

gentrification'[33–39]. Much of this work has focused on the environmental justice implications associated with urban parks and greenspaces[33,34], tree planting[36], and stormwater infrastructure[38,40]. Less work has been focused on the social concerns associated with coastal natural infrastructure, but early examples of 'climate gentrification' or 'resilience gentrification' highlight the potential to disproportionately impact vulnerable communities in climate resilience and adaptation planning[37,38,41].

All of these challenges are especially pronounced in California's San Francisco Bay Area. California is amongst the US states most exposed to sea-level rise and the San Francisco Bay Area is particularly at-risk[42]. The Bay Area is also one of the most ethnically and racially diverse regions in the country[43]. Within the Bay Area, San Mateo County (one of nine counties) stands out with over $39 billion in assets, more than 30,000 residential parcels, and 3000 commercial parcels at risk of exposure to flooding and erosion over the next 50–100 years[44]. Many populations throughout San Mateo are more vulnerable to the effects of sea-level rise because of factors such as age, race, income, housing vulnerability, and pre-existing health conditions[45]. Rising seas and land subsidence have already increased flooding in the Bay Area[44], making this threat difficult to ignore, especially for socially vulnerable communities.

There is a longstanding history of traditional shoreline engineering in the bay; 6% of the shoreline is behind levees and 75% of the shoreline consists of berms, embankments, transportation infrastructure, or other engineering[46]. More of these projects are planned and some existing hardened shorelines are being raised or rebuilt to address the growing threat of sea-level rise.

Green and hybrid adaptation strategies are also under consideration as design, evaluation of costs and benefits, and community acceptance and awareness of these approaches grows. There is an opportunity now to connect habitat protection and restoration to sea-level rise adaptation planning. At the regional scale, the Bay Area Conservation and Development Commission (BCDC) has recently completed an assessment of the vulnerability of critical assets to sea-level rise[47]. Within San Mateo County, planners are extending their local vulnerability assessment[45] to inform adaptation planning. The County recently created One Shoreline, an agency dedicated to increasing collaboration amongst the county and 20 cities to address inland flooding, sea-level rise, and stormwater[48].

To accompany political and governance opportunities, new science is necessary to understand where and when nature-based solutions are appropriate and what benefits they can provide. In the Bay Area, as in other regions, targets for the restoration of natural habitats exist[49], but little guidance is available about where restoration might be suitable from a biophysical perspective and where it might provide the most benefits to people. Also missing are studies that assess the multiple benefits of nature-based solutions in urban environments. The median cost of restoring a hectare of salt marsh is over $170,000 (2020 US dollars)[50]. Over 300,000 acres have been restored in the US between 2006 and 2015[51], implying over 50 billion in restoration expenditures in the US alone. Understanding and quantifying the diverse benefits of nature-based solutions remains a critical need for rationalizing these expenditures and sustaining support for such efforts.

Here, we report on the results of a partnership designed to co-develop nature-based solutions for climate adaptation planning in San Mateo County. The partnership included County staff, a regional science institute (San Francisco Estuary Institute, SFEI), and researchers from Stanford University's Natural Capital Project, as well as numerous government and NGO stakeholders engaged by the County. We started by working with stakeholders to create a set of guiding principles for adaptation efforts and then asked three key questions: (1) how does exposure to sea-level rise vary along the County's Bay shore? (2) where are nature-based solutions feasible in this highly urban environment? and (3) what additional benefits (ecosystem services) might be provided through the use of nature-based solutions as compared to more traditional, engineered solutions?

RESULTS

Guiding principles, exposure, and suitability

In partnership with stakeholders, we first created six guiding principles to shape the County's adaptation work (Supplementary Note 1). Here, we focus most on the fifth principle: 'Prioritize nature-based actions—work to withstand flooding and erosion while retaining the structure, function, and support of natural processes and ecosystem services,' though all other principles underpin this work.

To help prioritize nature-based solutions, we first summarized exposure to sea-level rise and the biophysical suitability of nature-based solutions throughout the County's five Operational Landscape Units (OLUs) (Fig. 1). OLUs are geographic areas that share certain physical characteristics that influence the production and flow of coastal ecosystem functions, services, and vulnerabilities[24,52]. For exposure, we considered three sea-level rise scenarios: the current sea-level baseline; the baseline plus 1 m sea-level rise; and the baseline plus 2 m sea-level rise, (all plus a 1% annual chance storm) (Fig. 2). Approximately 50% of the area of four OLUs will be inundated even under the mid-level scenario; only one OLU is expected to experience <15% inundation under all sea-level rise scenarios (Fig. 2b). Our exposure maps (adapted from the County-scale vulnerability assessment[45] to include OLUs) show where communities and infrastructure are vulnerable under different projections of sea-level rise (Fig. 2a, Supplementary Fig. 1).

Next, we used the San Francisco Bay Shoreline Adaptation Atlas[24] to summarize the suitability of the County's OLUs for five types of nature-based adaptation solutions that could help reduce flood exposure (Fig. 3, Supplementary Table 1, Supplementary Table 2). In the Atlas, suitability is determined using biophysical characteristics (e.g., water depth, substrate type, wave climate), historical habitats (e.g., maps from ca 1800), and current shoreline development (e.g., marinas, ports, urban development). Beach restoration, ecotone levees (combinations of marshes and traditional levees[53]), and tidal marsh restoration are suitable in 4/5 OLUs; there are opportunities for submerged aquatic vegetation restoration in 3/5 OLUs; and nearshore reefs can be incorporated in 2/5 OLUs (Fig. 3b). See "Methods" for further narrowing of this biophysical suitability to include more social dimensions as we created scenarios.

Adaptation scenario creation and assessment

Through engagement with stakeholders brought together by the County (Fig. 4), we co-developed three spatially explicit adaptation scenarios to inform adaptation decisions (Fig. 5). The scenarios incorporate the biophysical context of each reach of shoreline as well as adaptation options suitable for each OLU (Fig. 5). To allow for a comparison of the benefits of different adaptation solutions, we designed each of the three scenarios to deliver equivalent flood protection. Specifically, the levee crest elevations, marsh restoration widths, and other specifications of each adaptation scenario avoids overtopping from a 1% chance of flood and 1 m of sea-level rise. The first scenario ('What we might have done') represents what the shoreline could have looked like if decision-makers had armored the entire shoreline over the last several decades. This scenario serves as a reference point. The second scenario ('What we are doing') characterizes a future based on existing and planned conservation and restoration activities. In this scenario, we protect existing marshes and restore marshes in

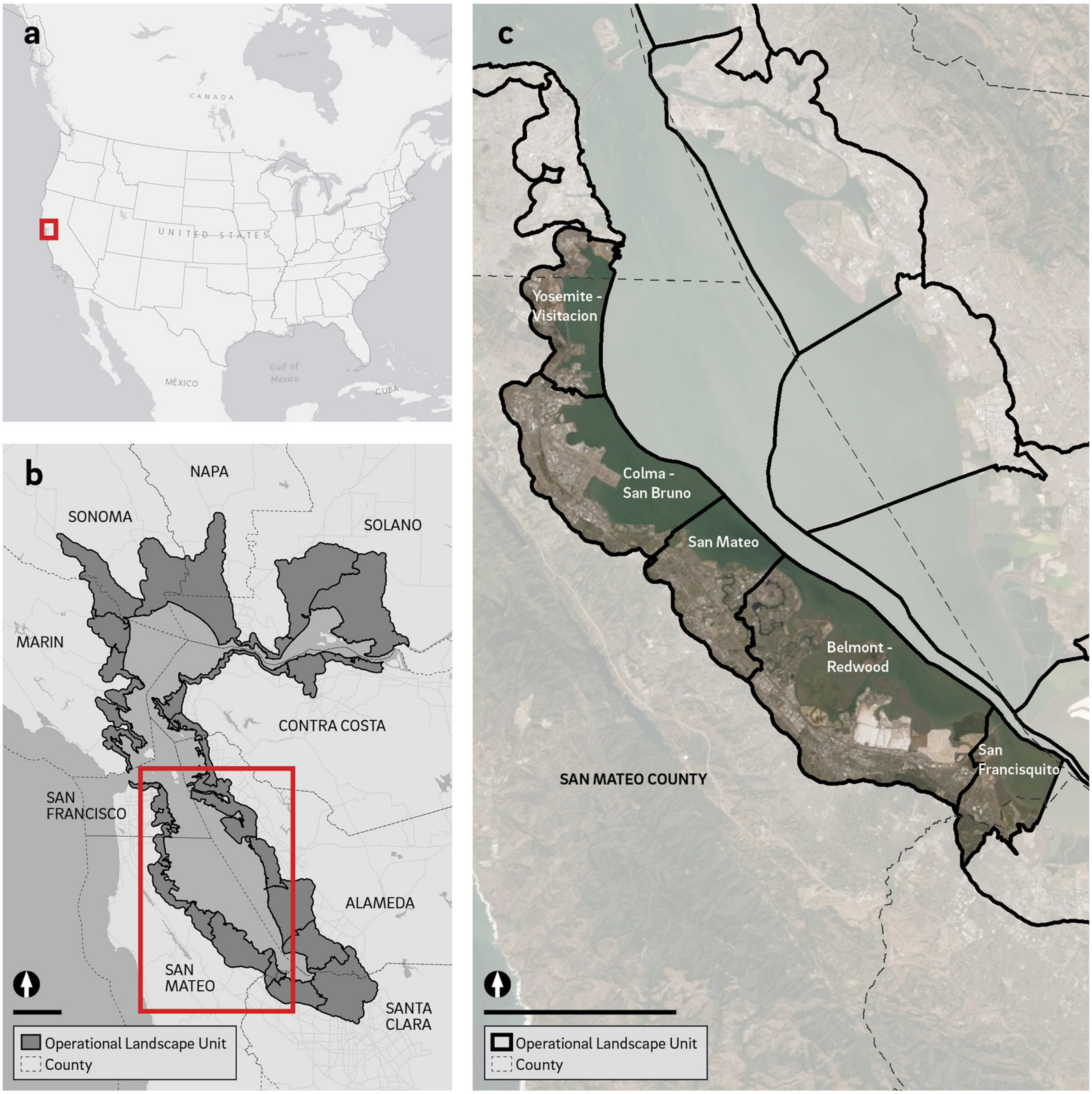


Fig. 1 Maps of the study area. a The San Francisco Bay Area, California, USA, **b** San Mateo County, and **c** the 5 Operational Landscape Units (OLUs) within the County. OLUs are connected geographic areas sharing physical characteristics that influence their shared vulnerability and adaptability to sea-level rise. Black scale bars in panels (**b**) and (**c**) represent 10 km.

locations where projects are underway or undergoing approval. The final scenario ('What we could do next') builds upon the second, adding additional nature-based features that protect marshes and communities where feasible, according to our suitability maps (Figs. 3, S2). To explore differences in the expected benefits provided to people by the year 2050 for each scenario, we quantified three ecosystem services—stormwater nutrient pollution reduction, recreation, and carbon sequestration—as well as the provision of habitat for a species of special concern.

Adaptation options that include investment in nature-based solutions deliver up to eight times the benefits of an engineered baseline (Table 1). Our models suggest that a future shoreline with existing and planned restoration projects will feature five times more marsh (which is habitat for, among other things, the endangered Ridgway's Rail (*Rallus obseletus*)), and deliver five times the carbon sequestration and six times the stormwater pollution reduction of an engineered shoreline. Such a future will also provide an additional 50 ha of beach. A future shoreline that incorporates additional feasible nature-based solutions could provide up to six times the marsh area, eight times the stormwater pollution reduction, and six times the carbon sequestration of an engineered baseline. Furthermore, this scenario provides an additional 170 ha of beach.

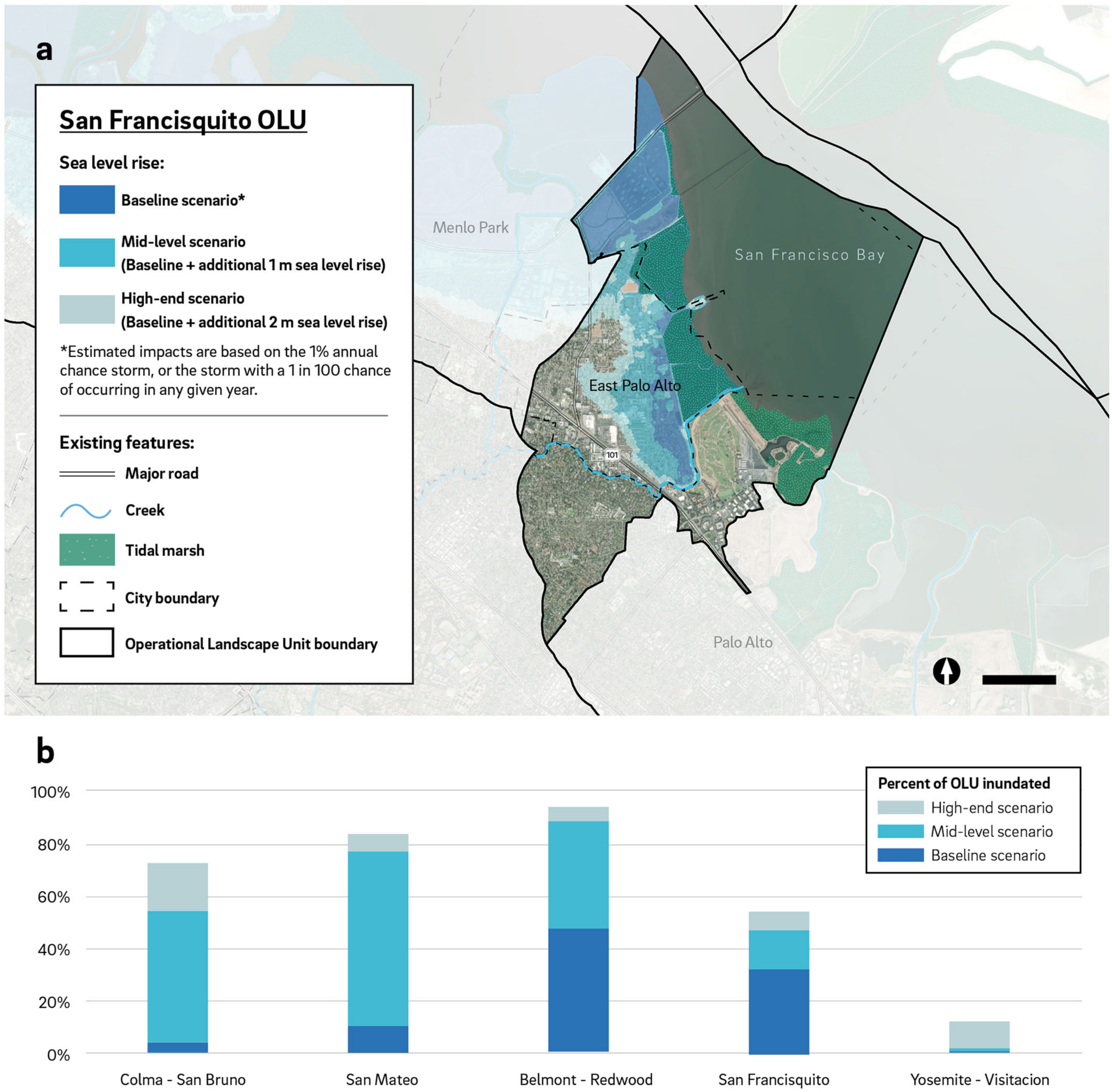
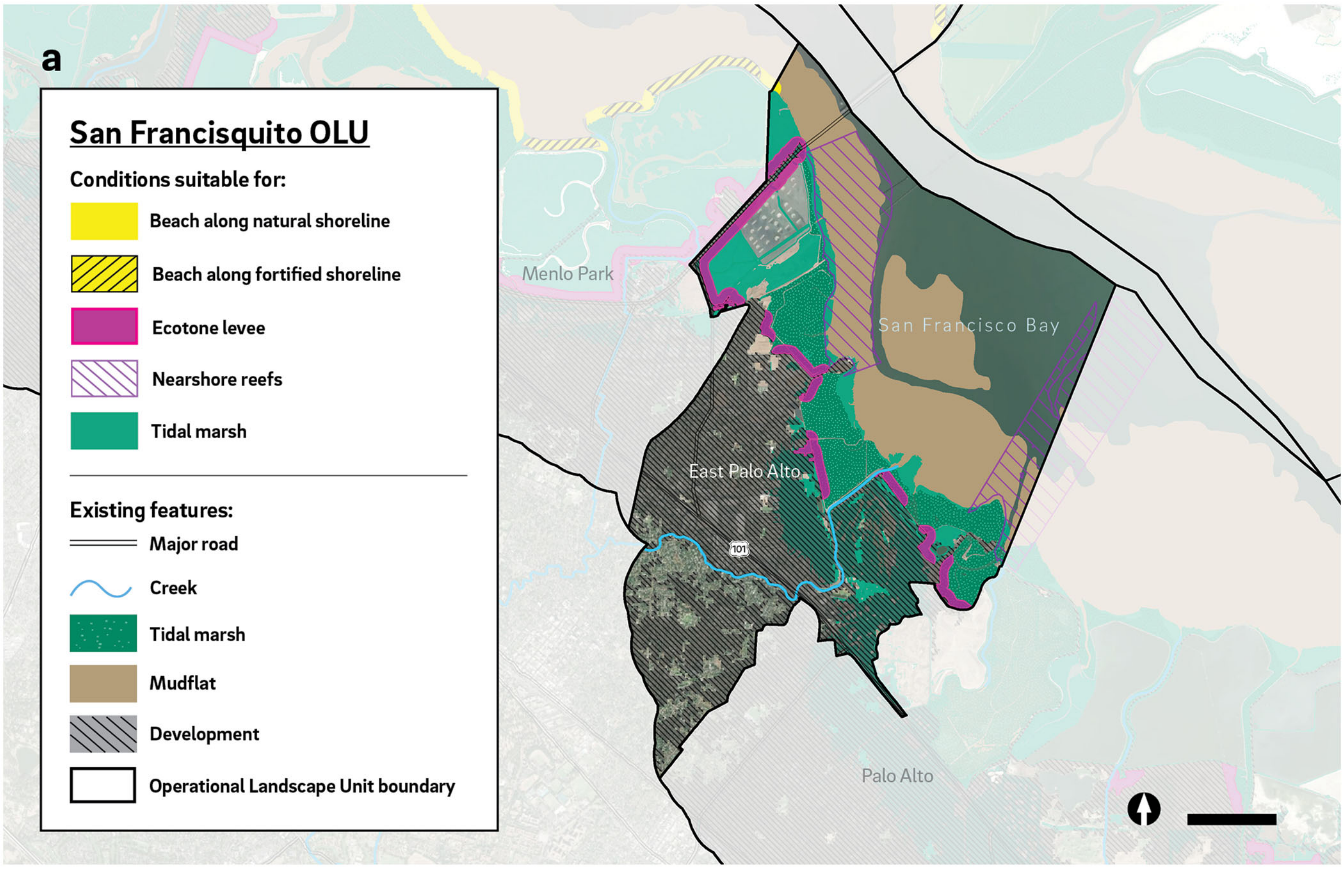


Fig. 2 Sea-level rise exposure. **a** Exposure in the San Francisquito Operational Landscape Unit (OLU) and **b** exposure throughout the County's 5 OLUs. San Francisquito is the southernmost OLU in San Mateo County. Darker blues represent expected flooding in the baseline scenario and lighter blues represent flooding in the mid-level and high-end scenarios. Black scale bar in panel (**a**) represents 1 km.

Summarized across the County, recreation does not differ across the three scenarios (Table 1). However, this result masks differential effects by OLU; the northern OLUs tend to gain or maintain visitors with beach restoration activities in scenarios 2 and 3, and southern OLUs tend to lose visitors with marsh restoration activities (Fig. 6). All else being equal, marshes are associated with lower recreation and beaches are associated with higher recreation. We also find that recreational use of engineered structures depends on their design. For example, engineered structures with trails are associated with more visitors than engineered structures without such infrastructure (Supplementary Table 10).

The distribution of existing and future coastal habitats and the range of services they provide to people varies significantly throughout the County (Fig. 6), driven by the geomorphic and ecological nature of the OLUs. For example, the Belmont-Redwood OLU is home to much of the County's existing and potential marshes. Thus, we see significant carbon sequestration, stormwater pollution reduction, and habitat provision provided by the marshes in this OLU. On the other hand, it receives relatively little coastal recreation in any scenario and sees reductions in recreation as the marsh area increases through restoration (Fig. 6).

To the north, the Yosemite-Visitacion OLU has no marsh area because of the shoreline's proximity to deep water and high wave



b

	Beaches	Ecotone levees	Nearshore reefs	Submerged aquatic vegetation (eelgrass)	Tidal marshes
San Francisquito	○	●	●	○	●
Belmont - Redwood	●	●	○	○	●
San Mateo	●	◐	○	●	◐
Colma - San Bruno	●	◐	○	●	◐
Yosemite - Visitacion	●	○	●	●	○

Legend: ○ Limited suitability ◐ Some suitability ● High suitability

Fig. 3 Biophysical suitability of nature-based adaptation opportunities—particularly ecotone levees, nearshore reefs, and tidal marshes. **a** Suitability in San Francisquito and **b** throughout the County's 5 OLUs (also including beaches and submerged aquatic vegetation). Neighboring regions are masked, but show differences: for example, the suitability of long stretches of the Belmont-Redwood OLU shoreline to the northwest for beaches along both natural and fortified shorelines. We summarized biophysical suitabilities by OLU from the regional suitability assessment in the San Francisco Bay Shoreline Adaptation Atlas[24]. Black scale bar in panel (**a**) represents 1 km.

energy and thus offers none of the services provided by marshes. However, this region offers significant beach access and experiences the most recreation in the county (~50% of the County's total modeled recreation). Our suitability analysis indicates restoration of an additional 43 ha of the beach is possible in this OLU. New beaches soften the shoreline, respond to high wave energy, and recreate the pocket beaches historically present in the area. Results from Scenario 3 ('What we could do next') suggest that further beach restoration—not currently underway or planned—would increase recreation in the Yosemite-Visitacion OLU (Fig. 6).

DISCUSSION

Throughout this work, we saw that science—delivered through discussions and as maps, tables, and figures—helped provide useful boundary objects for fostering conversations with leaders and stakeholders. Iterative, co-creation of guiding principles for sea-level rise adaptation planning enabled the identification of shared goals and outcomes as well as barriers to implementation. Co-development of shared goals, future scenarios, and knowledge exchange between stakeholders is an important part of adaptation as it enhances sustainable solutions for urban

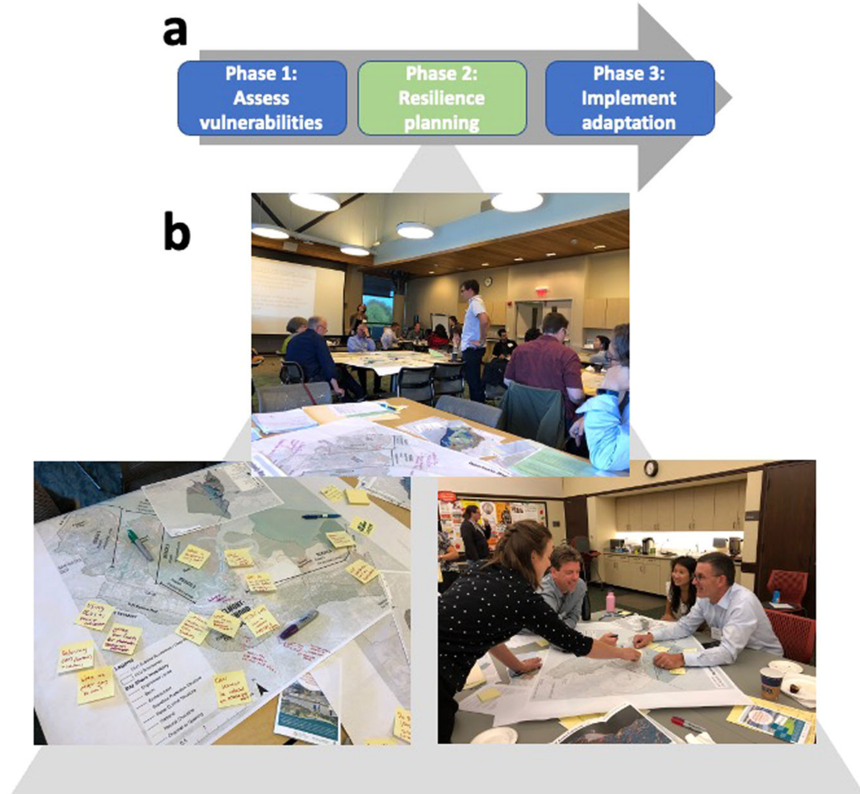


Fig. 4 The engagement process. We conducted this work in conjunction with the County of San Mateo's Office of Sustainability and their broader sea-level rise planning efforts, which includes three phases (**a**). This work was part of the second phase of that effort, going from information about vulnerabilities to the exploration of adaptation options. In partnership with the County, we participated in several stakeholder meetings (**b**) to help create the guiding principles to shape adaptation options and scenarios, to get feedback on the suitability of nature-based solutions, and to share results comparing ecosystem services delivered by different adaptation scenarios.

transformation[54,55]. Maps of exposure and of opportunities for adaptation sparked important conversations that informed our creation of the three adaptation scenarios. We found that co-creation of scenarios that connected different pathways of adaptation with impacts on nature and on nature's contributions to people allowed us to generate more salient results[56]. The work benefitted from candid discussions with public works directors and land managers about their own experiences with flooding and the feasibility of adaptation options. We ultimately produced fact sheets (Supplementary Note 2) that the County distributed amongst leaders to help communicate results and inform adaptation decisions.

However, throughout the engagement, we faced significant challenges. We saw how hard it is for leaders and communities to have conversations about changing or moving land uses. We saw the challenges of flood managers working to plan for the future while managing for flood protection today. And we saw how few options there are for nature-based solutions in cases of coastal squeeze[57,58] such as in San Mateo County, where rising sea levels, shoreline armoring, urban development, and other factors lead to limited space for coastal habitats. We had hoped to explore more dramatic and creative adaptation scenarios (e.g., those that can be generated from imaginative, arts-based processes[59]), but in consultation with partners and stakeholders, found that the exploration of the incremental changes included in our scenarios was a more practical, helpful approach (i.e., focusing on adaptive and strategic scenarios, rather than transformative ones[60]).

The Nature Futures Framework lays out three value perspectives on how people relate to nature: 'Nature for Nature'"(intrinsic value), 'Nature for Society' (instrumental value) and 'Nature as Culture' (relational value)[61]. While we focus on 'Nature for Society' by exploring how alternative adaptation solutions are likely to impact the flows of benefits to people, such values are intimately connected to 'Nature for Nature' (e.g., exploring changes in habitat for the endangered Ridgway's Rail) and 'Nature as Culture' (e.g., modeling changes in recreation, one embodiment of the reciprocal people-nature relationship that brings diverse health benefits to people and can encourage stewardship of natural spaces[62,63]).

Planning for sea-level rise often follows ownership or jurisdictional divides. However, changes to the shoreline in one location may have unintended consequences in other locations, for example as seawalls push water to other shorelines[64]. Thus, the scale of sea-level rise planning should reflect the scale at which natural processes—such as tides, waves, and sediment movement —affect shorelines[24]. Using shoreline planning areas such as OLUs provides communities with a way to develop coherent, geographically appropriate adaptation strategies[24].

Often the discourse about adaptation to sea-level rise includes false dichotomies between 'gray' and 'green' solutions. However, implemented solutions will often be hybrids, mixing gray and green infrastructure as feasible and desired. Creative combinations of hybrid measures have been shown to increase coastal protection benefits[65–67]. The goal of these combined approaches is that each line of defense will play a complementary role in reducing vulnerability to flooding and stabilizing the shoreline[65]. One example in our analysis is the possible addition of a beach

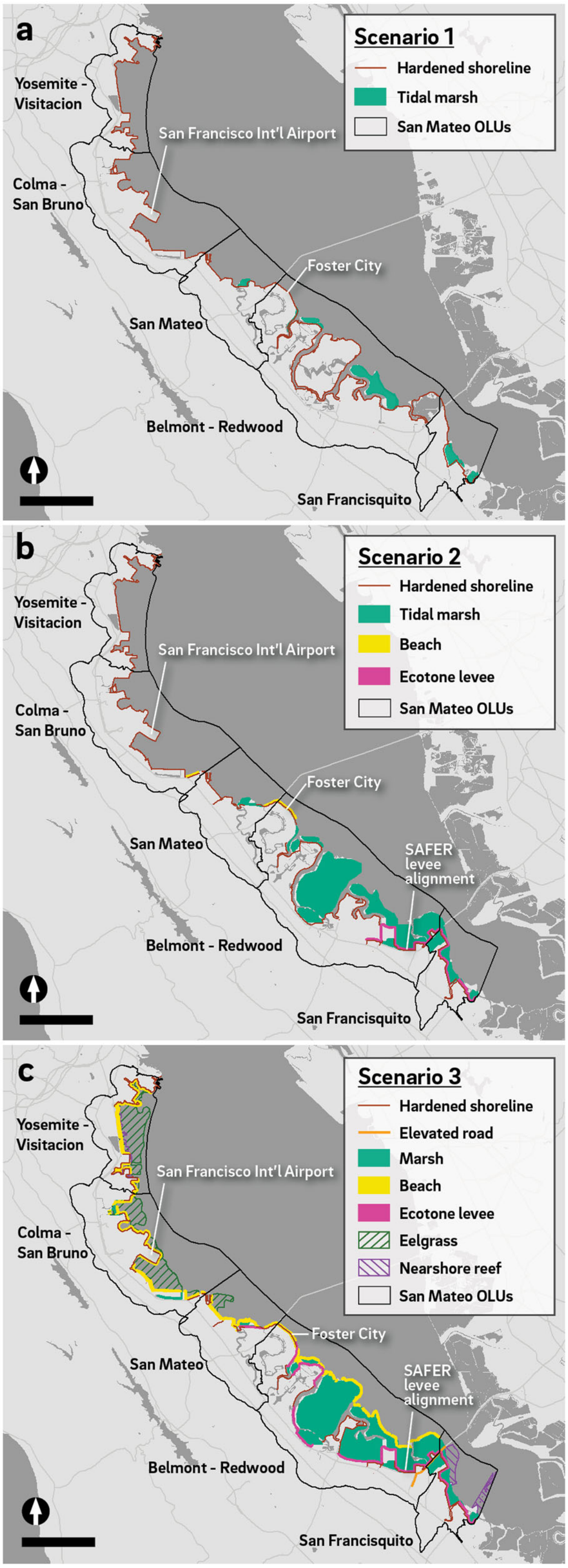


Fig. 5 Three scenarios of adaptation across the five OLUs of San Mateo County. Scenario 1 represents an engineered shoreline, or 'What we might have done.' This scenario serves as a baseline or comparison for the other two. Scenario 2 represents currently planned or permitted conservation and restoration projects, or 'What we are doing.' Scenario 3 uses information from our suitability assessment to include additional nature-based features, or 'What we could do next.' Black scale bars represent 5 km.

bayward of a vertical levee and flood wall along the northern reach of Foster City in Scenario 3 (Fig. 5).

A surprising finding from the analysis of ecosystem services was that restoring and protecting marsh reduces visitation. This result may be partly explained by policies that deliberately limit accessibility to protect the marshes and associated wildlife. Access to marshes in the region is limited during the nesting season for the endangered Ridgway's Rails (ca. 6 months per year) and thus this relationship only holds for our case study. Developing a better understanding of the drivers of this result is essential given the importance of salt marsh restoration elsewhere as part of the portfolio of adaptation strategies to sea-level rise.

An avenue for advancing this research is to explicitly map the beneficiaries of each scenario to better understand who benefits from nature-based solutions and resulting equity concerns. However, with the exception of recreation, the benefits we modeled are provided on a largely global (carbon) or regional (nutrient retention, habitat for Rails) basis. Given that increases in marsh areas are associated with decreases in visitation, further work is required to understand how and if the addition of these nature-based solutions may contribute to gentrification and other distributional issues.

Our approach has four important limitations. First, we considered upland land use as unchangeable. In the future, as sea level continues to rise, there will be difficult decisions about changing land use and the need to adapt, realign, or retreat[68–70]. The exposure and suitability maps do not reflect these changes because they are difficult to forecast; our scenarios do not include them because they were unacceptable to the stakeholders we engaged. Second, the co-benefits we explored here are only a subset of the multiple benefits that can be provided by urban nature. Third, we use relatively simple modeling approaches to estimate the benefits that will flow to people from the different adaptation options. Each model relies on simplifying assumptions and therefore yields first approximations that are best compared across scenarios. These assumptions are detailed in the Methods and Supplementary Methods. Finally, we did not include costs of different adaptation options (Scenarios 1–3), nor did we measure benefits in common units. Thus, this analysis cannot provide information about the net benefits of alternative scenarios in a cost-benefit analysis framework[32]. Methods for measuring adaptation costs in the study area were investigated in a 2017 study; it used an estimate of over $5,000 USD/m for simple levees[71], which is surely an underestimate given the current costs of materials. We seek to complement cost analyses by exploring the value of key ecosystem service benefits associated with a variety of adaptation approaches.

Additional work that explores a more complete assessment of both costs and benefits of adaptation options—in addition to the costs of doing nothing—will be an important next step for this field. Existing work has laid critical groundwork for such analyses[72–75]. An adaptation approach that meanders along the shoreline to maintain salt marsh frontage for seawalls could end up being more than double the overall length and cost than an approach that employs straighter lines further into the bay[32], suggesting a potential tradeoff with ecosystem benefits of salt marsh.

One important goal of this work was to bring siloed local government staff together to consider adaptation planning at a county-wide scale. A key next step will be to engage community members and other types of stakeholders to further discuss the social acceptability of different adaptation strategies and the lack thereof.

Some nature-based opportunities, as incorporated into Scenario 2, are already being implemented; others have funding and permitting in place and will be implemented soon. For example, in the San Francisquito Creek OLU, key projects aimed at reconnecting San Francisquito Creek to its marshes are complete. Also, green stormwater infrastructure in several locations within the watershed aims to reduce fluvial flooding in the lower-lying developed areas. In the Colma-San Bruno OLU, floodplain and marsh restoration as well as beach planning are underway to enhance the resilience of Colma Creek to sea-level rise[76]. Monitoring the impacts of these projects will be key. On the current trajectory, Scenario 2 could be fully implemented by 2030.

Scenario 3 ('What we could do next') shows where further natural and nature-based solutions are possible but does not explore pathways to achieving them. However, further nature-based opportunities (i.e., from Scenario 3) are under consideration. For example, decision-makers in Burlingame used our analyses to inform the creation of a shoreline adaptation plan for their hotel district[77]. Ultimately, implementation of Scenario 3 depends on funding (local, state, and federal), political will, and regulatory agreements. Also, it depends on planning and environmental compliance—which can together take upwards of 10–15 years from start to finish. Fortunately, the Bay Area Conservation and Development Commission (BCDC) recently removed a key barrier to allow bay filling for projects aimed at restoring and enhancing natural habitat to adapt to sea-level rise[31]. A central motivator of this work was to explore and quantify the multiple benefits of nature-based solutions as an input to planning discussions to, if warranted, help make the case for additional nature-based solutions.

Sea-level rise adaptation strategies in one part of the Bay can have implications for distant stretches of shoreline[64,78,79]. Working across jurisdictions to plan adaptation strategies is critical to addressing the problem of sea-level rise. Even at the scale of San Mateo County, the footprint of adaptation projects can span multiple cities and require the approval of several state and federal agencies with different priorities, compounding governance challenges. To address this, San Mateo County has set up a new flood- and sea-level rise district designed to work across the County[48]. This is a rare example of multiple cities working together to address more holistically the regional risk of flooding.

Table 1. Changes in habitat and ecosystem services provided by Scenario 2 ('What we are doing') and Scenario 3 ('What we could do next') relative to the engineered baseline ('What we might have done') without investing in nature-based solutions.

Co-benefits	Scenario 2	Scenario 3
Marsh area/Ridgeway Rail habitat	5x	6x
Beach area	+50 ha	+200 ha
Recreation	1x	1x
Runoff retention	6x	8x
Carbon sequestration	5x	6x

The risk from sea-level rise results not only from biophysical factors but also from socio-economic and historic ones. Before the establishment of BCDC, the development of marshes along the edges of the Bay was commonplace. Municipalities, such as Foster City, built upon artificial fill where coastal habitats once were, are more at risk as seas rise. Perhaps most importantly, communities with similar biophysical risks do not necessarily have similar vulnerabilities—some communities have more resources than others. For example, due to higher property values in some areas, some cities have access to funding through tax increases or assessment districts (e.g., City of Foster City or City of San Mateo), whereas cities with a lower tax base and lower property values have fewer options to generate the funding needed for adaptation through this strategy (e.g., East Palo Alto). Moreover, while jobs associated with adaptation actions are considered costs when making decisions using cost-benefit analysis[80], communities may actually assign a positive value to job creation if there is significant unemployment or a desire for higher skilled jobs. Careful thought about the variety of social objectives, resource gaps, and potential equity pitfalls are necessary as leaders at all levels consider risk, exposure, vulnerability, and adaptation.

This work adds to the growing body of research from around the world demonstrating that nature-based solutions help protect coastlines and yield diverse ecosystem services[14,15,72,81–83]. Nature-based solutions are often 'no- or low-regret' options because they serve multiple functions, reduce vulnerability, and help build resilience[84]. However, significant challenges still hamper their broader uptake. Nature-based solutions are not feasible in all locations (e.g., because of a lack of space in urban environments), the protective benefits (and co-benefits) they provide can depend on various ecological and storm-specific factors, they can take more time to be established than traditional engineered structures, the planning community lacks expertise in designing and executing them, and there are often regulatory or cultural barriers to their inclusion in adaptation portfolios[83]. The recent publication of the International Guidelines on Natural and

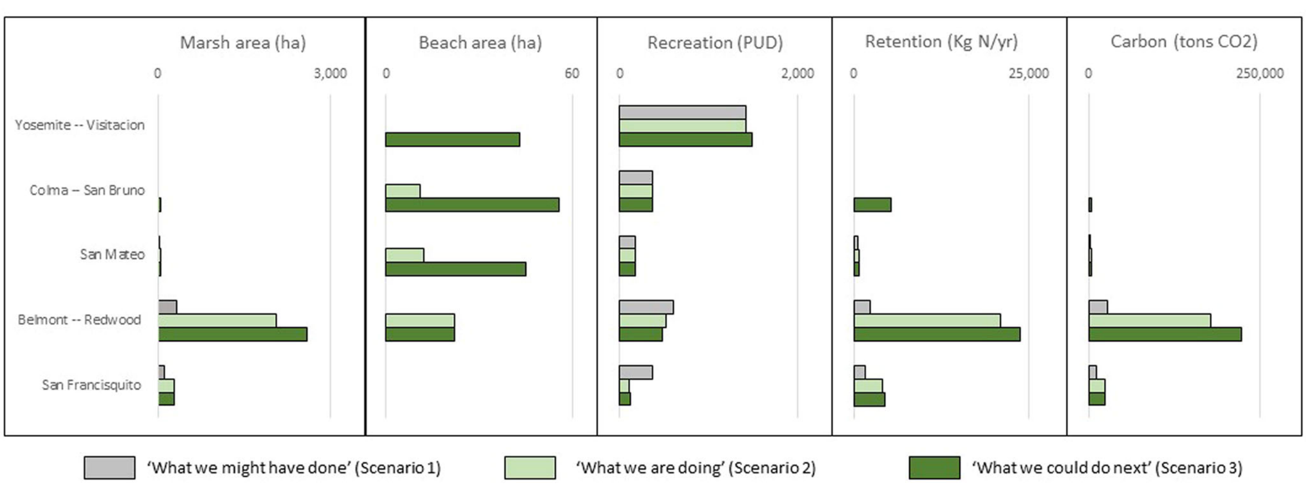


Fig. 6 Habitat and ecosystem services across San Mateo County's five Operational Landscape Units (OLUs) compared across the three adaptation scenarios. The scenarios compare: (1) 'What we might have done,' (2) 'What we are doing,' and (3) 'What we could do next.' Recreation is measured in 'PUD' or photo-user days, a proxy for the number of visitors. Carbon sequestration is measured from 2018–2050 for existing marsh and from 2030–2050 for new marsh.

Nature-Based Features for Flood Risk Management and accompanying Engineering With Nature Atlas that describes over 100 nature-based adaptation projects around the world is a key step in reducing some of these challenges[85–87].

Our approach included: co-developing guiding principles for adaptation; identifying exposure to sea-level rise and the suitability of nature-based solutions within functional landscape scale units; mapping and measuring the co-benefits of the nature-based solutions; and engaging with stakeholders throughout the process to ensure the relevance and utility of our results. By demonstrating the multiple benefits provided by nature-based approaches, this work can serve as an example for jurisdictions throughout the Bay and beyond seeking to leverage ecosystems in their efforts to adapt to climate change.

METHODS

Guiding principles

To generate the guiding principles at the foundation of this work, leaders at the County of San Mateo Office of Sustainability conducted numerous working sessions with stakeholders throughout the County. The team held meetings in libraries and other public spaces and often had 60–70 participants that included County and City planners, public works officials, staffers from offices of elected officials, NGO personnel, and land-managers. After listening sessions, the team crafted draft principles followed by additional meetings to revise and finalize the principles. We also held meetings throughout this work to gather feedback on maps, to inform the creation of scenarios, and to share ecosystem service modeling results.

Summarizing exposure to sea-level rise

We used the San Mateo County Sea Change Sea Level Rise Vulnerability Assessment[45] to summarize the extent of sea-level rise across the five OLUs in the County. The County's assessment summarized risk by city and by asset class (roads, hospitals, schools). We recast these analyses to visualize the exposure of multiple assets at the cross-jurisdictional and geophysically-connected OLU scale. Following the County lead, we examined three sea-level rise scenarios: a baseline scenario (a 1% annual chance flood event), a mid-level scenario (1% flood event plus 1 m sea-level rise), and a high-end scenario (1% flood event plus 2 m sea-level rise)[45].

Identifying suitability of nature-based opportunities for adaptation

We identified where a range of nature-based adaptation measures could be implemented in San Mateo County OLUs to mitigate the effects of sea-level rise. We define adaptation measures as specific interventions to manage the shoreline in response to or in anticipation of climate change vulnerabilities. We did not consider fluvial flooding and groundwater emergence. We drew on work completed previously as part of the San Francisco Bay Shoreline Adaptation Atlas[24], which defines, describes, and maps the biophysical suitability of more than two dozen sea-level rise adaptation measures across the 30 OLUs in the Bay. The five OLUs in San Mateo County are highly developed and lack open space on the Bay shore, limiting the suite of nature-based adaptation strategies suitable for this county to: restoration and creation of submerged aquatic vegetation, coarse beaches, tidal marsh, and nearshore oyster reef; as well as the establishment of ecotone levees.

Next, we identified locations along the shoreline which had the enabling conditions required for a given strategy. For example, for marsh restoration, we identified areas where ground elevations were suitable to allow for new marsh wide enough to attenuate local waves and reduce levee erosion. Where marshes already existed that were wide enough, we looked for opportunities to reduce marsh edge erosion by the creation of oyster reefs or eel grass beds to attenuate waves. In places where the land elevation was too low for marshes but there was a low-tide terrace, we looked for opportunities to create coarse beaches to provide the same wave attenuation function as marshes and reduce overtopping and erosion of levees and sea walls[24,88]. We considered coarse beaches (sand, gravel, and shell) in locations with wide enough shallows for sediment resuspension and onshore transport of materials for their potential to slow wave driven erosion of marshes and other shoreline types[24,88]. Constructed nearshore reefs and enhanced submerged aquatic vegetation have the ability to reduce waves reaching the marsh edge and could trap sediment and reduce marsh erosion, and require subtidal conditions suitable for their survival, which include turbidity and light thresholds[24]. Finally, we identified locations where marshes or diked baylands are adjacent to development or critical infrastructure and thus where ecotone levees[24,53] can provide flood protection to low-lying communities. For further details, see the San Francisco Bay Shoreline Atlas[24].

Creation of adaptation scenarios

To compare benefits across scenarios, we held flood protection equal. We designed the flood risk elements (levee crest elevation, width, and elevation of restored beach and marsh) of the three adaptation scenarios such that overtopping does not occur under the conditions of a 100-yr FEMA storm with 1 m of sea-level rise. For each scenario we calculated the minimum width of marsh needed to attenuate 100-year incident waves down to 1 ft in height before reaching the back edge of the marsh and the levee behind it following the method laid out by Bouma et al.[89]. For beaches, we calculated the crest elevation and beach volume for the incident wave conditions. We calculated crest elevations based on the runup of the 100-year significant wave height[90,91]. See the Adaptation Atlas[24] for more details. In all three scenarios we assume that marshes will accrete sediment and keep up with sea-level rise until 2050[61] and that maintenance and management of marshes will be needed beyond 2050. This assumption is reasonable (given high sediment concentrations) until our endpoint of 2050[92], but after that sediment augmentation for marshes will likely be necessary[93]. Furthermore, we assume no major land-use changes.

Scenario 1 ('What we might have done') describes a shoreline in 2050 that is hardened completely using levees and seawalls (a length of 130 km of hardened shoreline). This scenario envisions a world in which no large tidal marsh restoration had been done in the Bay and ignores existing or planned marsh restoration activities. We created this scenario to help stakeholders understand the value of restoration investments the region has made over the last 40 years. Using Scenario 1 as a basis, Scenario 2 ('What we are doing') incorporates existing and planned restoration projects and their nature-based features as well as existing and planned hardened shoreline (for a total length of 106 km of hardened shoreline). This scenario serves to quantify the benefits the County and region are already receiving from nature-based solutions that are in place or are currently planned.

Building on Scenario 2, Scenario 3 ('What we could do next') adds additional nature-based adaptation features where feasible from both a biophysical perspective (from the suitability analysis) and based on feedback from participants in listening sessions. Feedback from participants in workshops helped to narrow the suite of 'suitable' nature-based solutions from a biophysical perspective to those also 'suitable' in a more social dimension. For example, in our original suitability analysis we considered changes to current land uses (e.g., managed retreat to allow for marsh migration space), but stakeholders were reluctant to include such changes. Similarly, listening sessions helped us update maps based on local knowledge of existing flood protection structures, urban drainage systems, etc. This feedback allowed us to adjust our suitability maps to better match local knowledge and information. Scenario 3 has a total of 79 km of hardened shoreline, 60% of the hardened shoreline of Scenario 1. Restoration of tidal marshes in Scenarios 2 and 3 allow realignment of hardened infrastructure to protect shorter segments of shoreline. In both Scenario 2 and Scenario 3, multiple types of adaptation solutions are needed to achieve the desired level of flood protection. Thus, in many stretches of shoreline, nature-based solutions such as marshes and beaches are accompanied by levees and other hard infrastructure (Fig. 5). Both scenarios with nature-based solutions also involve increasing the length of hardened infrastructure over the current length (54 km)–52 additional km for Scenario 2 and 25 km for Scenario 3–but have their bayward edges softened by nature-based solutions.

Ecosystem service modeling

We estimated the spatial production of three ecosystem services associated with changes in the extent of tidal marsh and beach habitat—stormwater nutrient pollution reduction, recreation, carbon sequestration—as well as the provision of habitat for a key endangered species. We quantified and compared ecosystem services delivered by each of the three adaptation scenarios. We summarized services across the whole County for each adaptation scenario and explored spatial variation among OLUs in the production of services. As with all modeling, we had to make particular simplifying assumptions; these introduce potential sources of error and should be considered when interpreting results. Below, we provide basic information about each model, with additional details on each model and its underlying assumptions in the Supplementary Methods.

To estimate stormwater nutrient pollution reduction from marshes for each of the three scenarios we used the InVEST Urban Stormwater Retention model[94] (Supplementary Methods, Supplementary Tables 3–8). We modeled the spatial distribution of pollutant loads in stormwater runoff draining to the Bay (kg N per year) at a 30 m resolution based on precipitation, land cover, and soil data. We estimated stormwater pollution reduction by marshes based on empirical data on nutrient removal rates by marshes for the Bay (Supplementary Methods). We applied removal rates to nutrient loads discharged near (<100 m) marsh areas and estimated the total amount of pollution reduction as the sum of pollutant removal from each marsh section in the area of interest.

To estimate recreation along the Bay's shoreline, we used the InVEST Recreation model to summarize standardized, unique geotagged Flickr "photo user days" by 500 m hexagonal grid cells along the shoreline of the Bay over the period 2005–2017, as a relative proxy for recreation[94–96] (Supplementary Methods, Supplementary Fig. 2). Drawing only from the narrow 500 m buffer centered directly on the shoreline, we assumed that all observed photo user days are representative of recreational visits. We used a count multiple regression model to estimate the relationship between visitation and shoreline type along the entire Bay shoreline (e.g., seawall, tidal marsh, horizontal levee, beach, etc.) (Supplementary Methods, Supplementary Tables 10 and 11), controlling for other factors associated with visitation such as adjacent populations and access (Supplementary Tables 9 and 10). We used the correlational relationship between shoreline type and visitation to predict potential changes in recreation under our three scenarios (Supplementary Fig. 3).

We estimated the carbon sequestered and stored by tidal marshes under each scenario using the InVEST Coastal Blue Carbon model[94,97]. The model estimates carbon stored and sequestered by coastal ecosystems over time in three pools: aboveground biomass, litter, and soil (Supplementary Methods). We gathered key model parameters including carbon stock, accumulation rates, and half-life from studies in the Bay when available, using values from elsewhere in California, or global averages when local data was not available (Supplementary Table 12). For this analysis we assumed that new marsh reflected in adaptation Scenarios 2 and 3 was fully established by 2030 and was not providing any carbon sequestration service from 2018–2030 during a phase of restoration and marsh establishment. In addition, we assumed that all marsh in the County began with the same carbon pool values, accumulated soil carbon at the same (linear) rate, and that none accumulated biomass or litter over time.

Finally, we summarized the habitat availability for Ridgway's Rail (*Rallus obsoletus*), a species listed as 'endangered' according to the US Endangered Species Act, and thus a species of special concern. Ridgway's Rail habitat is restricted almost entirely to the marshes of the San Francisco Bay, making it a good "umbrella" species for the conservation community–protection and restoration of Ridgway's Rail is tightly connected to protection and restoration of marshes, and thus to the support of other elements of marsh-dependent biodiversity. We used a simple linear regression to define the relationship between tidal marsh habitat and rail distribution and found that marsh explained 80% of rail occurrence ($p < 0.01$). Using the relationship determined under current conditions (Ridgway's Rail area = −0.0745 + 0.80805*marsh area), we estimated Ridgway's Rail habitat area for each future scenario. This model is a first approximation of how marsh area might translate to habitat for this important species; more complex modeling would be necessary to understand the quality of habitat, dispersal across patches, and the persistence of populations. This simple model of Ridgway's Rail habitat helps provide an additional metric–beyond marsh area–that resonated with local stakeholders.

DATA AVAILABILITY

Data are available at The Center for Open Science's OSF: https://osf.io/jsx9m/.

CODE AVAILABILITY

Source code for the InVEST software is available at: https://github.com/natcap/invest.

Received: 4 November 2021; Accepted: 25 April 2022;
Published online: 09 June 2022

REFERENCES

1. IPCC. IPCC, 2018: Summary for policymakers. In *Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (eds. Masson-Delmotte, V. et al.). (World Meteorological Organization, 2018).
2. The World Bank. *Cities and Climate Change: An Urgent Agenda*. http://hdl.handle.net/10986/17381 (2010).
3. Kulp, S. A. & Strauss, B. H. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nat. Commun.* **10**, 4844 (2019).
4. Revi, A. et al. Urban areas. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* (eds. Field, C. B. et al.) 535–612 (Cambridge University Press, 2014).
5. Crabbé, P. & Robin, M. Institutional adaptation of water resource infrastructures to climate change in Eastern Ontario. *Clim. Change* **78**, 103–133 (2006).
6. Measham, T. G. et al. Adapting to climate change through local municipal planning: barriers and challenges. *Mitig. Adapt. Strateg. Glob. Change* **16**, 889–909 (2011).
7. Cohen-Shacham, E., Janzen, C., Maginnis, S. & Walters, G. Nature-based solutions to address global societal challenges. https://doi.org/10.2305/IUCN.CH.2016.13.en (2016).
8. Cohen-Shacham, E. et al. Core principles for successfully implementing and upscaling nature-based solutions. *Environ. Sci. Policy* **98**, 20–29 (2019).
9. Convention of Biological Diversity (CBD). *Connecting Biodiversity and Climate Change Mitigation and Adaptation: Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change*. https://www.cbd.int/doc/publications/cbd-ts-41-en.pdf (2009).
10. Bridges, T. S. et al. *Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience*. https://usace.contentdm.oclc.org/digital/collection/p266001coll1/id/3442/ (2015).
11. Whelchel, A. W., Reguero, B. G., van Wesenbeeck, B. & Renaud, F. G. Advancing disaster risk reduction through the integration of science, design, and policy into eco-engineering and several global resource management processes. *Adv. Ecosyst. Disaster Risk Reduct. Policy Plan. Implement. Manag.* **32**, 29–41 (2018).
12. Arkema, K. K. et al. Coastal habitats shield people and property from sea-level rise and storms. *Nat. Clim. Change* **3**, 913–918 (2013).
13. Hochard, J. P., Hamilton, S. & Barbier, E. B. Mangroves shelter coastal economic activity from cyclones. *Proc. Natl. Acad. Sci. USA* **116**, 12232 (2019).
14. Shepard, C. C., Crain, C. M. & Beck, M. W. The protective role of coastal marshes: a systematic review and meta-analysis. *PLoS ONE* **6**, e27374 (2011).
15. Gedan, K. B., Kirwan, M. L., Wolanski, E., Barbier, E. B. & Silliman, B. R. The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Clim. Change* **106**, 7–29 (2011).
16. Bilkovic, D. M., Mitchell, M., Mason, P. & Duhring, K. The role of living shorelines as estuarine habitat conservation strategies. *Coast. Manag.* **44**, 161–174 (2016).
17. Scyphers, S. B. et al. Natural shorelines promote the stability of fish communities in an urbanized coastal system. *PLoS ONE* **10**, e0118580 (2015).
18. Arkema, et al. In *Living Shorelines; The Science and Management of Nature-Based Coastal Protection* (eds. Bilkovic, D. M. et al.) 11–30 (Taylor and Francis, 2017).
19. Currin, C., Davis, J. & Malhotra, A. *Living Shorelines - the Science and Management of Nature-Based Coastal Protection* (CRC Press, 2016).
20. Gittman, R., Popowich, A., Bruno, J. & Peterson, C. Marshes with and without sills protect estuarine shorelines from erosion better than bulkheads during a category 1 hurricane. *Ocean Coast. Manag.* **102**, 94–102 (2014).
21. Guerry, A. D. et al. Natural capital and ecosystem services informing decisions: from promise to practice. *Proc. Natl. Acad. Sci. USA* **112**, 7348 (2015).
22. Díaz, S. et al. Assessing nature's contributions to people. *Science* **359**, 270 (2018).
23. Doody, J. P. Coastal squeeze and managed realignment in southeast England, does it tell us anything about the future?*Ocean Coast Manag.* **79**, 34–41 (2013).
24. Beagle, J. et al. *San Francisco Bay Shoreline Adaptation Atlas: Working with Nature to Plan for Sea Level Rise Using Operational Landscape Units*. https://www.sfei.org/documents/adaptationatlas (2019).
25. Brinson, M., Christian, R. & Blum, L. Multiple states in the sea-level induced transition from terrestrial forest to estuary. *Estuaries* **18**, 648–659 (1995).

26. Peteet, D. M. et al. Sediment starvation destroys New York City marshes' resistance to sea level rise. *Proc. Natl Acad. Sci. USA* **115**, 10281–10286 (2018).
27. Schoellhamer, D. H. Sudden clearing of estuarine waters upon crossing the threshold from transport to supply regulation of sediment transport as an erodible sediment pool is depleted: San Francisco Bay, 1999. *Estuaries Coasts* **34**, 885–899 (2011).
28. Stralberg, D. et al. Evaluating tidal marsh sustainability in the face of sea-level rise: a hybrid modeling approach applied to San Francisco Bay. *PLoS ONE* **6**, e27388 (2011).
29. Hurlimann, A. et al. Urban planning and sustainable adaptation to sea-level rise. *Landsc. Urban Plan.* **126**, 84–93 (2014).
30. Eichenberg, T., Bothwell, S. & Vaughn, D. Climate change and the public trust doctrine: using an ancient doctrine to adapt to rising sea levels in San Francisco Bay. *Environ. Law J.* (2001).
31. San Francisco Bay Conservation and Development Commission. Bay fill for habitat restoration, enhancement, and creation in a changing bay. https://www.bcdc.ca.gov/BPAFHR/20190524ChangingBay.pdf (2019).
32. Hirschfeld, D. & Hill, K. E. Choosing a future shoreline for the San Francisco Bay: strategic coastal adaptation insights from cost estimation. *J. Mar. Sci. Eng*. **5**, 42 (2017).
33. Black, K. J. & Richards, M. Eco-gentrification and who benefits from urban green amenities: NYC s high line. *Landsc. Urban Plan.* **204**, 103900 (2020).
34. Wolch, J. R., Byrne, J. & Newell, J. P. Urban green space, public health, and environmental justice: the challenge of making cities 'just green enough'. *Landsc. Urban Plan.* **125**, 234–244 (2014).
35. Mullenbach, L. E., Baker, B. L. & Mowen, A. J. Does public support of urban park development stem from gentrification beliefs and attitudes? *Landsc. Urban Plan.* **211**, 104097 (2021).
36. Donovan, G., Prestemon, J., Butry, D., Kaminski, A. & Monleon, V. The politics of urban trees: tree planting is associated with gentrification in Portland, Oregon. *For. Policy Econ*. **124**, 102387 (2021).
37. Anguelovski, I. et al. Opinion: why green "climate gentrification" threatens poor and vulnerable populations. *Proc. Natl. Acad. Sci. USA* **116**, 26139 (2019).
38. Shokry, G., Connolly, J. J. T. & Anguelovski, I. Understanding climate gentrification and shifting landscapes of protection and vulnerability in green resilient Philadelphia. *Urban Clim.* **31**, 100539 (2020).
39. Hoover, F.-A., Meerow, S., Grabowski, Z. J. & McPhearson, T. Environmental justice implications of siting criteria in urban green infrastructure planning. *J. Environ. Policy Plan* **23**, 665–682 (2021).
40. Walker, R. H. Engineering gentrification: urban redevelopment, sustainability policy, and green stormwater infrastructure in Minneapolis. *J. Environ. Policy Plan* **23**, 646–664 (2021).
41. Gould, K. A. & Lewis, T. L. Resilience gentrification: environmental privilege in an age of coastal climate disasters. *Front. Sustain. Cities* **3**, 687670 (2021).
42. California Ocean Protection Council. State of California Sea-Level Rise Guidance 2018 Update. https://opc.ca.gov/webmaster/ftp/pdf/agenda_items/20180314/Item3_Exhibit-A_OPC_SLR_Guidance-rd3.pdf (2018).
43. PolicyLink & PERE, USC Program for Environmental and Regional Equity. An Equity Profile of the San Francisdo Bay Area Region. https://www.policylink.org/sites/default/files/documents/bay-area-profile/BayAreaProfile_21April2015_Final.pdf (2015).
44. Blackwell, E., Shirzaei, M., Ojha, C. & Werth, S. Tracking California's sinking coast from space: Implications for relative sea-level rise. *Sci. Adv.* **6**, eaba4551 (2020).
45. Papendick, H. *County of San Mateo Sea-Level Rise Vulnerability Assessment*. 215 (2018).
46. SFEI. San Francisco Bay shore inventory: mapping for sea level rise planning. https://www.sfei.org/sites/default/files/biblio_files/SFBayShoreInventoryReport_SFEI_2016.pdf (2016).
47. Bay Conservation and Development Commission. Adapting to Rising Tides Bay Area: Regional Sea Level Rise Vulnerability and Adaptation Study. http://www.adaptingtorisingtides.org/wp-content/uploads/2020/03/ARTBayArea_Main_Report_Final_March2020_ADA.pdf (2020).
48. San Mateo County Flood and Sea Level Rise Resiliency District. One Shoreline; Building solutions for a changing climate. https://oneshoreline.org. (2022).
49. San Francisco Bay Area Wetlands Ecosystem Goals Project. Goals Project. 2015. The Baylands and Climate Change: What We Can Do. Baylands Ecosystem Habitat Goals Science Update 2015. 265 (2015).
50. Bayraktarov, E. et al. The cost and feasibility of marine coastal restoration. *Ecol. Appl.* **26**, 1055–1074 (2016).
51. Gittman, R. K. et al. Voluntary restoration: Mitigation's silent partner in the quest to reverse coastal wetland loss in the USA. *Front. Mar. Sci* **6**, 511 (2019).
52. Verhoeven, J. T. A., Soons, M. B., Janssen, R. & Omtzigt, N. An operational landscape unit approach for identifying key landscape connections in wetland restoration. *J. Appl. Ecol* **45**, 1496–1503 (2008).
53. Cecchetti, A. R., Stiegler, A. N., Graham, K. E. & Sedlak, D. L. The horizontal levee: a multi-benefit nature-based treatment system that improves water quality and protects coastal levees from the effects of sea level rise. *Water Res. X* **7**, 100052 (2020).
54. Elmqvist, T. et al. Sustainability and resilience for transformation in the urban century. *Nat. Sustain.* **2**, 267–273 (2019).
55. Hamel, P. et al. Blending ecosystem service and resilience perspectives in planning of natural infrastructure: lessons from the San Francisco Bay area. *Front. Environ. Sci.* **9**, 239 (2021).
56. Rosa, I. M. D. et al. Multiscale scenarios for nature futures. *Nat. Ecol. Evol* **1**, 1416–1419 (2017).
57. Silva, R. et al. A framework to manage coastal squeeze. *Sustainability* **12**, 10610 (2020).
58. Lithgow, D., Martínez, M. L., Gallego-Fernández, J. B., Silva, R. & Ramírez-Vargas, D. L. Exploring the co-occurrence between coastal squeeze and coastal tourism in a changing climate and its consequences. *Tour. Manag.* **74**, 43–54 (2019).
59. Pereira, L., Sitas, N., Ravera, F., Jimenez-Aceituno, A. & Merrie, A. Building capacities for transformative change towards sustainability: imagination in intergovernmental science-policy scenario processes. *Elem. Sci. Anthr*. **7**, (2019).
60. Iwaniec, D. M. et al. The co-production of sustainable future scenarios. *Landsc. Urban Plan.* **197**, 103744 (2020).
61. Pereira, L. M. et al. Developing multiscale and integrative nature–people scenarios using the Nature Futures Framework. *People Nat.* **2**, 1172–1195 (2020).
62. Tonge, J., Ryan, M. M., Moore, S. A. & Beckley, L. E. The effect of place attachment on pro-environment behavioral intentions of visitors to coastal natural area tourist destinations. *J. Travel Res* **54**, 730–743 (2015).
63. James, P., Banay, R. F., Hart, J. E. & Laden, F. A review of the health benefits of greenness. *Curr. Epidemiol. Rep.* **2**, 131–142 (2015).
64. Hummel, M. A., Griffin, R., Arkema, K. K. & Guerry, A. D. Economic evaluation of sea-level rise adaptation strongly influenced by hydrodynamic feedbacks. *Proc. Natl Acad. Sci. USA* **118**, e2025961118 (2021).
65. Lopez, J. The multiple lines of defense strategy to sustain coastal Louisiana. *J. Coast. Res.* **54**(SI), 186–197 (2009).
66. Gillis, L. G. et al. Opportunities for protecting and restoring tropical coastal ecosystems by utilizing a physical connectivity approach. *Front. Mar. Sci* **4**, 374 (2017).
67. Vuik, V., van Vuren, S., Borsje, B. W., van Wesenbeeck, B. K. & Jonkman, S. N. Assessing safety of nature-based flood defenses: dealing with extremes and uncertainties. *Coast. Eng.* **139**, 47–64 (2018).
68. Nicholls, R. J. In *Resilience* (eds. Zommers, Z. & Alverson, K.) 13–29 (Elsevier, 2018).
69. Hino, M., Field, C. B. & Mach, K. J. Managed retreat as a response to natural hazard risk. *Nat. Clim. Change* **7**, 364–370 (2017).
70. Esteves, L. S. In *Managed Realignment: A Viable Long-Term Coastal Management Strategy*? (ed. Esteves, L. S.) 19–31 (Springer Netherlands, 2014).
71. Santa Clara Valley Water District. Preliminary Feasibility Study for South San Francisco Bay Shoreline Economic Impact Areas 1–10 *Final Evaluation Report*. https://www.valleywater.org/sites/default/files/E7_Final_Evaluation_Report_022117.pdf (2017).
72. Reguero, B. G., Beck, M. W., Bresch, D. N., Calil, J. & Meliane, I. Comparing the cost effectiveness of nature-based and coastal adaptation: a case study from the Gulf Coast of the United States. *PLoS ONE* **13**, e0192132 (2018).
73. Reddy, S. M. et al. Evaluating the role of coastal habitats and sea-level rise in hurricane risk mitigation: an ecological economic assessment method and application to a business decision. *Integr. Environ. Assess. Manag.* **12**, 328–344 (2016).
74. Barbier Edward, B. et al. Coastal ecosystem-based management with nonlinear ecological functions and values. *Science* **319**, 321–323 (2008).
75. Dundas, S. J. Benefits and ancillary costs of natural infrastructure: Evidence from the New Jersey coast. *J. Environ. Econ. Manag.* **85**, 62–80 (2017).
76. Okamoto, A. Colma Creek Collect and Connect. *Estuary News* 8–10 (2018).
77. Simons, E. Open Space Park or Hotel? The Future of the Burlingame Shoreline Could Set a Precedent for Climate Adaptation. *Bay Nature* (2019).
78. Papakonstantinou, I., Lee, J. & Madanat, S. M. Game theoretic approaches for highway infrastructure protection against sea level rise: co-opetition among multiple players. *Transp. Res. Part B Methodol.* **123**, 21–37 (2019).
79. Hummel, M. A. & Stacey, M. T. Assessing the influence of shoreline adaptation on tidal hydrodynamics: the role of shoreline typologies. *J. Geophys. Res. Oceans* **126**, e2020JC016705 (2021).
80. OECD. *Cost-Benefit Analysis and the Environment*. https://doi.org/10.1787/9789264085169-en. (2018).
81. Temmerman, S. et al. Ecosystem-based coastal defence in the face of global change. *Nature* **504**, 79–83 (2013).
82. Narayan, S. et al. The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS ONE* **11**, e0154735 (2016).

83. Sutton-Grier, A. E., Wowk, K. & Bamford, H. Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environ. Sci. Policy* **51**, 137–148 (2015).
84. Cheong, S.-M. et al. Coastal adaptation with ecological engineering. *Nat. Clim. Change* **3**, 787–791 (2013).
85. Bridges, T. et al. *Engineering with nature: An atlas*. https://doi.org/10.21079/11681/27929 (2018).
86. Bridges, T., Bourne, E., Suedel, B., Moynihan, E. & King, J. *Engineering With Nature: An Atlas*, Vol. 2. https://doi.org/10.21079/11681/40124 (2021).
87. Bridges, T. et al. International guidelines on natural and nature-based features for flood risk management. https://doi.org/10.21079/11681/41946 (2021).
88. Baye, P. *New Life for Eroding Shorelines: Beach and Marsh Edge Change in the San Francisco Estuary*. (2020).
89. Bouma, T. J. et al. Identifying knowledge gaps hampering application of intertidal habitats in coastal protection: opportunities & steps to take. *CoastsRisks THESEUS New Wave Coast. Prot.* **87**, 147–157 (2014).
90. Danish Hydraulic Institute (DHI). Regional Coastal Hazard Modeling Study for North and Central San Francisco Bay, Final Draft Report. (2011).
91. Danish Hydraulic Institute (DHI). Regional Coastal Hazard Modeling Study for South San Francisco Bay, Final Draft Report. (2013).
92. Hayden, M. et al. Informing sea level rise adaptation planning through quantitative assessment of the risks and broader consequences of tidal wetland loss: a case study in San Mateo County. https://rdjzr2agvvkijm6n3b66365n-wpengine.netdna-ssl.com/wp-content/uploads/2019/04/PointBlue_SanMateoWetlands_TechnicalReport_final_Jan2019_hires.pdf (2019).
93. Dusterhoff, S., McKnight, K., Grenier, L. & Kauffman, N. *Sediment for Survival: A Strategy for the Resilience of Bay Wetlands in the Lower San Francisco Estuary*. https://www.sfei.org/documents/sediment-for-survival (2021).
94. Sharp, R. et al. *InVEST 3.9.0 User's Guide*. https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/index.html (2021).
95. Wood, S. A., Guerry, A. D., Silver, J. M. & Lacayo, M. Using social media to quantify nature-based tourism and recreation. *Sci. Rep.* **3**, 2976 (2013).
96. Wood, S. A. et al. Next-generation visitation models using social media to estimate recreation on public lands. *Sci. Rep.* **10**, 15419 (2020).
97. Wedding, L. M. et al. Incorporating blue carbon sequestration benefits into subnational climate policies. *Glob. Environ. Change* **69**, 102206 (2021).

ACKNOWLEDGEMENTS

This work was supported by the Gordon and Betty Moore Foundation and the Marianne and Marcus Wallenberg Foundation.

AUTHOR CONTRIBUTIONS

All authors contributed to the design and execution of this project and reviewed and edited the manuscript. A.D.G., J. Silver, J.B., P.H., and R.G. wrote the original draft. J.B. and J.L. conducted the exposure and suitability analyses. J. Silver, P.H., R.G., S.W., K.W., K.A., and A.D.G. conducted the ecosystem service modeling. E.P. made the maps. H.P., M.G., and J. Sharma led the engagement with County stakeholders.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s42949-022-00056-y.

Correspondence and requests for materials should be addressed to A. D. Guerry.

Reprints and permission information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2022

Attachment C

National Wildlife Federation and American Rivers Comments
Modernization of Army Civil Works Policy Priorities
Docket ID No. COE-2022-0006

Economic evaluation of sea-level rise adaptation strongly influenced by hydrodynamic feedbacks

Michelle A. Hummel[a,1], **Robert Griffin**[b,c], **Katie Arkema**[b,d], **and Anne D. Guerry**[b,d]

[a]Department of Civil Engineering, University of Texas at Arlington, Arlington, TX 76019; [b]The Natural Capital Project, Stanford University, Stanford, CA 94305; [c]School for Marine Science and Technology, University of Massachusetts Dartmouth, Dartmouth, MA 02747; and [d]School of Environmental and Forest Sciences, University of Washington, Seattle, WA 98195

Edited by Peter H. Gleick, Pacific Institute for Studies in Development, Environment, and Security, Oakland, CA, and approved May 30, 2021 (received for review December 17, 2020)

Coastal communities rely on levees and seawalls as critical protection against sea-level rise; in the United States alone, $300 billion in shoreline armoring costs are forecast by 2100. However, despite the local flood risk reduction benefits, these structures can exacerbate flooding and associated damages along other parts of the shoreline—particularly in coastal bays and estuaries, where nearly 500 million people globally are at risk from sea-level rise. The magnitude and spatial distribution of the economic impact of this dynamic, however, are poorly understood. Here we combine hydrodynamic and economic models to assess the extent of both local and regional flooding and damages expected from a range of shoreline protection and sea-level rise scenarios in San Francisco Bay, California. We find that protection of individual shoreline segments (5 to 75 km) can increase flooding in other areas by as much as 36 million m^3 and damages by $723 million for a single flood event and in some cases can even cause regional flood damages that exceed the local damages prevented from protection. We also demonstrate that strategic flooding of certain shoreline segments, such as those with gradually sloping baylands and space for water storage, can help alleviate flooding and damages along other stretches of the coastline. By matching the scale of the economic assessment to the scale of the threat, we reveal the previously uncounted costs associated with uncoordinated adaptation actions and demonstrate that a regional planning perspective is essential for reducing shared risk and wisely spending adaptation resources in coastal bays.

sea-level rise | adaptation | economic damages | externalities | flooding

Sea-level rise (SLR) threatens to produce more frequent and severe flooding in coastal regions and is expected to cause trillions of dollars in damages globally by 2100 if society does not take action to adapt to this threat (1). Lives and livelihoods are at risk as well; globally, hundreds of millions of people could be exposed to SLR by 2100 (2–4). A critical challenge in responding to this threat is that decisions about strategies for adaptation to coastal flooding are often made by individual communities or private entities with limited cross-jurisdictional coordination and at a scale that does not match the hydrodynamic extent of the threat (5–7). Populated coastal areas are coupled human–natural systems, where spatial and temporal interactions between hydrodynamics and shoreline modification influence patterns of flooding, erosion, and resulting damage to communities (8, 9). In these settings, individual action tends to impact other parties (externalities) and yield outcomes different from those that would arise from collective decision-making (10), generally resulting in reduced overall social welfare (11). Even so, collective approaches to shoreline adaptation are often hindered by existing governance structures that rely on local oversight of coastal management or fragmented approaches to project permitting and implementation (7).

Spatial externalities are common in coupled human–natural systems. High-profile examples include the "dead zone" in the Gulf of Mexico and its link to upstream nutrient runoff from agriculture carried down the Mississippi, widespread acid rain in the northeastern United States originating from power plants in the Midwest that led to revisions of the Clean Air Act in 1990, and the visual impacts on adjacent property owners from the Cape Wind offshore wind farm near Nantucket, MA, that led to its eventual demise after more than a decade of litigation. Spatial externalities are also common and varied in the context of shoreline protection and management. In river systems, it has long been known that channel modifications and levee building at one location can influence water levels and flood potential at locations both upstream and downstream (12–15). On open coasts, alongshore currents can affect the efficacy of beach nourishment projects through mobilization and loss of sediment to neighboring beaches (16, 17). As a result, individual communities may be incentivized to nourish their beaches less frequently, either to avoid paying for sediment that is subsequently lost to undernourished beaches in neighboring communities or in the hopes of benefiting from sediment input from nourishment projects elsewhere (18). Waves can also interact with protection structures to induce erosion in adjacent areas (19). A recent study found that these interactions reduced property values for adjacent shoreline properties that are ineligible to build their own protection structures by 8% on average in coastal Oregon (20).

Shoreline armoring will play a key role in responding to SLR moving forward. It is forecast to represent nearly 60% of the

Significance

As sea levels rise, coastal cities will rely on shoreline protection strategies such as levees and seawalls to mitigate flooding. Although these strategies provide local flood-reduction benefits, they can increase inundation along other shorelines within the same estuary or bay. Using hydrodynamic and economic models, we quantify previously unmeasured regional economic damages (up to $723 million per flood event) that result from the protection of individual shoreline segments in San Francisco Bay, CA. We also highlight and quantify opportunities to alleviate regional flood damage through strategic floodwater storage in low-lying areas. Integrating the findings into coordinated planning efforts that account for the regional impacts of local shoreline actions could provide opportunities to reduce shared risk in coastal regions globally.

Author contributions: M.A.H., R.G., K.A., and A.D.G. designed research; M.A.H. and R.G. performed research; M.A.H. and R.G. analyzed data; and M.A.H., R.G., K.A., and A.D.G. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

This open access article is distributed under Creative Commons Attribution License 4.0 (CC BY).

[1]To whom correspondence may be addressed. Email: michelle.hummel@uta.edu.

This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2025961118/-/DCSupplemental.

Published July 12, 2021.

Downloaded from https://www.pnas.org by 45.62.176.121 on July 20, 2022 from IP address 45.62.176.121.

ENVIRONMENTAL SCIENCES

roughly $500 billion in US adaptation costs by 2100 (21). Despite evidence for a wide range of spillover effects resulting from shoreline modification and the billions in planned expenditures on these modifications, there is limited understanding about how they influence shared economic risk across the coastal zone (5). Erosion and beach nourishment are better understood than coastal flooding, where the only economic assessment of externalities is on the performance of critical infrastructure systems (22, 23).

To address these gaps and account for the physical and economic impacts of flooding on communities, here we couple dynamic simulations of coastal inundation with models of building damage to examine flood damage externalities expected under a range of shoreline modification and SLR scenarios. We focus on the densely populated San Francisco Bay Area, as bay and estuarine systems in particular are characteristic of coastal locations that feature regional coastal hydrodynamic interactions. In these settings, engineered protection can lead to amplification of water levels, cause additional flooding in other locations, and in some cases adversely affect coastal vegetation and the shoreline protection benefits it provides (24, 25). Conversely, shoreline modification to strategically store water can have the opposite effect, providing dissipation that attenuates water levels and produces regional flood reduction benefits (26–30). Bays and estuaries represent 21% of overall shoreline length and 54% of global population at risk from SLR and flooding—nearly half a billion people (see *Materials and Methods*). These densely populated areas with complex jurisdictional boundaries are increasingly facing difficult and expensive decisions that demand a better understanding of shared risk along the coastline.

Approach

San Francisco Bay is the largest coastal embayment in California and is composed of four distinct subembayments: Suisun Bay, San Pablo Bay, Central Bay, and South Bay (Fig. 1). Buildings adjacent to the bay that are exposed to the effects of SLR over the next 150 y represent more than $180 billion in replacement value and are home to a population of over 1.4 million people (see *Materials and Methods*). Together, the nine counties that surround San Francisco Bay represent the majority of population and building exposure to coastal flooding in California (31). Shoreline modification is widespread throughout the bay, with 6% of the shoreline behind levees designed specifically for

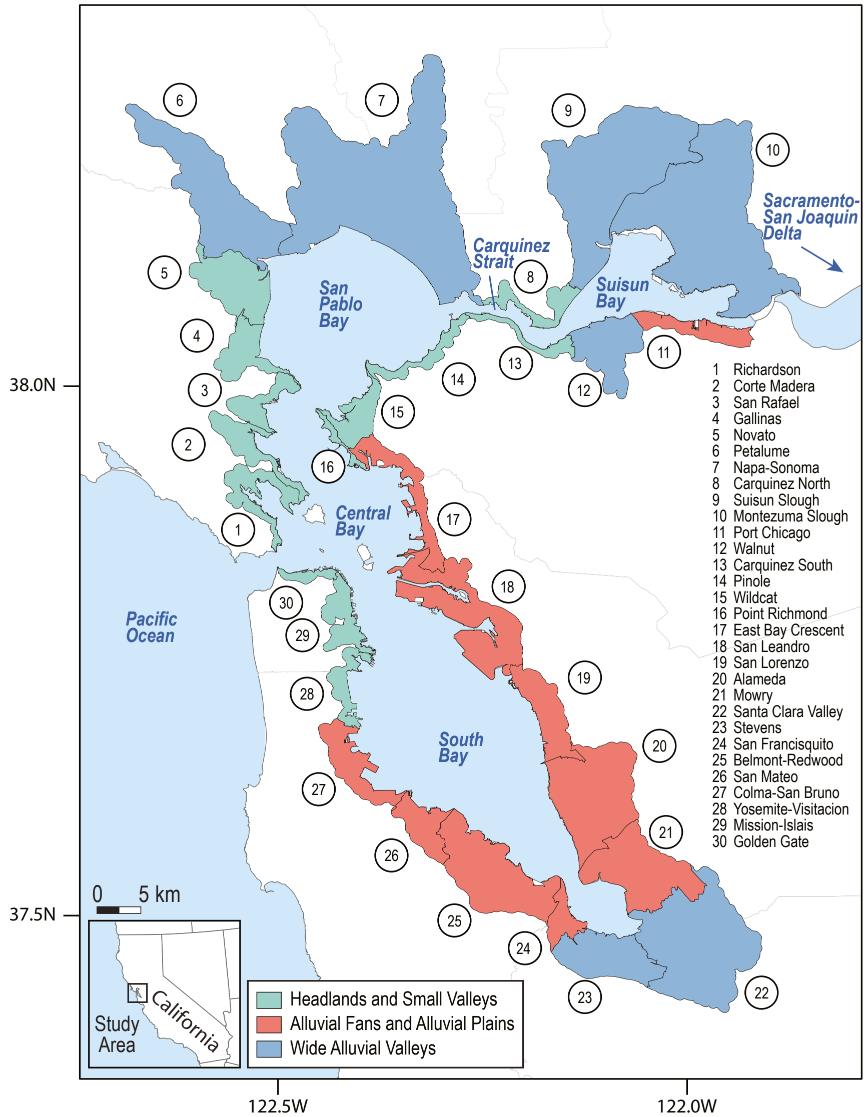


Fig. 1. Map of the San Francisco Bay Area, showing the 30 OLUs developed by ref. 35, their geomorphic classifications, and their names.

Downloaded from https://www.pnas.org by 45.62.176.121 on July 20, 2022 from IP address 45.62.176.121.

flood protection and 75% of the shoreline modified as berms, embankments, transportation infrastructure, or other engineering that affects flooding and flood routing (32). Recent modeling studies of shoreline adaptation and SLR in San Francisco Bay have demonstrated that shoreline protection using engineered structures like seawalls can cause amplification of the tides by reducing frictional damping in shallow areas along the perimeter of the bay and enhancing reflection of the incoming tidal wave at the shoreline (26, 28, 29). These changes in tidal amplitude can influence the magnitude and spatial distribution of peak water levels and inundation around the bay.

To assess the distribution of regional economic impacts associated with local-scale shoreline protection from SLR, we quantify the spatial change in inundation and economic damages from implementing protection strategies in the San Francisco Bay Area under four SLR scenarios (50, 100, 150, and 200 cm above a January 2010 baseline). SLR projections for San Francisco Bay suggest a likely range (67% probability) of 30 to 104 cm of SLR above the 1991 to 2009 mean by 2100 (33), although SLR exceeding 200 cm is also possible under rapid Antarctic ice-sheet melt (34). For each SLR scenario we simulate an existing shoreline scenario that includes all present-day infrastructure, as well as 30 shoreline modification scenarios in which a single segment of the shoreline is completely protected by a seawall while the rest of the shoreline is maintained as is, such that it remains vulnerable to flooding where not currently protected. For all SLR and shoreline modification scenarios we assume no landward migration of the shoreline. The 30 shoreline segments are based on operational landscape units (OLUs) delineated by ref. 35 along the San Francisco Bay shoreline to inform SLR adaptation planning (Fig. 1). These OLUs represent terrestrial and coastal regions, ranging in coastline length from 5 to 75 km, with similar physical and ecological processes that together provide a cohesive set of ecosystem functions and similar adaptation possibilities (36). These are classified into one of three geomorphic categories that account for the geologic history of the region and its influence on landscape features. Wide alluvial valleys are characterized by wide baylands and gradual slopes, alluvial fans and alluvial plains consist of baylands of intermediate width and moderate slopes, and headlands and small valleys exhibit narrow baylands and steep slopes (35) (*SI Appendix*, Fig. S1).

We use a two-dimensional, depth-averaged hydrodynamic model of San Francisco Bay (37, 38) to simulate tidal circulation and interactions with the bay shorelines for each scenario (see *Materials and Methods*). Changes in tidal dynamics and bay water levels resulting from these modeled scenarios are described in ref. 29. Here, we extract spatially varying maximum water depths from the model at high tide during a spring tide cycle to capture inundation in areas that experience tidal flooding or permanent inundation. We integrate these values across the land area to find the total volume of flood water in each OLU in each scenario. Comparing this flood volume to similarly derived volume estimates for the existing shoreline scenario at the same SLR provides spatially explicit estimates of internal (within the protected OLU) and external (in other OLUs) tidal flooding for each shoreline protection scenario. To estimate associated economic impacts from this flooding, we overlay the flood depth maps with building stock data from the HAZUS flood model (39) and use depth-damage curves to compute changes in damages between the existing and protected shoreline scenarios for a one-off flood event. We use the existing building stock data to estimate economic damages and do not attempt to forecast future changes in land use or shoreline habitat distribution in the region. The combined flood and damage results allow for an analysis of the spatial extent of interactions, from local effects on neighboring OLUs in the same subembayment to regional or baywide effects.

Effect of Shoreline Protection Scenarios on Inundation

OLU Interactions. Fig. 2 summarizes the flood impacts due to the modeled shoreline protection scenarios at (*A*) 50 cm, (*B*) 100 cm, (*C*) 150 cm, and (*D*) 200 cm of SLR. The OLU protection scenarios are listed along the horizontal axis. Each column shows the net change in flood volume in all other OLUs resulting from that protection scenario. OLU numbering is shown in Fig. 1. Values along the diagonal represent the reduction in internal flooding in the protected OLU as compared to the existing shoreline scenario and range from −1,900 m^3 for OLU 30 (Golden Gate) at 50 cm of SLR to −551 million m^3 for OLU 7 (Napa–Sonoma) at 200 cm of SLR.

Off-diagonal values represent protection-induced external flooding in other OLUs, which is generally greatest between OLUs in the same subembayment. In Suisun Bay (OLUs 9 to 12), protection and subsequent loss of floodwater storage capacity in any one OLU typically leads to an increase in flooding in other OLUs. For example, when OLU 10 (Montezuma Slough) protects its shoreline, flooding in OLU 9 (Suisun Slough) increases by almost 30 million m^3 at 100 cm of SLR, as water that formerly flooded OLU 10 is redirected elsewhere. In South Bay (OLUs 18 to 27), protection of certain OLUs similarly exacerbates flooding in other South Bay OLUs, although the magnitude of interactions is smaller, with a maximum increase of 4.2 million m^3 of flooding in OLU 20 (Alameda) due to protection of OLU 22 (Santa Clara Valley) at 200 cm of SLR.

Notably, protection of South Bay OLUs can lead to a reduction in flooding in neighboring OLUs under certain SLR scenarios (Fig. 2), as flood pathways across lateral OLU boundaries stretching inland from the coast are eliminated. For example, Foster City, which is part of OLU 25 (Belmont–Redwood) (Fig. 3), is surrounded by a levee that provides full protection from direct coastal flooding at 50 cm of SLR. However, the elevated sea level pushes additional water into the mouth of a neighboring channel, Seal Slough, along the shoreline of OLU 26 (San Mateo), which leads to widespread flooding behind the levee in OLU 25 (Fig. 3*A*). With protection of the shoreline of OLU 26 comes elimination of the flood pathway at the mouth of Seal Slough, such that Foster City remains dry (Fig. 3*B*), leading to a reduction of 6.5 million m^3 of flooding for OLU 25 due to protection in OLU 26. At 100 cm of SLR, parts of the Foster City levee are overtopped, causing direct flooding along the shoreline of OLU 25 (Fig. 3*C*). However, protecting OLU 26 still provides substantial benefits for OLU 25 (Fig. 3*D*), reducing flooding by 5.5 million m^3. At 150 cm of SLR and higher these benefits are lost; protecting OLU 26 leads to an additional 1.1 million m^3 of flooding in OLU 25 (Fig. 3*F*) compared with the existing shoreline scenario (Fig. 3*E*). As this example demonstrates, the external impact of shoreline protection may change over time as SLR progresses.

Some OLU protection scenarios also cause external flooding that extends regionally to other subembayments. These cross-embayment interactions are most notable between OLU 7 in San Pablo Bay and OLUs in Suisun Bay and South Bay (Fig. 2). In both cases, the physical characteristics and geographic location of OLU 7 play an important role in its relationship to regional inundation patterns. When OLUs in Suisun Bay are protected, tides propagating from the ocean inlet landward toward the Sacramento–San Joaquin Delta interact with the shoreline infrastructure to create feedbacks that affect the down-estuary (seaward) water level response and cause additional flooding in OLU 7. Protecting the OLU 7 shoreline similarly leads to additional flooding up-estuary (landward) in Suisun Bay, particularly in OLUs 9 and 10. The relationship between South Bay OLUs and OLU 7 is also bidirectional. For example, protection of South Bay shorelines (OLUs 20 to 22 and 25 to 27) causes additional inundation in OLU 7. Similarly, when OLU 7 is protected,

ENVIRONMENTAL SCIENCES

Downloaded from https://www.pnas.org by 45.62.176.121 on July 20, 2022 from IP address 45.62.176.121.

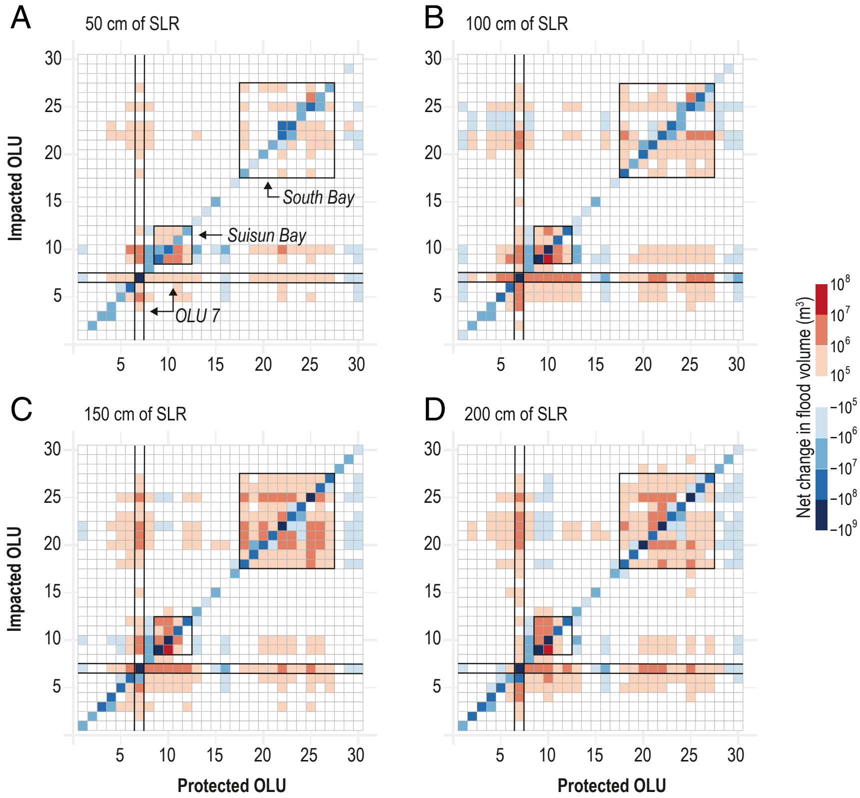


Fig. 2. Net change in flood volume for OLU protection scenarios at (*A*) 50 cm, (*B*) 100 cm, (*C*) 150 cm, and (*D*) 200 cm of SLR. Individual OLU protection scenarios are along the horizontal axis. Each column shows the net change in flood volume in all other OLUs resulting from that protection scenario. OLU numbering is shown in Fig. 1. Subembayment interactions in Suisun Bay and South Bay are indicated by boxes. OLU 7 (Napa–Sonoma), which experiences strong interactions with other OLUs under shoreline protection scenarios, is also highlighted.

flooding is exacerbated in several South Bay OLUs, most notably OLUs 20 to 23 and 25. OLU 7's low elevation and large area provide substantial storage space for floodwaters when shorelines are not modified, but this space is lost when protection is implemented along its shoreline. Unlike OLUs 9 and 10, which provide similar storage space but are separated from the rest of

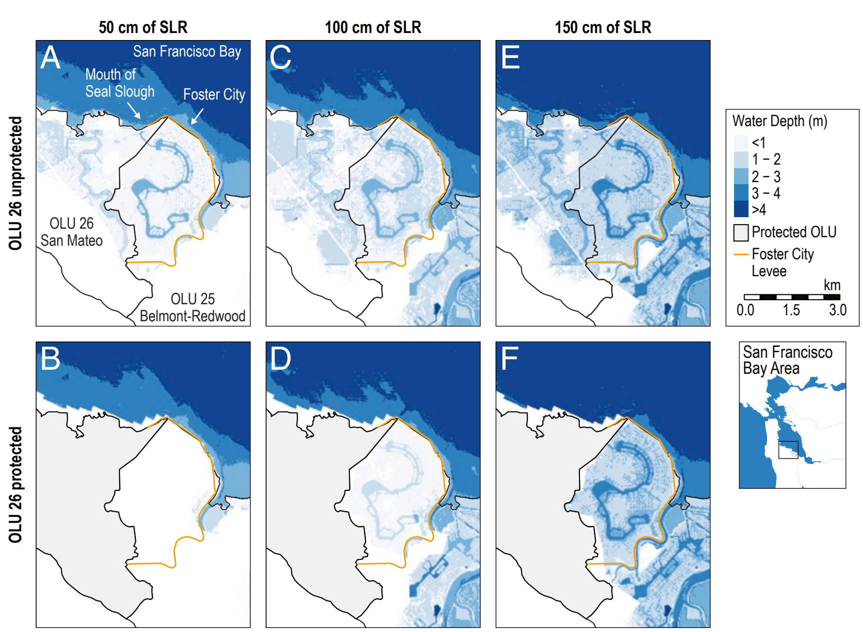


Fig. 3. Interaction between OLUs 25 (Belmont–Redwood) and 26 (San Mateo) in South San Francisco Bay. At 50 cm of SLR (*A* and *B*), protection of the OLU 26 shoreline eliminates the flood pathway at the mouth of Seal Slough, such that Foster City, located behind the levee in OLU 25, remains dry. At 100 cm of SLR (*C* and *D*), the Foster City levee is overtopped, so protection of the OLU 26 shoreline provides only partial flood reduction in OLU 25. At 150 cm of SLR (*E* and *F*), protecting the OLU 26 shoreline causes additional flooding in OLU 25. The 200-cm SLR scenario shows the same interaction as the 150-cm scenario and thus is not included here.

Downloaded from https://www.pnas.org by 45.62.176.121 on July 20, 2022 from IP address 45.62.176.121.

the bay via the narrow Carquinez Strait, OLU 7's position at the northern boundary of the bay leads to changes in down-estuary water levels in San Pablo Bay and Central Bay that propagate into South Bay.

Geomorphic Influence. Geomorphic characteristics play an important role in determining the internal and external impacts of shoreline protection. Large decreases in internal flooding result from protection of OLUs classified as wide alluvial valleys, as low-lying areas are disconnected from the bay (Fig. 4*A*). Alluvial fans and alluvial plains and headlands and small valleys experience smaller decreases. Increases in external flooding are also generally largest for protection of wide alluvial valleys and least for headlands and small valleys. The low elevations and gradual slopes that characterize wide alluvial valleys can provide frictional damping of the tides (29) and store floodwaters more readily than other geomorphic types. However, when the shoreline is protected, this storage space is lost and the OLU boundary shifts from dissipative to reflective, leading to tidal amplification within the bay (29) and exacerbating flooding in other OLUs. In contrast, protection of certain headlands and small valleys leads to small decreases in external flooding, indicating the potential for a regional benefit to protecting these areas (Fig. 4*C*). Because these OLUs are typically located at narrower parts of the bay, shoreline protection leads to additional narrowing that may slightly reduce tidal energy transmission through these areas. For example, protecting OLUs 8 (Carquinez North) and 13 (Carquinez South) along the Carquinez Strait leads to a reduction in up-estuary flooding in OLUs 9 to 12 surrounding Suisun Bay (Fig. 2), as less water is able to move through the constricted channel into Suisun Bay during the tidal cycle. Overall, reductions in internal flooding due to shoreline protection are generally greater than increases in induced external flooding, resulting in a net decrease, regionally, in flood volume for almost all OLU shoreline protection scenarios across all three geomorphic types (Fig. 4*E*).

Economic Damages Due to Coastal Inundation

OLU Interactions. Fig. 5 summarizes the damage interactions resulting from the modeled shoreline protection scenarios at (*A*) 50 cm, (*B*) 100 cm, (*C*) 150 cm, and (*D*) 200 cm of SLR. Internal reductions in economic damages, shown along the diagonal, are generally largest in the South Bay (OLUs 18 to 27), where dense development lies right along the shoreline. In OLU 25 alone, internal damages are reduced by $1.4 to 6.1 billion across the four SLR scenarios when the shoreline is protected. Internal benefits are smallest along the southern extent of Suisun Bay, the Carquinez Strait, and San Pablo Bay (OLUs 11 to 16), ranging from $0.4 to 55 million.

In contrast to the flooding results, which exhibit strong external interactions between OLUs in Suisun Bay, the damage interactions within Suisun Bay are not as notable. Development in this region is more sparse compared to parts of Central and South Bay, and large portions of the shoreline consist of wetlands, leading to relatively low building replacement costs per unit area (*SI Appendix*, Table S2) and limiting the potential magnitude of damage externalities. On the other hand, protecting South Bay OLUs leads to large external damages in other OLUs in South Bay (top right of Fig. 5 *A*–*D*), which become more pronounced and widespread at higher sea levels. These externalities primarily result in increased damages in other OLUs at 50 cm, 150 cm, and 200 cm of SLR (Fig. 5 *A*, *C*, and *D*), except for adjacent OLUs, which may experience damage reductions due to lateral flood protection. Damage externalities are especially notable for the OLU 22 protection scenario, which leads to additional damages in all other South Bay OLUs, totaling $723 million at 200 cm of

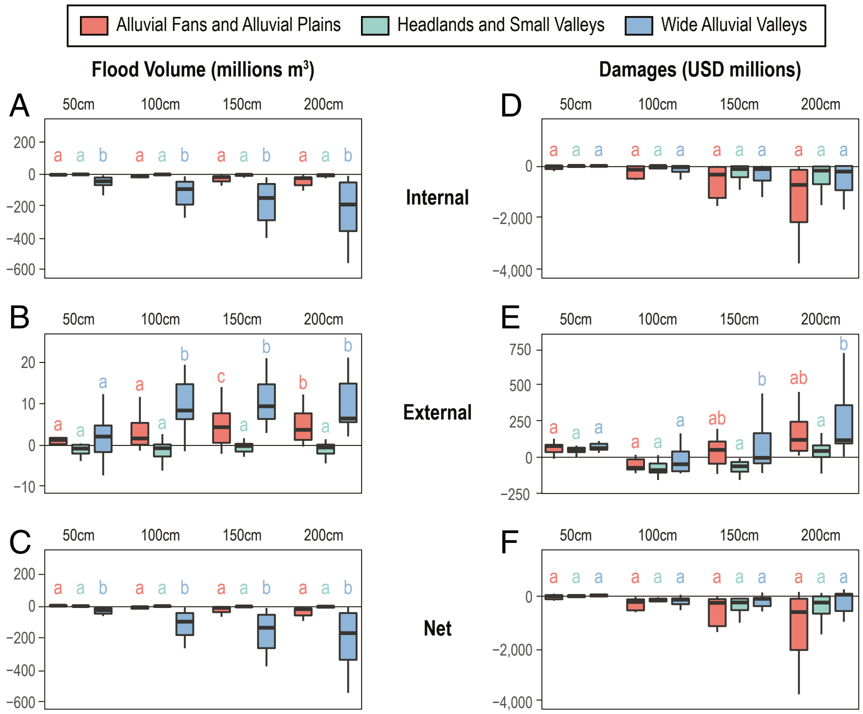


Fig. 4. Distribution of OLU flood and damage results, summarized by geomorphic type. (*Left*) The change in (*A*) internal flooding within the protected OLU, (*B*) external flooding across all other OLUs, and (*C*) net flooding (internal plus external) with protection. (*Right*) The change in (*D*) internal damages within the protected OLU, (*E*) external damages across all other OLUs, and (*F*) net damages (internal plus external) with protection. Letters represent statistically similar mean values for all pairwise comparisons across geomorphic types within a SLR scenario, based on a Tukey honest significant difference test at 5% significance level. The significance test results for all pairwise comparisons are provided in *SI Appendix*, Table S1.

ENVIRONMENTAL SCIENCES

Downloaded from https://www.pnas.org by 45.62.176.121 on July 20, 2022 from IP address 45.62.176.121.

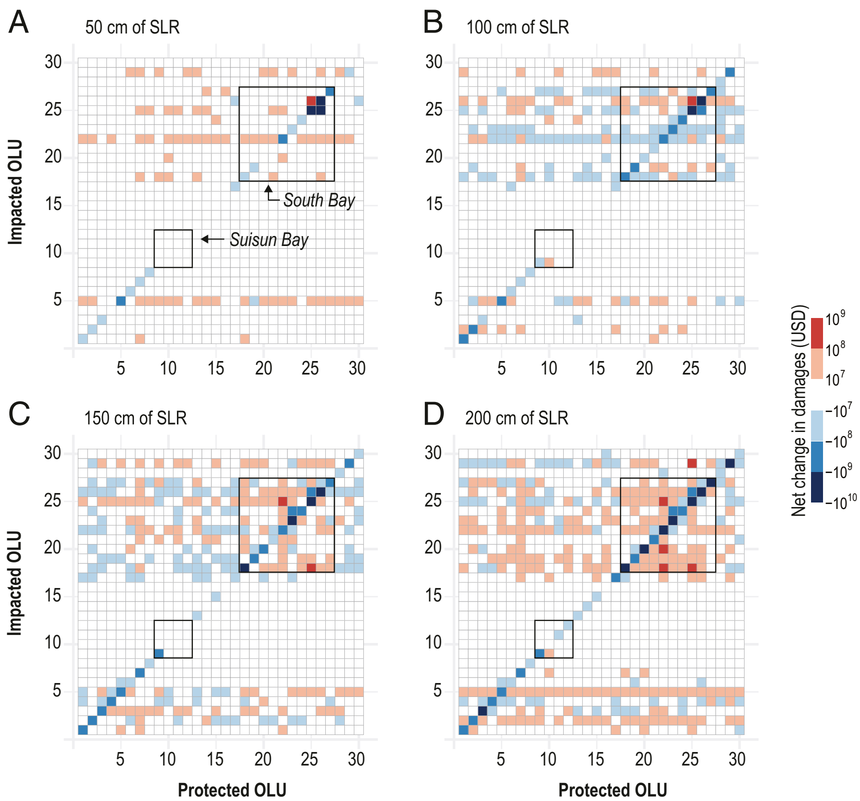


Fig. 5. Net change in economic damages for OLU protection scenarios at (*A*) 50 cm, (*B*) 100 cm, (*C*) 150 cm, and (*D*) 200 cm of SLR. The OLU protection scenarios are listed along the horizontal axis. Each column shows the net change in economic damages in all other OLUs resulting from that protection scenario. OLU numbering is shown in Fig. 1. Subembayment interactions in South Bay and Suisun Bay are indicated by the boxes in each plot.

SLR. In contrast, South Bay interactions at 100 cm of SLR lead to generally small but widespread damage reductions that are not limited to adjacent OLUs (Fig. 5*B*). For example, protecting OLU 20 provides flood reduction benefits for its neighbors, OLUs 19 (San Lorenzo) and 21 (Mowry), but also for OLUs 23 (Stevens) and 24 (San Francisquito) on the opposite shoreline. Thus, while the flooding results show a more consistent pattern of increasing external flood volume across all SLR scenarios (Fig. 2), the damage results exhibit greater variation, as they are a function of both the hydrodynamic–shoreline interactions that govern flooding as well as the spatial distribution of development and high-value properties.

Regional external damage interactions are also present in some protection scenarios, especially at higher sea levels (Fig. 5 *C* and *D*). When OLU 7 is protected at 200 cm of SLR, OLUs 22 and 18 (San Leandro) in South Bay experience an additional \$82 million and \$70 million in damages, respectively, while OLU 3 (San Rafael) in San Pablo Bay experiences an additional \$53 million in damages (Fig. 5*D*). OLU 22, with the highest building replacement cost for a wide alluvial valley in the bay (*SI Appendix*, Table S2), is susceptible to damage interactions with nearly every external protection scenario at 200 cm of SLR.

While the focus of our analysis is on damage to structures, population impacts are another important consideration when developing shoreline adaptation strategies. The individual shoreline protection scenarios considered here can cause as many as 5,900 additional people to be affected by external flooding (*SI Appendix*, Table S3), as is the case when OLU 22 is protected. We provide an example of how population impacts could be used to supplement economic damage data in *Discussion*.

Geomorphic Influence. Differences between OLU geomorphic classifications are more muted for economic damages than for flood volume. Estimated reductions in internal economic damages appear greatest in OLUs classified as alluvial fans and alluvial plains (Fig. 4*D*), though this is not statistically significant for any pairwise comparison. Surprisingly, the large internal flood reductions estimated for protecting wide alluvial valleys do not translate to similarly large damage reductions. The coastal landscape configuration in this type of OLU is generally a mix of coastal wetlands, grassland, and pasture land (based on 2016 National Land Cover Database; *SI Appendix*, Fig. S2) that limits its exposure of development to flooding. While external damage patterns for protecting wide alluvial valleys are qualitatively consistent with external flood patterns by geomorphic type, most of these relationships are not statistically significant, with the exception of observed greater external damages than headlands and small valleys under 150 cm and 200 cm of SLR (Fig. 4*E*).

Discussion

Regional externalities resulting from hydrodynamic feedbacks are an important consideration when evaluating protection strategies in highly developed coastal embayments. Although there are large potential benefits from avoided flood damage behind protective infrastructure in the San Francisco Bay Area, this analysis shows that these benefits can come at a cost to other shoreline communities, both nearby and in other parts of the bay. The increase in baywide inundation volume and external damages that results from the protection of a single OLU can be as large as 36 million m^3 and \$723 million, respectively. Assessing flood patterns by geomorphic type, we identify factors that contribute to external changes in flood volume from protection, including space for water storage and proximity

Downloaded from https://www.pnas.org by 45.62.176.121 on July 20, 2022 from IP address 45.62.176.121.

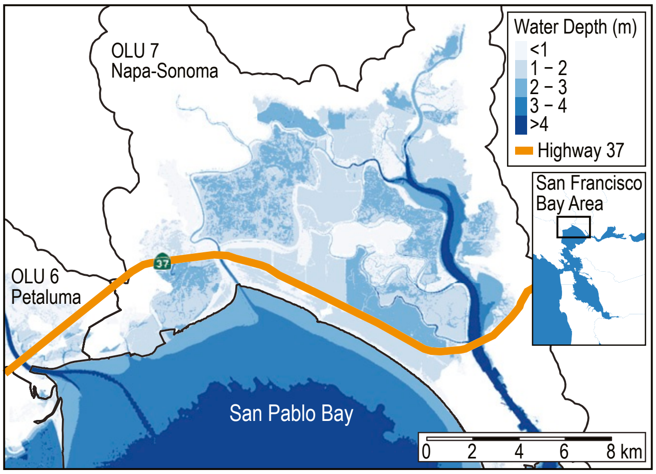


Fig. 6. Highway 37, a transportation corridor of regional importance, spanning the OLU 7 (Napa–Sonoma) shoreline. Highway 37 is susceptible to SLR-induced flooding and will need to be adapted to prevent future disruptions, either by building the road on top of a raised levee or embankment or rebuilding it as a causeway. The choice of adaptation strategy will influence local and regional inundation and associated economic damages. Flooding caused by the 100-cm SLR scenario with existing shorelines is shown for reference.

to narrow straits. While these factors extend to other coastal embayments, external changes in flood damage rely on the spatial distribution and overlap of flooding and exposed buildings and will require a model like we have introduced here to estimate these impacts elsewhere.

From a project-level perspective, understanding flood externalities can help enhance cost–benefit analyses. A specific example from San Francisco Bay is the case of Highway 37 (Fig. 6), which runs along the northern shoreline of San Pablo Bay and connects two major thoroughfares in the region: Interstate 80 and Highway 101. More than half of the length of Highway 37 runs along the OLU 7 shoreline. Segments of this road already experience flooding during high-water events, and the state transportation agency, Caltrans, is considering adaptation alternatives to mitigate the effects of future flooding. The alternatives that are being considered include 1) building the road on top of a raised levee or embankment, estimated to cost $650 million, or 2) constructing a causeway that maintains tidal exchange between the bay and marshlands, estimated to cost $2.2 to 2.5 billion (40). These adaptation options can be seen as proxies for the two possible shoreline strategies examined in this study, including protecting the shoreline (Alternative 1: levee scenario) or maintaining flood pathways between the bay and the surrounding landscape (Alternative 2: causeway scenario). Although Alternative 2 would cost nearly four times as much to build as Alternative 1, the economic analysis presented here suggests that building a barrier along the OLU 7 shoreline could lead to a net increase of $293 million in damages across the bay at 200 cm of SLR due to the loss of flood storage space and induced flooding elsewhere. This estimate only captures damage to buildings at the highest annual tidal flood level and is not a probabilistic estimate of repetitive damage, which would likely lead to higher damages for any given SLR scenario. In addition, it does not include damage to other infrastructure systems (e.g., transportation, water, and energy) or land use types (e.g., agriculture) that will also be affected by flooding (31, 41). Even with these caveats, our results demonstrate that these damage externalities may be a substantial contributor to the overall cost–benefit analysis of proposed infrastructure alternatives and should not be neglected when evaluating and selecting infrastructure adaptation strategies.

Estimates of baywide change in damages due to shoreline protection provide insight into potential opportunities for strategic regional adaptation planning. In most cases, protecting an OLU leads to a net reduction in aggregate damages across the region (Fig. 4*F*), although individual OLUs may experience increased losses. For example, while protecting the OLU 25 shoreline leads to higher damages in other South Bay OLUs, the net regional damage reduction from shoreline protection still exceeds $1 billion in all SLR scenarios (*SI Appendix*, Table S2), highlighting the economic importance of this area. In cases such as this, compensation for communities that experience negative externalities is a possible solution (42), considering the high net benefit of shoreline protection. In some cases, however, shoreline protection leads to a net increase in damages across the entire region. For example, protecting OLU 7 causes up to $293 million in regional net damages at 200 cm of SLR, impacting both San Pablo Bay and South Bay, where total replacement values are generally the highest. Shoreline protection in OLU 21 also leads to a regional net increase in damages up to $194 million at 200 cm of SLR (*SI Appendix*, Table S2). Protecting OLUs 7 and 21, which are both classified as wide alluvial valleys, is thus difficult to justify from a regional economic perspective; instead, strategic flooding in these areas could provide substantial regional benefits by avoiding the negative economic externalities associated with shoreline protection. A transfer of development rights program that allows property owners to sign over their development rights for a portion of the proceeds from development elsewhere could be a mechanism that allows already densely developed areas to incentivize communities in wide alluvial valleys to avoid further development and allow strategic flooding to reduce flood levels throughout the bay. Importantly, the damage estimates we report here do not include the cost of construction and maintenance of armoring, nor do they include the potential degradation of coastal habitats (25) and loss of recreation, fisheries, and other ecosystem services that may influence the net benefits and costs of armoring (24, 43).

There are, of course, other related factors that may influence the decision about protecting specific shoreline segments, including protection of vulnerable populations, agricultural areas, places of historical or cultural significance, and critical infrastructure assets of regional importance. For example, Fig. 7 shows the magnitude and demographic breakdown of the population affected by flooding when (*A*) OLU 7 and (*B*) OLU 21 are allowed to strategically flood, as suggested above. For each SLR scenario, the left column represents the people living in OLU 7 or 21 who experience flooding as a result of this decision, while the right column represents people living in other OLUs who avoid flooding. Strategic flooding of OLU 21 leads to protection of people throughout the bay at 50 cm, 100 cm, and 150 cm of SLR without flooding local residents. At 200 cm of SLR, strategic flooding leads to an increase in the flooded population within OLU 21. However, both with respect to the total number of people flooded and their racial composition, allowing flooding in OLU 21 provides benefits for more people of all races across the bay. Thus, the decision to allow OLU 21 to strategically flood to mitigate external impacts could be justified by both the damage and population data. However, individuals, communities, and decision-makers within OLU 21 would likely object to sacrificing local assets for the benefit of the broader community within the bay, even if compensated. Inclusive discussions among multiple stakeholders and decision-makers would certainly be a critical step in evaluating and implementing any such strategy.

In contrast, allowing OLU 7 to strategically flood at 50 cm of SLR causes flooding for 500 people (61% Black, indigenous, or people of color [BIPOC]) in OLU 7 while avoiding flooding for 570 people (30% BIPOC) elsewhere. At 100 cm and 150 cm of SLR, the number of people outside OLU 7 who benefit from strategic flooding in OLU 7 outweighs the number

ENVIRONMENTAL SCIENCES

Downloaded from https://www.pnas.org by 45.62.176.121 on July 20, 2022 from IP address 45.62.176.121.

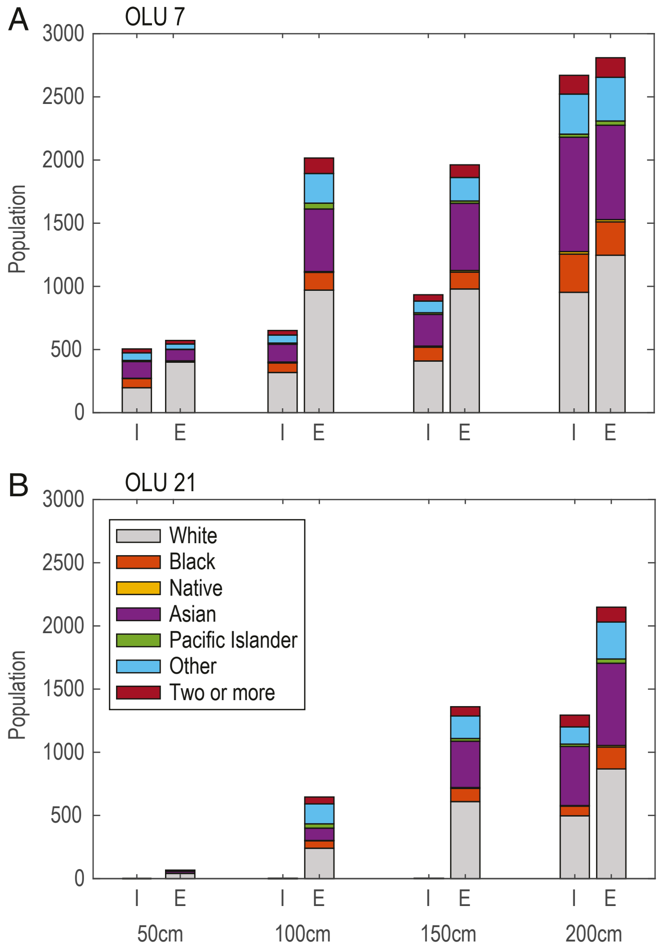


Fig. 7. Total number and racial composition of people affected by the decision to strategically flood (*A*) OLU 7 and (*B*) OLU 21. For each SLR scenario, the left column (I = internal) represents the people living in OLU 7 or 21 who experience flooding as a result of this decision, while the right column (E = external) represents people living in other OLUs who avoid flooding.

of people in OLU 7 who are affected, with comparable racial composition between both groups. However, at 200 cm of SLR, the flooded population in OLU 7 (2,670 people, 64% BIPOC) is once again similar in magnitude to the population that avoids flooding elsewhere (2,810 people, 56% BIPOC) and includes a higher percentage of BIPOC residents, who often have fewer resources to prepare for, respond to, and recover from natural hazards such as flooding (44). In this case, accounting for the number of residents internal to OLU 7 that experience flooding and the potential disparate impacts on the BIPOC population may lead to alternative decisions about shoreline adaptation in OLU 7. As this example illustrates, augmenting information about physical and economic externalities with estimates of associated human impacts can provide an additional means through which to evaluate proposed shoreline adaptation projects and to inform more equitable risk reduction.

The work summarized here is an important first step toward understanding previously uncounted regional damage interactions and thus fills a critical information gap in the understanding of shoreline protection and its consequences within San Francisco Bay. However, internalizing this information into decision making will require overcoming the "governance gap" that separates the scale of decision-making from the scale of the threat of SLR (7). Currently, the San Francisco Bay Area lacks a mechanism to reorient smaller-scale planning toward a coordinated, regional focus across jurisdictions. Possible avenues to address the gap include expanding the authority of existing regional planning and permitting agencies, such as the San Francisco Bay Conservation and Development Commission, or developing a collaborative management structure composed of multiple agencies working together to implement a regional vision, as proposed by the recent Bay Adapt initiative (45). Given the sizable potential flood damage externalities observed in this study, coordinated action is more likely to succeed if incentives are aligned to address disparate impacts across parties. Direct transfer payments as mentioned above may be an option to compensate areas that are strategically allowed to flood to reduce damages elsewhere; this is analogous to other payment for environmental service programs like water funds that preserve upstream land to ensure downstream water quantity and quality (46). A more targeted approach could be modeled after the Measure AA parcel tax, which funds restoration of the San Francisco Bay shoreline by taxing all parcels in the nine counties that border the bay $12 annually for 20 y. By raising funding for SLR adaptation at the regional level and tying it to development density, projects and policies could be prioritized based on regionally defined criteria and funded principally by developed areas that stand to benefit most.

Our results provide an initial estimate of the magnitude and distribution of flood damage externalities across communities when implementing coastal protection and strategic flood storage measures and can serve as a basis for transparent regional engagement that acknowledges these external costs. Although the OLU-scale shoreline protection scenarios presented here are not necessarily representative of likely SLR adaptation plans for the region, the results highlight how geomorphic factors, development density, and geographic location in the bay are likely to influence the regional impacts of shoreline protection projects. This information can support the evaluation and selection of actual adaptation plans and individual projects for the San Francisco Bay Area, which may include multiple simultaneous shoreline modifications that are implemented at smaller scales than examined here (e.g., sub-OLU). Similar analyses that consider other drivers of extreme water levels and associated patterns of flooding in addition to the tidal flooding mechanisms considered here would also help to inform adaptation decisions. Our approach can be extended to other coastal estuaries with low-lying, dense development, such as the Chesapeake Bay on the US East Coast or the Bohai Sea in China, which exhibit similar hydrodynamic feedbacks (27, 47, 48) and would presumably benefit from an analysis of interrelated economic outcomes from protection strategies. Accounting for the connectivity of local actions in coastal estuaries is a critical step toward identifying shoreline adaptation strategies that provide regional benefits while also mitigating unintended negative impacts.

Materials and Methods

Hydrodynamic Modeling. We applied a two-dimensional depth-averaged hydrodynamic model of San Francisco Bay developed as part of the US Geological Survey's (USGS) Coastal Storm Modeling System (CoSMoS) (37, 38). The model uses the Delft3D Flexible Mesh software (49), which applies a finite volume approach on an unstructured grid to solve the governing shallow water equations

$$\frac{\delta h}{\delta t} + \frac{\delta uh}{\delta x} + \frac{\delta vh}{\delta y} = 0$$

$$\frac{\delta u}{\delta t} + u\frac{\delta u}{\delta x} + v\frac{\delta u}{\delta y} = -g\frac{\delta h}{\delta x} + \nu\left(\frac{\delta^2 u}{\delta x^2} + \frac{\delta^2 u}{\delta y^2}\right) - \frac{1}{C^2}\frac{g}{h}\|u\|u$$

$$\frac{\delta v}{\delta t} + u\frac{\delta v}{\delta x} + v\frac{\delta v}{\delta y} = -g\frac{\delta h}{\delta y} + \nu\left(\frac{\delta^2 v}{\delta x^2} + \frac{\delta^2 v}{\delta y^2}\right) - \frac{1}{C^2}\frac{g}{h}\|v\|v,$$

where h is the water depth, u and v are the depth-averaged velocities, g is the gravitational acceleration, ν is the viscosity, C is the drag coefficient, and x, y, and t are the space and time coordinates. Wetting and drying

Downloaded from https://www.pnas.org by 45.62.176.121 on July 20, 2022 from IP address 45.62.176.121.

is accomplished by adding or removing grid points from the flow domain based on a threshold flood depth. Spatially variable roughness is applied using the Manning roughness formulation.

The model domain included San Francisco Bay and upstream channels in the Sacramento–San Joaquin Delta and extended offshore to the −1,500-m depth contour (*SI Appendix*, Fig. S3). Grid cells ranged in size from approximately 3 km in offshore areas to less than 50 m in overland areas. We used seamless topography and bathymetry data available at 2-m horizontal resolution from the USGS Coastal National Elevation Database (50) across the model domain. We further delineated existing shoreline protection features, such as engineered levees, floodwalls, berms, and embankments, in areas where the grid resolution was not fine enough to capture these features. Elevation data for these structures was extracted from the San Francisco Estuary Institute's San Francisco Bay Shore Inventory database (32).

We forced the model at the oceanic boundary with January 2010 water levels and currents extracted from Oregon State University's TPXO8 tidal model for eight harmonic constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, and Q_1) (51). For each SLR scenario we added an additional tidal component with zero frequency and amplitude equal to the SLR increment (i.e., 50, 100, 150, and 200 cm). We applied historical discharge data for the Sacramento and San Joaquin Rivers as point inflows into the model. We did not include meteorological forcing in the simulations because the focus of the study is on tidally driven interactions with the shorelines. Outputs from the simulations represent the inundation that would occur at high tide during a spring tide cycle, which persists for approximately 2 wk each month. This results in permanent flooding in some low-lying areas and shorter-duration (minutes to hours) but frequent (multiple days per month) flood disruptions at higher elevations.

Shoreline Scenarios. We developed the shoreline scenarios from the OLU boundary delineation conducted by ref. 35 for the San Francisco Bay Area. Briefly, ref. 35 divided the bayshore broadly by geomorphic type, including wide alluvial valleys, alluvial fans and alluvial plains, and headlands and small valleys. They then further delineated the lateral boundaries between individual OLUs using major watershed boundaries or the apex points of major headlands and alluvial fans. In the cross-shore direction, OLUs extend from the offshore point where wind-driven waves are capable of mobilizing sediment to the inland extent of the 500-cm SLR scenario plus a 500-m transitional zone.

We implemented protection scenarios for each OLU shoreline individually in the hydrodynamic model using infinitely high impermeable walls. The walls generally follow the coastal boundary of each OLU, as well as the lateral boundaries up to the 200-cm SLR flooding extent modeled using existing shorelines. This prevents flooding between the protected OLU and its neighbors along overland flow pathways.

For each scenario, we calculated the change in inundation volume across the land surface in each OLU using the integral

$$V_{OLU} = \int_{A_{OLU}} \Delta h \, dA,$$

where V_{OLU} is the inundation volume, A_{OLU} is the surface area of the OLU, and Δh is the change in water depth in each grid cell as compared to the existing shoreline scenario for that amount of SLR.

Economic Damages. We simulated flood damages using the expected damage function methodology (52), estimating both the expected repair cost to flooded properties and the replacement cost of damaged building contents under the baseline no-intervention condition and all protection and SLR scenarios. Using this approach, the change in repair cost between a baseline scenario and protection scenario provides an estimate of compensating variation, or the social welfare gain/loss, associated with that protection scenario (53). This assumes risk neutrality of property owners and would underestimate the change in social welfare if affected owners were risk averse. We conducted this analysis for structures across the San Francisco Bay region represented in the Federal Emergency Management Agency's (FEMA's) HAZUS 2015 General Building Stock database, a nationwide spatially explicit inventory of structures classified by occupancy type. The spatial resolution of this dataset is the census block, and as such the expected damage function here is a lumped model where all structure classes are assumed to be evenly spread across the census block. We reconstructed aggregate structure and content repair/replacement costs by occupancy class for each census block outside of the HAZUS software following guidance in FEMA's HAZUS 3.2 release notes (39). We derived total repair cost values at risk to SLR over the next 150 y by aggregating over all census blocks across OLUs, consistent with the risk profile definition used to create the OLUs (35). We calculated the total population at risk by aggregating across OLUs based on the Environmental Protection Agency's 30-m dasymetric population map for the coterminous United States available from EnviroAtlas (54).

We assessed flood damages for each occupancy class across census blocks via depth-damage functions that relate flood depth to repair costs, as a fraction of total building replacement cost. From HAZUS, we extracted appropriate functions for all structure classes, as developed by FEMA and the US Army Corps of Engineers using empirical data from past flood events (55, 56). Census blocks are generally less than 3 ha, but in less densely populated areas they can be much larger and in all cases in the study area were larger than the resolution of the flood raster. To deal with variation in flood depth and nonlinear depth-damage functions to produce a single estimate of repair cost for each census block we randomly sampled 100 cells from the flood map within each census block and estimated repair costs across all occupancy types for each draw. From this we derived summary statistics for aggregate repair costs across occupancy classes for each census block and reported on sample means.

Modeling was treated as a one-off tidal flood event under each SLR scenario and did not account for repeat flood events. All else being equal, this significantly underpredicts long-term value estimates. We examined only economic damages to buildings and did not incorporate other infrastructure systems (e.g., transportation, water, and energy) or land-use types (e.g., agriculture), which will also be affected by flooding and contribute to economic damages (31, 41). Crop agriculture is a small portion of land by area, even in wide alluvial valleys (*SI Appendix*, Fig. S2), so we do not expect large systematic damage underestimates. We did not account for changes in socioeconomic development or population distribution over time (57), which could bias results depending on their future trajectory. While our analysis focused on property replacement values, protection of vulnerable populations may be a priority for communities but may be undervalued through traditional property value–based analyses such as the one presented here (58, 59).

Population at Risk in Bays and Estuaries. We defined population at risk from SLR and flooding here as those living adjacent to the shoreline at less than 10 m elevation, excluding areas that would not be hydrologically connected to the coast, consistent with prior work estimating SLR risk in what has been termed the "Low Elevation Coastal Zone" (2, 60). Global population in 2020 was mapped using WorldPop (61), and global elevation data were sourced from the Consultative Group on International Agricultural Research's hole-filled Shuttle Radar Topography Mission global digital elevation model (62). The digital elevation model was reprocessed to identify areas below 10 m in elevation that are contiguous with the coastline, using the public domain World Data Bank II global shoreline vector layer as the reference coastline. This layer was then used to extract the global population that met these criteria. Finally, using a globally mapped typology of nearshore coastal systems (63), we extracted populations nearest to coastal systems defined as predominantly tidally influenced (class 2) to estimate total population at risk in this nearshore system. This process estimates that 864 million people globally are at risk, and 468 million of these live closest to shorelines classified as tidally influenced bays and estuaries. The overall global exposure estimate of 867 million here is within 4% of the mean value of two prior studies that calculated this risk metric (2, 60).

To estimate population impacts for the shoreline protection scenarios modeled here, we extracted block-level population counts across the San Francisco Bay region from the 2010 decennial census (64). We calculated the proportion of each census block that was flooded under each shoreline scenario and then applied that value to the block-level population count to determine the number of people affected by flooding. This approach assumes that the population is evenly distributed throughout each census block, which could lead to biases in larger census blocks or in areas where residential development is concentrated in only part of a block. We then compared the population counts in each OLU for each protection scenario with the existing shoreline scenario at the same SLR to determine the number of people across the region who experience flooding or who obtain protective benefits as a result of the protective action.

Data Availability. The data and code used in this analysis are available through the Dryad data repository at https://doi.org/10.5061/dryad.2z34tmpmb (65) and https://doi.org/10.5061/dryad.g79cnp5pt (66).

ACKNOWLEDGMENTS. We thank Mark Stacey for insightful and constructive comments. This project was supported by NSF Award 1541181, the Gordon and Betty Moore Foundation, the Wallenberg Foundation, and the

ENVIRONMENTAL SCIENCES

Downloaded from https://www.pnas.org by 45.62.176.121 on July 20, 2022 from IP address 45.62.176.121.

National Oceanic and Atmospheric Administration's Cooperative Institute for the North Atlantic Region. This research used the Savio computational cluster resource provided by the Berkeley Research Computing program at the University of California, Berkeley (supported by the University of California, Berkeley Chancellor, Vice Chancellor for Research, and Chief Information Officer).

1. J. Hinkel *et al.*, Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 3292–3297 (2014).
2. S. A. Kulp, B. H. Strauss, New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nat. Commun.* **10**, 4844 (2019).
3. B. Neumann, A. T. Vafeidis, J. Zimmermann, R. J. Nicholls, Future coastal population growth and exposure to sea-level rise and coastal flooding—A global assessment. *PloS One* **10**, e0118571 (2015).
4. World Economic Forum, "The global risks report 2019 14th edition" (Technical report, World Economic Forum, Geneva, Switzerland, 2019).
5. S. Gopalakrishnan, C. E. Landry, M. D. Smith, J. C. Whitehead, Economics of coastal erosion and adaptation to sea level rise. *Annu. Rev. Res. Econ.* **8**, 119–139 (2016).
6. T. A. Thaler, S. J. Priest, S. Fuchs, Evolving inter-regional co-operation in flood risk management: Distances and types of partnership approaches in Austria. *Reg. Environ. Change* **16**, 841–853 (2016).
7. M. Lubell, "The governance gap: Climate adaptation and sea-level rise in the San Francisco Bay area" (Technical report, University of California, Davis, 2017).
8. B. T. Werner, D. E. McNamara, Dynamics of coupled human-landscape systems. *Geomorphology* **91**, 393–407 (2007).
9. E. D. Lazarus, M. A. Ellis, A. B. Murray, D. M. Hall, An evolving research agenda for human–coastal systems. *Geomorphology* **256**, 81–90 (2016).
10. W. Brock, A. Xepapadeas, Pattern formation, spatial externalities and regulation in coupled economic–ecological systems. *J. Environ. Econ. Manag.* **59**, 149–164 (2010).
11. A. C. Pigou, *The Economics of Welfare* (Macmillan and Company, 1929).
12. G. A. Tobin, The levee love affair: A stormy relationship? *J. Am. Water Res. Assoc.* **31**, 359–367 (1995).
13. B. E. Montz, G. A. Tobin, Livin' large with levees: Lessons learned and lost. *Nat. Hazards Rev.* **9**, 150–157 (2008).
14. R. A. Heine, N. Pinter, Levee effects upon flood levels: An empirical assessment. *Hydrol. Process.* **26**, 3225–3240 (2012).
15. N. Pinter, F. Huthoff, J. Dierauer, J. W. F. Remo, A. Damptz, Modeling residual flood risk behind levees, Upper Mississippi River, USA. *Environ. Sci. Pol.* **58**, 131–140 (2016).
16. Z. C. Williams, D. E. McNamara, M. D. Smith, A. B. Murray, S. Gopalakrishnan., Coupled economic-coastline modeling with suckers and free riders. *J. Geophys. Res. Earth Surf.* **118**, 887–899 (2013).
17. D. Jin, A. D. Ashton, P. Hoagland, Optimal responses to shoreline changes: An integrated economic and geological model with application to curved coasts. *Nat. Resour. Model.* **26**, 572–604 (2013).
18. S. Gopalakrishnan, D. McNamara, M. D. Smith, A. B. Murray, Decentralized management hinders coastal climate adaptation: The spatial-dynamics of beach nourishment. *Environ. Resour. Econ.* **67**, 761–787 (2017).
19. W. J. Beasley, S. J. Dundas, Hold the line: Modeling private coastal adaptation through shoreline armoring decisions. *J. Environ. Econ. Manag.* **105**, 102397 (2021).
20. S. J. Dundas, D. J. Lewis, Estimating option values and spillover damages for coastal protection: Evidence from Oregon's Planning Goal 18. *J. Assoc. Environ. Res. Econ.* **7**, 519–554 (2020).
21. J. E. Neumann *et al.*, Joint effects of storm surge and sea-level rise on US coasts: New economic estimates of impacts, adaptation, and benefits of mitigation policy. *Climatic Change* **129**, 337–349 (2014).
22. I. Papakonstantinou, J. Lee, S. M. Madanat, Game theoretic approaches for highway infrastructure protection against sea level rise: Co-opetition among multiple players. *Transp. Res. Part B Methodol.* **123**, 21–37 (2019).
23. M. A. Hummel, A. T. Siwe, A. Chow, M. T. Stacey, S. M. Madanat, Interacting infrastructure disruptions due to environmental events and long-term climate change. *Earth Future* **8**, e2020EF001652 (2020).
24. K. K. Arkema *et al.*, Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities. *Ann. N. Y. Acad. Sci.* **1399**, 5–26 (2017).
25. J. E. Dugan *et al.*, Generalizing ecological effects of shoreline armoring across soft sediment environments. *Estuar. Coast* **41**, 180–196 (2018).
26. R. C. Holleman, M. T. Stacey, Coupling of sea level rise, tidal amplification, and inundation. *J. Phys. Oceanogr.* **44**, 1439–1455 (2014).
27. S. B. Lee, M. Li, F. Zhang, Impact of sea level rise on tidal range in Chesapeake and Delaware Bays. *J. Geophys. Res.: Oceans* **122**, 3917–3938 (2017).
28. R. Q. Wang, M. T. Stacey, L. M. M. Herdman, P. L. Barnard, L. Erikson, The influence of sea level rise on the regional interdependence of coastal infrastructure. *Earth Future* **6**, 677–688 (2018).
29. M. A. Hummel, M. T. Stacey, Assessing the influence of shoreline adaptation on tidal hydrodynamics: The role of shoreline typologies. *J. Geophys. Res. Oceans* **126**, e2020JC016705 (2021).
30. C. L. Lopes, J. M. Dias, Tidal dynamics in a changing lagoon: Flooding or not flooding the marginal regions. *Estuar. Coast Shelf Sci.* **167**, 14–24 (2015).
31. M. Heberger, H. Cooley, P. Herrera, P. H. Gleick, E. Moore, Potential impacts of increased coastal flooding in California due to sea-level rise. *Climatic Change* **109**, 229–249 (2011).
32. San Francisco Estuary Institute, "San Francisco Bay shore inventory: Mapping for sea level rise planning" (Technical report, San Francisco Estuary Institute and the Aquatic Science Center, 2016).
33. G. Griggs *et al.*, "Rising seas in California: An update on sea-level rise science" (Technical report, California Ocean Science Trust, 2017).
34. W. V. Sweet *et al.*, "Global and regional sea level rise scenarios for the United States" (Technical report, National Oceanic and Atmospheric Administration, 2017).
35. J. Beagle *et al.*, "San Francisco Bay shoreline adaptation atlas" (Technical report, San Francisco Estuary Institute and San Francisco Bay Area Planning and Urban Research Association, 2019).
36. J. T. A. Verhoeven, M. B. Soons, R. Janssen, N. Omtzigt, An Operational Landscape Unit approach for identifying key landscape connections in wetland restoration. *J. Appl. Ecol.* **45**, 1496–1503 (2008).
37. P. L. Barnard *et al.*, "The framework of a coastal hazards model —A tool for predicting the impact of severe storms" (US Geological Survey, 2009).
38. P. L. Barnard *et al.*, Development of the Coastal Storm Modeling System (CoSMoS) for predicting the impact of storms on high-energy, active-margin coasts. *Nat. Hazards* **74**, 1095–1125 (2014).
39. Federal Emergency Management Agency, "Hazus 3.2 user release notes" (Technical report, FEMA, 2016).
40. J. Villafranca, K. May, J. Vandever, "State route 37 integrated traffic, infrastructure and sea level rise analysis: Final report" (Technical report, University of California, Davis Road Ecology Center, 2015).
41. M. A. Hummel, M. S. Berry, M. T. Stacey, Sea level rise impacts on wastewater treatment systems along the U.S. coasts. *Earth Future*, e312 (2018).
42. S. McCarthy, C. Viavattene, J. Sheehan, C. Green, Compensatory approaches and engagement techniques to gain flood storage in England and Wales. *J. Floor Risk Manag.* **11**, 85–94 (2018).
43. S. M. W. Reddy *et al.*, Evaluating the role of coastal habitats and sea-level rise in hurricane risk mitigation: An ecological economic assessment method and application to a business decision. *Integrated Environ. Assess. Manag.* **12**, 328–344 (2016).
44. A. Fothergill, E. G. M. Maestas, J. A. D. R. Darlington, Race, ethnicity and disasters in the United States: A review of the literature. *Disasters* **23**, 156–173 (1999).
45. San Francisco Bay Conservation and Development Commission. Bay Adapt: Regional strategy for a rising bay (2021). https://www.bayadapt.org/. Accessed 26 June 2021.
46. L. L. Bremer *et al.*, One size does not fit all: Natural infrastructure investments within the Latin American water funds partnership. *Ecosyst. Serv.* **17**, 217–236 (2016).
47. D. Song, X. H. Wang, X. Zhu, X. Bao, Modeling studies of the far-field effects of tidal flat reclamation on tidal dynamics in the East China Seas. *Estuar. Coast Shelf Sci.* **133**, 147–160 (2013).
48. L. Zhu, R. Hu, H. Zhu, S. Jiang, Y. Xu, N. Wang, Modeling studies of tidal dynamics and the associated responses to coastline changes in the Bohai Sea, China. *Ocean Dynam.* **68**, 1625–1648 (2018).
49. Deltares. Delft3d flexible mesh suite (2020). https://www.deltares.nl/en/software/delft3d-flexible-mesh-suite/. Accessed 26 June 2021.
50. US Geological Survey. Topobathymetric model of San Francisco Bay, California (2013). https://topotools.cr.usgs.gov/topobathy_viewer/. Accessed 26 June 2021.
51. G. D. Egbert, S. Y. Erofeeva, Efficient inverse modeling of barotropic ocean tides. *J. Atmos. Ocean. Technol.* **19**, 183–204 (2002).
52. E. B. Barbier, Valuing ecosystem services as productive inputs. *Econ. Pol.* **22**, 178–229 (2007).
53. E. B. Barbier, Valuing the storm protection service of estuarine and coastal ecosystems. *Ecosystem Services* **11**, 32–38 (2015).
54. B. R. Pickard, J. Daniel, M. Mehaffey, L. E. Jackson, A. N. EnviroAtlas, A new geospatial tool to foster ecosystem services science and resource management. *Ecosystem Services* **14**, 45–55 (2015).
55. US Army Corps of Engineers, "Business depth-damage analysis procedures" (Technical Report 85-R-5, US Army Engineer Institute for Water Resources, 1985).
56. US Army Corps of Engineers, "Catalog of residential depth-damage functions" (Technical Report 92-R-3, US Army Engineer Institute for Water Resources, 1992).
57. M. E. Hauer, J. M. Evans, D. R. Mishra, Millions projected to be at risk from sea-level rise in the continental United States. *Nat. Clim. Change* **6**, 691–695 (2016).
58. J. Martinich, J. Neumann, L. Ludwig, L. Jantarasami, Risks of sea level rise to disadvantaged communities in the United States. *Mitig. Adapt. Strategies Glob. Change* **18**, 169–185 (2013).
59. M. A. Hummel *et al.*, Clusters of community exposure to coastal flooding hazards based on storm and sea level rise scenarios—Implications for adaptation networks in the San Francisco Bay region. *Reg. Environ. Change* **18**, 1343–1355 (2018).
60. G. McGranahan, D. Balk, B. Anderson, The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environ. Urbanization* **19**, 17–37 (2007).
61. A. J. Tatem, Worldpop, open data for spatial demography. *Sci. Data* **4**, 1–4 (2017).
62. A. Jarvis *et al.*, Hole-filled SRTM for the globe version 4. https://cgiarcsi.community/data/srtm-90m-digital-elevation-database-v4-1/. Accessed 26 June 2021.
63. H. H. Dürr *et al.*, Worldwide typology of nearshore coastal systems: Defining the estuarine filter of river inputs to the oceans. *Estuar. Coast* **34**, 441–458 (2011).
64. US Census Bureau. 2010 census summary file 1 dataset. https://www.census.gov/data/datasets/2010/dec/summary-file-1.html. Accessed 26 June 2021.
65. R. Griffin, M. Hummel, K. Arkema, A. Guerry, Economic evaluation of sea-level rise adaptation strongly influenced by hydrodynamic feedbacks: Dataset 1. Dryad. https://doi.org/10.5061/dryad.2z34tmpmb. Deposited 24 June 2021.
66. R. Griffin, M. Hummel, K. Arkema, A. Guerry, Economic evaluation of sea-level rise adaptation strongly influenced by hydrodynamic feedbacks: Dataset 2. Dryad. https://doi.org/10.5061/dryad.g79cnp5pt. Deposited 24 June 2021.

Downloaded from https://www.pnas.org by 45.62.176.121 on July 20, 2022 from IP address 45.62.176.121.