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Bridging climate science, law, and policy to advance coastal adaptation planning

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ABSTRACT

Rising seas, more frequent storms and other climate-driven coastal hazards necessitate adaptation planning measures to protect people and property. To date, coastal vulnerability assessments have prioritized the most exposed areas of coastline, but there is a gap between recognized climate science and the feasibility or suitability considerations relevant for implementing coastal adaptation strategies—including legal, policy, financial, or engineered approaches—to address coastal threats. This paper sets forth a methodology for bridging the gap between climate science, law and coastal adaptation policies. This methodology seeks to connect spatial analysis methods with attributes of coastal adaptation strategies that make them inherently place-based—ranging from engineered solutions, to legal strategies and financial tools—to determine where they are legally feasible and suitable. Both spatial and non-spatial limiting and enabling conditions of coastal adaptation policies drive these determinations. The methodology integrates a spatial framework using feasibility statements derived by 1) coupling these conditions and features with spatial information (e.g., zoning, land use/land cover, geomorphologic features), and 2) identifying suitability conditions through synthesizing policy considerations for each coastal adaptation strategy.

1. Introduction

Climate change, rising seas and increasingly destructive winter storms prompt swift, proactive planning to deal with a rapidly changing California coastline. A wealth of scientific information quantifies the effects of these impacts on the coast, including a range of predicted sea level rise scenarios and the potential loss of coastal property and natural habitats [1]. Coastal communities have used vulnerability assessments featuring this climate science to identify areas that are most exposed to coastal hazards in their jurisdictions [2–5]. While coastal vulnerability assessments convey a vast amount of information that is useful for policymakers (e.g. number of people at risk, potential habitat degradation and loss, and value of infrastructure exposed to erosion and flooding), these summaries are only a first step. Specifically, these assessments stop short of identifying the coastal adaptation strategies that are feasible or suitable in certain locations—i.e. they do not directly link the science to specific, preferred place-based policies [6]. Similarly, vulnerability assessments have been critiqued for not providing actionable science [7].

To address this science-policy gap, this project applied scientific coastal climate impact information integrated with legal and policy considerations to assist California communities with ongoing coastal planning efforts. This effort focused on California, a state that has been a leader in sea level rise projection science, coastal adaptation policy development, and planning in response to the challenges posed by climate change. California agencies have made substantial progress in assessing the vulnerability of the state's coastline and assisting local communities with their respective vulnerability assessments. The California Coastal Commission's Sea Level Rise Policy Guidance [8] lays the groundwork for local communities to plan for and adapt to rising seas. The subsequent Draft Residential Adaptation Policy Guidance [9] provides additional details for residential property owners in the crosshairs of rising sea levels. These documents are useful preliminary resources in informing coastal adaptation decisionmaking at the local level in California.

The project group is an interdisciplinary team of legal and spatial analysts, ecologists, technologists and community engagement specialists tasked with bridging the gap between climate science, law and

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coastal adaptation policies in coastal California. The team developed a novel science-policy approach that links coastal climate sciences and spatial planning. This approach aligns potential coastal adaptation strategies with potential locations for their implementation along the California coast. Furthermore, the identification of enabling and limiting conditions can inform which adaptation strategies are most feasible (physically possible based on existing coastal setting) or suitable (appropriate based on current legal or social setting) for a given location [6].

2. Methodology

This section explains the methodological framework the team developed to identify potential coastal adaptation locations on California's coastline. First, it recounts the project's engagement process. Next, it defines "coastal adaptation strategy" and explains how these strategies are organized. It then sets forth how these strategies can be filtered, specifically based on identified enabling and limiting conditions. The methodology for identifying feasible place-based climate adaptation strategies through geospatial analysis is explored. Finally, the feasibility statements connecting the spatially explicit information are outlined.

2.1. Engagement process

To develop a methodological framework linking science and policy, the research team directly engaged local governments, including cities and counties, as well as state government agencies. These engagements significantly influenced the project's process, goals, and products. In all, the project team engaged state and local planning staff members in 27 meetings over a nine-month period. At the state level, the project team held meetings at the California Coastal Commission (CCC) and the California State Coastal Conservancy (SCC), Fig. 1 where it presented the methodological approach presented in this article to state agency staff. These meetings helped groundtruth the project's investigative assumptions and guided its research of relevant topics.

At the local government level, the team first met with county- and city-level planners with whom the researchers held existing relationships. The goal of these initial meetings was to develop a discourse with stake- and knowledge-holders throughout the outer coast. Next, the researchers identified local jurisdictions to target for engagement meetings—primarily focusing on jurisdictions that had applied for local coastal program (LCP) update funding from state agencies. These meetings with local jurisdictions focused on listening, so the researchers would not steer the discussions in any preconceived direction. This approach ensured that the identified research questions, methods, and products respected state considerations while also reflecting the needs of local communities. This loosely-formatted and inquisitive approach provided the researchers flexibility to address a wide range of topics. It also identified several distinct themes based on these conversations, including information gaps, implementation barriers, legal questions, recent successes, community engagement, and lessons learned.

In addition to meetings with city and county staff members, the researchers also met with several non-governmental organization (NGO) staff and academic organizations working on local coastal adaptation issues. Discussions with adaptation practitioners provided additional context relevant to implementing adaptation strategies in a given setting—especially environmental considerations and possible social or political pitfalls—and public support for certain responses. These audiences also provided feedback on the structure and content of resources that would be most informative for specific adaptation strategies under consideration. Co-developed policy briefs, shared with planners and managers as online PDFs, featured strategy descriptions,

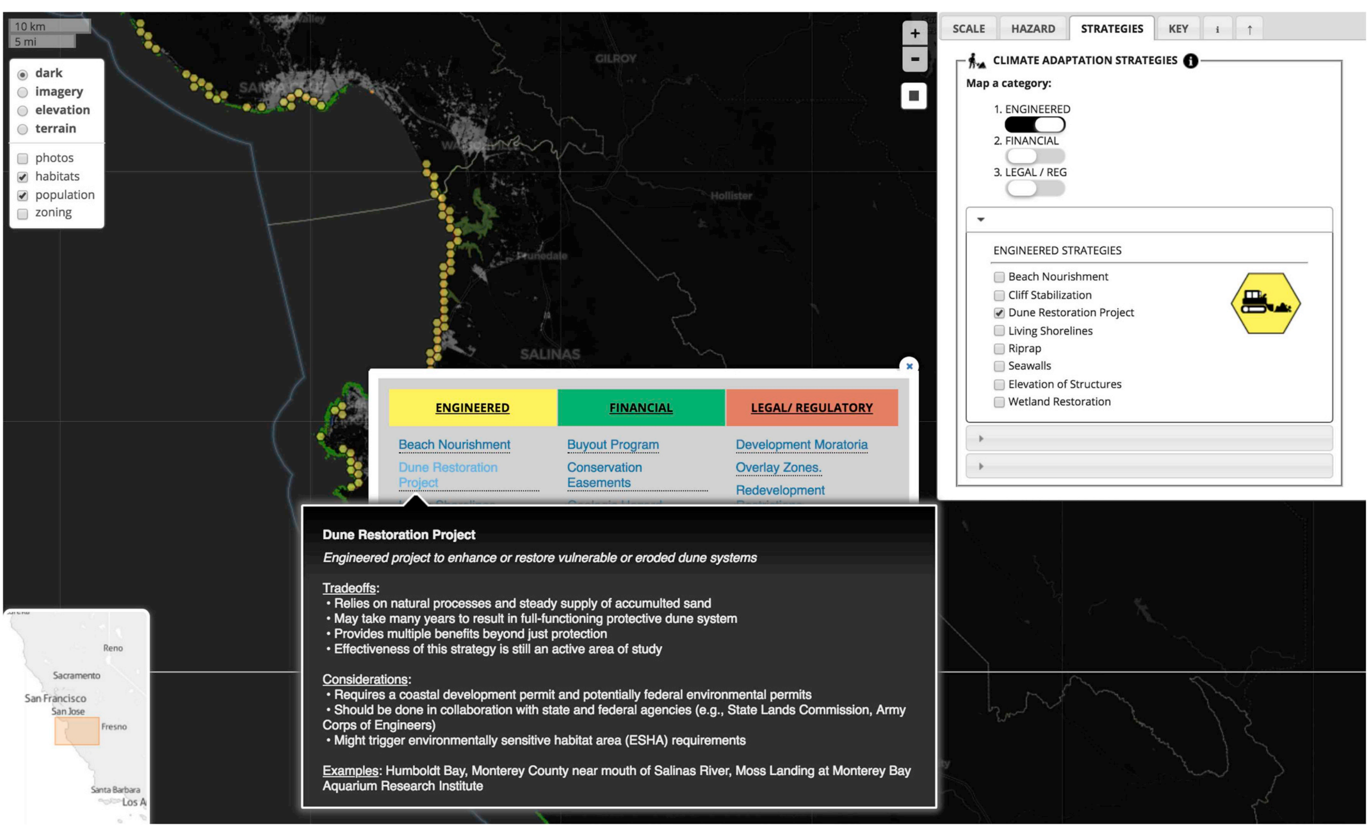

Fig. 1. Screenshot of online viewer tool highlighting coastal segments along Monterey Bay where a dune restoration project is feasible (yellow hexagons) in Monterey and Santa Cruz Counties. The tool enables users to filter from 15 adaptations strategies and list potential tradeoffs, policy considerations, and examples of successful implementation. Reference information (e.g., location of natural habitats and densely populated areas, aerial imagery, and zoning maps) can be overlayed on the map to provide additional context for investigating site sutiability by strategy or geography.

tradeoffs in the form of advantages and disadvantages, legal considerations, and contemporary examples when possible.[1]

2.2. Defining “coastal adaptation strategy”

The team adopted a broad definition of the term “coastal adaptation strategy” to be as inclusive as possible of the current and potential interventions to address rising seas and eroding coastlines. Accordingly, in the context of this project “coastal adaptation strategies” means feasible and suitable options that aid communities in reducing exposure to climate impacts, especially coastal hazards exacerbated by rising seas. “Feasibility” is a function of the existing coastal setting and the way in which the presence of certain conditions allows even the possibility of pursuing a given strategy (e.g., a dune restoration would not be feasible along a steep cliff face). “Suitability” is a function of the likelihood that a coastal community would implement an adaptation strategy due to existing legal conditions or the social and cultural perspective or risk tolerance of the community. While a strategy might be feasible in some place it does not necessarily follow that it will also be suitable there. Further, some strategies will be less suitable generally just by virtue of their likely environmental drawbacks (e.g. seawalls or beach nourishment)—implying that they would not be environmentally favorable. Feasibility and suitability should be considered holistically by decisionmakers together.

This definition of coastal adaptation strategies includes all planning and decisionmaking interventions related and responsive to erosion, inundation, and effects of coastal storm events. This broad definition includes within its ambit several different kinds of strategies, including engineered, planning, legal, regulatory and financial tools contemplated or currently in use in the coastal adaptation context.

2.3. Organization and filtering of strategies

Coastal adaptation strategies can be organized in several different ways. Perhaps the most common approach to organizing these strategies is based on the goal sought for a particular location [10]. This "objective-based" classification scheme organizes strategy goals—also known as “responses”—into three categories: protect, accommodate and retreat. Organizations ranging from global scale to local scale have used this categorization [8,11]. The CCC, recognizing the limitations of a narrow, objective-based approach, proposes a hybrid approach using strategies from multiple categories for different time horizons [8]. While this hybrid approach can be useful for long-term planning and top-down decisionmaking for certain geographies, it is less useful for near-term decisions local communities—i.e. California cities and counties—are currently grappling with in their distinct jurisdictions, as there is need for greater specificity to aid implementation. Instead, these jurisdictions seek practical information and guidance for what they can implement now to plan for anticipated rising seas.

Local coastal planners can benefit from practical comparisons between competing adaptation strategies. Specifically, comparisons between similar strategies can reveal the tradeoffs and true costs relevant to implementing any specific set of strategies. For instance, comparing a seawall with a beach nourishment project reveals distinct ecological impacts and monetary costs of these competing strategies. Further, a local community might be interested in comparing a certain category of strategies (e.g., only nature-based solutions). To foster these comparisons, this methodology used a modified typological approach, and the traditional goal-based framework was largely eschewed. The approach adopted grouped strategies into three method-based categories: (1) engineered; (2) legal and regulatory; and (3) financial. This method-based approach allows similar, competing strategies to be compared with one another (e.g., an engineered solution could be compared with other engineered solutions). While these three categories may seem mutually exclusive, several strategies likely fit in more than one group.

To narrow the number strategies to a more manageable targeted list, the team garnered certain data points and identified specific filtering criteria, based on commentary from adaptation practitioners. The broad definition of coastal adaptation strategies adopted for this project encompassed many strategies. Because only certain strategies have been pursued to date, and only certain additional strategies are being investigated for future application, this project focused on developing a non-exhaustive list of strategies that would be most helpful to decisionmakers. Feedback received directly from local communities was used to highlight especially germane coastal adaptation strategies. The team mindfully avoided investigating duplicative strategies. For example, *riprap*—large loose stones used to reduce wave energy—was investigated, but the similar coastal adaptation strategy *revetment*—a barricade of sandbags or a concrete wall—was not.

2.4. Limiting and enabling conditions of these strategies

“Conditions” are the physical, political and legal characteristics of a coastal area subject to coastal adaptation strategies. For coastal adaptation purposes, it is helpful to divide these conditions into spatial and non-spatial categories. These conditions are important because they tend to limit or enable the feasibility and suitability of adaptation strategies. A non-exhaustive list of spatial conditions includes: (1) geomorphologic features; (2) zoning restrictions; (3) current land uses; (4) natural habitats; and (5) political boundaries and jurisdictional factors [6]. Non-spatial conditions include: (1) cultural attachment and values; (2) “not in my backyard” or “NIMBY” perspectives; (3) “Takings” challenges; (4) cost concerns; and (5) political will [6]. Additional conditions that inform coastal adaptation decisions include population density [6] and socioeconomic conditions [12].

2.5. Spatial analysis: identifying feasible place-based climate adaptation strategies

In a Geographic Information System (GIS), the team compiled mapped features representing the biophysical, legal, and ecological factors that identify feasible coastal adaptation strategies to further understand the role of spatial conditions stated above. Next, the suitability of coastal adaptation strategies was investigated in two distinct ways—strategy and geography. First, a specific adaptation *strategy* was selected and then considered within a geography to determine where in a given location the adaptation strategy was suitable. Alternatively, a specific *geography* can be chosen and then a subset of coastal adaptation strategies identified based on the characteristics of that location. The two lenses, strategic and geographic, represent complementary ways that coastal adaptation strategies can be investigated across space. While the former might be useful for state agencies or non-governmental organizations seeking to implement specific strategies, it is less useful for a local community that has to make practical coastal adaptation decisions within its jurisdictional borders based on competing tradeoffs of possible strategies. To enable local communities to identify feasible locations for specific strategies, the adopted methodological framework focused on the strategy-based approach while utilizing an online viewer such that a user can zoom in on a specific geography for greater detail.

2.6. Spatial coverage, data and mapping units to evaluate adaptation strategies and visualize findings

The spatial coverage of this project's analysis encompassed the coastal zone of California. California's coastal zone is a legally defined area, delineated by the legislature, extending seaward three miles and landward several hundred feet in urban areas to up to five miles in some

[1] Policy briefs are hosted on this webpage: https://oceansolutions.stanford.edu/coastal-adaptation-policy-briefs.

rural coastal regions [13]. The project team leveraged existing spatial data within the CCC's jurisdiction of the Pacific Coastal Zone of California. This area excludes San Francisco Bay, a region within the jurisdiction of the Bay Conservation and Development Commission and one where climatic forcing conditions (wind and waves) and sea level rise impacts have previously been mapped using locally-calibrated models designed for large bays and estuaries.[2]

The California coastline features diverse habitats including dense kelp forests, wetlands, and expansive beach and dune systems. The team focused on the coastal vulnerability analysis of these biogenic habitates, referred to as “nature's shield” by Arkema and colleagues [1], that reduce coastal exposure to storm-induced flooding and erosion and can be exacerbated by rising sea levels and king tides. Coastal vulnerability information was compiled by first calculating a physical exposure index based on the geographic extent of habitats known to provide natural protection (i.e., wave attenuation) and seven additional biological and physical variables at each shoreline segment. The resulting exposure index was then coupled with social and biophysical metrics to highlight nature-based climate adaptation options, including restoration or preservation of dune and wetland habitats. Emphasizing these areas helped identify where certain nature-based strategies were most feasible (e.g. dune restoration, wetland restoration) and currently delivering ecosystem service co-benefits to nature and people such as coastal protection, recreation opportunities, and blue carbon sequestration.

The shoreline of California's 15 outer coast counties was segmented into segments at 250 m in length, using the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) coastal vulnerability assessment tool and OpenStreetMap polygons for all land areas of the world, clipped to California (http://openstreetmapdata.com). These 250 m segments became the basis of subsequent analyses as well as the minimum mapping unit for the feasibility logic statements. The team further summarized the coastal units with hexagonal cells, 1 km in length ($n = 2201$). The resulting hex cells were organized into a spatial database to communicate feasibility of individual strategies at the state and county scales (see next section: 2.7 Developing feasibility statements). Natural habitats displayed as irregular polygons, InVEST coastal exposure index scores as linear segments, and adaptation strategies as hexagons served to differentiate the outputs in the online viewer display and static map products (Fig. 1).[3]

The project team compiled coastal zoning, land use layers (developed vs. undeveloped land), and geomorphologic features known to influence the feasibility of each potential climate adaptation strategy. To map zoning types throughout the coastal zone, we acquired zoning layers piecemeal from a total of 54 coastal municipalities and counties in California. Next, the team determined and consolidated hundreds of unique zoning codes from each source (e.g., R-1 = single family residence) based on ordinance documents, and then distilled those zones into five general zoning categories: (1) Agriculture; (2) Residential; (3) OpenSpace/Parks/Public Land; (4) Commercial/Industrial; and (5) Special Use/Uncategorized. The results from each agency source were unified as a single zoning layer for the state. The zoning categories differed by source, county and local jurisdiction, such that incomplete GIS layers (e.g., shoreline armoring database) did not match the ordinance documents for the respective city or county. After these challenges were addressed, the team integrated the zoning information from each agency source into a single zoning layer for the state.

The project included four coastal geomorphologic features known to influence feasibility of strategies: (i) *bluff top* - high elevation lands near the coast, often fronted by a rocky or sandy beach or no beach at all; (ii) *beach front* - low elevation lands comprised of sand or rocks of various grain sizes; (iii) *estuary* - low-lying lands comprised of small-grain sands that may also be fronted by rivers, marshes, bays, or lagoons; (iv) *hard coast* - coastal features that are highly resistant to erosion either from natural low-erosion rock or built structures. These four features adopted into the analysis stemmed from recently published materials and through dialogue with CCC staff [9,14]. Further, “hard coast” was added to reflect the amount of hardened shoreline, including natural or built structures that are highly resistant to erosion. To incorporate four geomorphologic features into the viewer for outreach, they were related to geomorphologic types described in NOAA's Environmental Sensitivity Index (ESI) (Table 1).

2.7. Developing feasibility statements

A prioritized list of California-relevant coastal adaptation strategies was inventoried and assessed for site suitability using GIS. Based on a literature review of existing laws and policies, information from government agencies and other stakeholders, guidelines were drafted for the three categories of adaptation strategies. Next, in-situ feasibility was codified using strategy-specific logic statements (Table 2). For example, a living shoreline strategy has necessary conditions including emergent wetland habitat *and* developed land use *and* shoreline geomorphology where it is sufficient to have either beachfront *or* estuary *or* hard coast. To connect each adaptation strategy to spatially-relevant enabling and limiting conditions, the team designed a look-up table to relate coastal segments (rows) with key attributes (columns). For each strategy, the following were drafted: a) a concise definition in layman's terms, b) a list of factors that either enable or limit successful implementation, and c) logic statement to define the spatial queries conducted in GIS and automated with the Python programming language. These logic statements filtered nearly 7,500 coastal segments into a more tractable set of options by strategy.

Map outputs enabled the research team to visualize adaptation options across the area of interest and articulate a response to the place-based question: What are the physical parameters that dictate whether a strategy is possible in a given location? Results were summarized using the same 250 m segments from the coastal vulnerability assessment and resampled at 1 km hexagon cells to differentiate this layer from other analytical outputs displayed in the online viewer. An adaptation strategy was deemed “feasible” if at least one 250 m segment intersected the larger 1 km cells.

3. Results

Extensive engagements and discussions with local coastal planners at the city, county, and state scales revealed recurring requests for a means to distill complex interactive components relevant to adaptation planning. Planners expressed interest in a structured approach to filter their options to an abridged list of what would actually be feasible in a given location based on the coastal setting. Statewide engagement meetings with coastal planners and managers revealed the importance of identifying possible adaptation strategies along the California coast, with an emphasis on feasible options for local jurisdictions facing near-term climate change impacts.

Results in the form of map layers and storylines highlight where 15 climate adaptation strategies, prioritized by state and local agencies, are feasible along California's outer coast. Findings from legal analyses for each strategy were synthesized as considerations, tradeoffs, and examples of successful implementation. This analysis found that connecting a statewide zoning layer to these adaptation options filled a critical data gap because the quality of zoning information varies greatly across jurisdictions. Our zoning product was the result of acquiring county- and municipal-level data piecemeal and merging hundreds of unique land use codes into five general zoning categories.

[2] For example, see spatially-relevant adaptation planning information for the San Francisco Bay hosted through Our Coast Our Future (http://data.pointblue.org/apps/ocof/cms/) and Adapting to Rising Tides (https://www.adaptingtorisingtides.org/).

[3] https://oceansolutions.stanford.edu/coast-adapt.

Table 1
Conversion Key Between Environmental Sensitivity Index and Geomorphology Rank. The geomorphologic types from the Environmental Sensitivity Index are translated into a binary code for four geomorphologic features and then scored for erodability (2–5)—with higher ranks signifying higher erodability.

Geomorphology Type (from Environmental Sensitivity Index)	Blufftop	Beaches	Estuary	Hard Structure	Geomorphology Rank
Exposed Rocky Cliffs	1	0	0	0	2
Exposed Rocky Cliffs/Boulder Talus Base	1	0	0	0	2
Exposed rocky cliffs/Boulder rubble	1	0	0	0	2
Exposed Rocky Cliffs/Coarse-Grained Sand to Granule Beaches	1	1	0	0	2
Exposed Rocky Cliffs/Fine- to Medium-Grained Sand Beaches	1	1	0	1	2
Exposed Rocky Cliffs/Mixed Sand and Gravel Beaches	1	1	0	0	2
Exposed Seawall	0	0	0	1	2
Exposed Seawall/Coarse-Grained Sand to Granule Beaches	0	1	0	0	2
Exposed seawall/Fine- to Medium -Grained Sand Beaches	0	1	0	0	2
Exposed seawall/Fine- to Medium -Grained Sand Beaches/Exposed wave cut platforms in bedrock	1	1	0	0	2
Exposed Seawall/Fine- to Medium-Grained Sand Beaches	0	1	0	1	2
Exposed Seawall/Fine- to Medium-Grained Sand Beaches/Wave Cut Rocky Platforms	1	1	0	1	2
Exposed Seawall/Mixed Sand and Gravel Beaches	0	1	0	1	2
Exposed seawall/Mixed sand and gravel beaches/Exposed wave cut platforms in bedrock	1	1	0	1	2
Exposed Seawall/Wave Cut Rocky Platform	1	0	0	1	2
Exposed wave cut platforms in bedrock	1	0	0	0	2
Sheltered Man-Made Structures	0	0	0	0	2
Sheltered Man-Made Structures/Sheltered tidal flats	0	0	1	0	2
Wave Cut Rocky Platforms	1	0	0	1	2
Wave Cut Rocky Platforms/Fine- to Medium-Grained Sand Beaches	1	1	0	1	2
Gravel beaches/Exposed rocky cliffs	1	1	0	0	3
Gravel Beaches/Exposed wave cut platforms in bedrock	1	1	0	0	3
Gravel Beaches/Fine- to Medium-Grained Sand Beaches/Wave Cut Rocky Platform	1	1	0	1	3
Gravel Beaches/Mixed Sand and Gravel Beaches	0	1	0	1	3
Gravel Beaches/Wave Cut Rocky Platforms	1	1	0	0	3
Mixed Sand and Gravel Beaches/Wave Cut Rocky Platforms	1	1	0	0	3
Riprap	0	0	0	1	3
Riprap/Coarse-Grained Sand to Granule Beaches	0	1	0	1	3
Riprap/Exposed Tidal Flats	0	0	1	0	3
Riprap/Exposed wave cut platforms in bedrock	1	0	0	0	3
Riprap/Fine- to Medium -Grained Sand Beaches	0	1	0	0	3
Riprap/Fine- to Medium-Grained Sand Beaches	0	1	0	1	3
Riprap/Sheltered tidal flats	0	0	1	0	3
Salt and brackish water marshes	0	0	1	0	3
Salt and brackish water marshes/Exposed Tidal Flats	0	0	1	0	3
Salt and brackish water marshes/Fine- to Medium -Grained Sand Beaches	0	1	1	0	3
Salt and brackish water marshes/Sheltered tidal flats	0	0	1	0	3
Salt Marshes	0	0	1	0	3
Salt Marshes/Exposed Tidal Flats	0	0	1	0	3
Salt Marshes/Sheltered Tidal Flats	0	0	1	0	3
Sheltered riprap	0	0	0	1	3
Sheltered riprap/Sheltered tidal flats	0	0	1	0	3
Sheltered rocky shores/Mixed sand and gravel beaches/Exposed wave cut platforms in bedrock	1	1	0	0	3
Sheltered Tidal Flats/Salt Marshes	0	0	1	0	3
Unknown/Salt and brackish water marshes	0	0	1	0	3
Boulder Rubble/Mixed Sand and Gravel Beaches	0	1	0	0	4
Coarse-Grained Sand to Granule Beaches/Exposed wave cut platforms in bedrock	1	1	0	0	4
Coarse-Grained Sand to Granule Beaches/Wave Cut Rocky Platforms	1	1	0	0	4
Fine to medium grained sand beaches/Exposed wave cut platforms in bedrock	1	1	0	0	4
Fine to medium grained sand beaches/Sheltered Rocky Shores	1	1	0	0	4
Fine to medium grained sand beaches/Sheltered tidal flats	0	1	1	0	4
Fine- to Medium-Grained Sand Beaches/Wave Cut Rocky Platforms	1	1	0	0	4
Gravel Beaches	0	1	0	0	4
Mixed Sand and Gravel Beaches/Exposed wave cut platforms in bedrock	1	1	0	0	4
Mixed Sand and Gravel Beaches/Sheltered Rocky Shores	0	1	0	0	4
Mixed Sand and Gravel Beaches/Sheltered tidal flats	0	1	1	0	4
Sheltered Rocky Shores	0	0	0	1	4
Sheltered Rocky Shores/Fine to Medium -Grained Sand Beaches	0	1	0	0	4
Sheltered Rocky Shores/Mixed Sand and Gravel Beaches	0	1	0	0	4
Sheltered Rocky Shores/Mixed Sand and Gravel Beaches/Sheltered tidal flats	0	1	1	0	4
Sheltered Rocky Shores/Sheltered tidal flats	0	0	1	0	4
Coarse-Grained Sand to Granule Beaches	0	1	0	0	5
Exposed Tidal Flats	0	0	1	0	5
Exposed Tidal Flats/Fine to Medium -Grained Sand Beaches	0	1	1	0	5
Fine to Medium -Grained Sand Beaches	0	1	0	0	5
Fine to Medium -Grained Sand Beaches/Exposed Tidal Flats	0	1	1	1	5
Fine- to Medium-Grained Sand Beaches	0	1	0	0	5
Gravel Beaches/Coarse-Grained Sand to Granule Beaches	0	1	0	0	5
Gravel Beaches/Fine to Medium -Grained Sand Beaches	0	1	0	0	5
Gravel Beaches/Fine- to Medium-Grained Sand Beaches	0	1	0	1	5
Mixed Sand and Gravel Beaches	0	1	0	0	5
Mixed Sand and Gravel Beaches/Fine to Medium -Grained Sand Beaches	0	1	0	0	5
Sandy Beach	0	1	0	1	5
Sheltered tidal flats	0	0	1	0	5
Sheltered tidal flats/Salt and brackish water marshes	0	0	1	0	5

Table 2
Coded Feasibility and Logic Statements. Selected adaptation strategies are organized by category with noted feasibility and logic statements. This includes the boolean expressions for four spatial features: habitat, zoning type, development type, and geomorphology.

Category	Adaptation Strategy	Feasibility Statements	Habitat		Zoning Type					Dev't Type		Geomorphology				Logic Statements
			dunes	marsh	resident	agriculture	comm_ind	park_open	uncategor-ized	developed	undeveloped	blufftop	beach-front	estuary	hard_-coast	
Engineere-d	Beach Nourishment	Beach nourishment can occur at any of the zoning types, yet it ismore common in front of residential or public property. There would be very limited value from nourishing a beach in front of undeveloped land. Geomorphologic features include beaches and estuaries or over hardened structures, but not bluff tops.								1 must			1 can	1 can		S = (developed = 1) AND ((beachfront = 1) OR (estuary = 1))
	Dune Restoration	Dune restoration strategies are effective where dunes are present. Zoning types include residential, agricultural, parks/open space/public, or uncategorized. Geomorphology includes estuaries or some hardened coastal areas.	1 must										1 can	1 can		S = (dunes > 1) AND ((beachfront = 1) OR (estuary = 1))
	Elevation of Structures	Feasible only where currently developed with structures. More suitable for residential single family homes than for larger structures and developments. Structures could be elevated at all geomorphologic types other than bluff tops as there would be no benefit to elevating a bluff top property.								1 must		0 can	1 can	1can		S = (developed = 1) AND (blufftop = 0) AND ((beachfront = 1) OR (estuary = 1))
	Living Shorelines	The presence of wetland habitats increases the feasibility of a living shoreline system, especially when proximate to developed land. Living shorelines are rarely included along blufftop edges.		1 must						1 must			1 can	1 can	1can	S = ((marsh > 0) AND (developed = 1) AND ((beachfront = 1) OR (estuary = 1) OR (hard_coast = 1))
	Riprap	Riprap would most likely be used only in front of developed land. All geomorphology types could be relevant locations for use of riprap.								1 must		1can	1 can		1 can	S = (developed = 1) AND ((blufftop = 1) OR (beaches = 1) OR (hard_coast = 1))
	Seawalls	Seawalls would most likely be used only in front of developed land. All geomorphology types could be relevant locations for use of seawalls.								1 must		1 can	1 can		1 can	S = (developed = 1) AND ((blufftop = 1) OR (beaches = 1) OR (hard_coast = 1))
	Wetland Restoration	Wetland restoration projects should include areas with existing wetland habitat or areas conducive to wetland systems. Wetlands can be restored in estuary areas.		1 can										1can		S = (march > 1) AND (estuary = 1)

(*continued on next page*)

Table 2 (*continued*)

Category	Adaptation Strategy	Feasibility Statements	Habitat		Zoning Type					Dev't Type		Geomorphology				Logic Statements
			dunes	marsh	resident	agriculture	comm_ind	park_open	uncategorized	developed	undeveloped	blufftop	beachfront	estuary	hard_coast	
Financial	Buyout Programs	Buyout programs or downzoning efforts are more common in residential, agricultural, or industrial areas. These would occur only on developed lands.			1 can	1 can	1 can			1 must	0 can					S = ((residential = 1) OR (agriculture = 1) OR (comm_ind = 1)) AND ((developed = 1) OR (undeveloped = 0))
	Conservation Easements	Conservation easements are more likely near open, undeveloped spaces rather than built locations (developable vs. less developable). This includes agricultural areas, open spaces, or uncategorized land.				1 can		1 can	1 can		1 must					S = ((agriculture = 1) OR (park_open = 1) OR (uncategorized = 1)) AND (undeveloped = 1)
	Geologic Hazard Abatement Districts (GHADS)	GHADs are most common in residential areas, but can be near other commercial or agricultural areas. They are less likely in parks or open spaces as they are formed by local land owners, yet they are still possible in those locations.			1can	1can	1can	1can		1must	0can					S = ((residential = 1) OR (agriculture = 1) OR (comm_ind = 1) OR (park_open = 1)) AND (developed = 1) AND (blufftop = 0)
	Transfer of Development Rights (sending areas)	Transfer of development rights (TDR) "sending" areas could be prioritized in areas that are both: (1) undeveloped; and (2) most susceptible to sea level rise, including residential, agricultural, and commercial land.			1 can	1 can	1 can				1must					S = ((residential = 1 OR (agriculture = 1) OR (comm_ind = 1)) AND (undeveloped = 1)
Legal and Regulatory	Development Moratoria	Development moratoria can be used in residential, Ag, commercial, or open space land; yet they would rarely be used in uncategorized land. They can be pursued on developed or undeveloped land.			1 can	1 can	1 can			1 can	1 can					S = ((residential = 1) OR (agriculture = 1) OR (comm_ind = 1)) and ((developed = 1) OR (undeveloped = 1))
	Rebuilding and Redevelopment Restrictions	Zoning type depends more on extent of hazard areas; however, downzoning is more common in residential, agricultural, commercial, and public areas. Redevelopment restrictions would only be used on developed lands.			1 can	1can	1 can	1 can		1 must						S = ((resident = 1) OR (ag = 1) OR (comm_ind = 1) OR (park_open = 1)) AND (developed = 1)
Additional Topics	Public Trust Doctrine	These topics are relevant throughout the coast.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Overlay Zones		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Takings Concerns		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Trigger Language		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

During engagement meetings with state and local planners, these audiences repeatedly requested a means to distill disparate sources of information into meaningful units for adaptation planning. The project team's viewer satisfies this need by visualizing feasible strategies based on zoning, habitat, land use and legal requirements.

This prototypical approach aims to link coastal land use and policy information for the purpose of systematically filtering climate adaptation strategies in terms of their suitability. Each strategy was evaluated according to its unique policy characteristics and then displayed in the viewer as engineered, financial, or legal/regulatory options. For some financial and legal strategies, feasibility spanned the majority of California's coastline (e.g., Transfer of Development Rights and Buyout Program, 74% and 70% of total length respectively). Others were linked to only one factor, e.g., Living Shorelines with existing marsh and Dune Restoration Project with dune habitat. A few strategies—e.g., Overlay Zones and Trigger Language—were determined to be applicable everywhere, thus we did not evaluate their location-specific feasibility. While full-state applicability may not be highly informative at the local level, it can be helpful at the state level to know what can be broadly applicable—showing the multi-scale benefit of this spatial approach.

Visualizing strategies in the context of other options and spatial reference information such as natural habitats, zoning, and land use made what drives the site-level feasibility of a given strategy and the tradeoffs associated with implementation more explicit to the target audience. It was notable that Elevation of Structures as a strategy can only be informed by incorporating a spatial layer indicating the present location of existing hard structures. Conservation Easements are only appropriate in undeveloped areas as economic investment informs suitability. For a property that is currently developed, it is a much tougher argument to move—i.e. retreat—where the landowner possesses financial investment backed expectations.

3.1. Feasibility statements

Feasibility statements for each strategy served to connect adaptation strategies to spatial features. These statements define in simplified language where a specific strategy is feasible—or possible to implement—and the underlying logic why. For instance, elevating structures would only be a feasible strategy where a current structure exists on developed land. Accordingly, the model identifies this strategy as feasible in developed areas of the California coastline. Yet feasibility does not necessarily entail suitability. Instead, while a strategy might be feasible in many locations along the coast, these strategies would likely not be suitable in many of these locations due to other factors. Likewise, the mere feasiblility of a strategy in a location is less helpful than holistically considering both its feasibility and its suitability for that location. For example, most large buildings would not be *suitable* for elevation due to engineering and cost considerations. The model similary identifies wide ranges of the California coastline as feasible for seawalls. Again, this output does not mean that these strategies are suitable in all of these locations. Similarly, environmentally harmful strategies like seawalls should be branded as such out of hand and likely would not be suitable or favored in most locations along the coast for this reason. The online results viewer visualizes potential locations for implementing strategies based on the presence of biogenic habitats, zoning information, coastal exposure results, as well as the results of the feasibility logic statements for each proposed adaptation strategy.

3.2. Suitability conditions

For local context, the next tier of decisions would focus on how suitable—or appropriate—a specific strategy is in a given setting. Again, for example, all but the most valuable and immovable residential homes are likely not suitable for elevation, even though it may be feasible. This research was conducted in conjunction with other efforts in which the team compiled seventeen coastal adaptation briefs designed to further inform decisionmaking. The spatial component adds feasibility criteria for each adaptation strategy while the coastal adaptation briefs drafted address suitability considerations [15]. Specifically, the viewer shows where specific adaptation strategies are feasible to implement in a given location. This resource is designed to assist planners and legal counsel at local governments with these emerging coastal issues and hazards. The policy briefs are a targeted resource developed to provide additional considerations that address the suitability—or likelihood of uptake—for each strategy. Simply put, feasibility and suitability should be considered together by decisionmakers. Specifically, the briefs provide descriptions, tradeoffs, legal considerations, and case study examples from California or the U.S for each proposed strategy.

4. Discussion

The inherently place-based nature of local land use planning highlights the need for a dynamic geospatial approach as a means to map and communicate feasibility and suitability considerations for adaptation planning. A common challenge for policy and decisionmakers is identifying strategies that both safeguard people and property from coastal hazards and also preserve or enhance the ability of natural habitats to provide ecosystem service co-benefits to nature and people into the future. This project found that a simple screening approach is often a necessary first step towards advancing adaptation strategies from planning to implementation. The interactive online viewer tool spans the boundary between climate science, adaptation planning, and land use policy to support state- and county-level agencies tasked with evaluating the feasibility of different adaptation strategies as well as local planners considering a smaller subset of options in specific locations.

4.1. Role of habitats in natural protection

Diverse habitats along California's coastline (e.g., seagrasses, kelp forests, salt marshes, dunes) play an important role in reducing exposure to storm impacts while also providing a variety of additional services [3,5]. As coastal development and rising sea levels degrade or damage these habitats, the neighboring coastlines, communities, and infrastructure become increasingly vulnerable to storms. An important challenge for decisionmakers is determining the best climate adaptation strategies that protect people and property while also protecting the ability of coastal habitats to provide a protective service into the future. Understanding the role that nearshore habitats play in the protection of coastal communities is increasingly important in the face of a changing climate and rising seas.

The nuances of pursuing natural protection strategies can be seen by interpreting the viewer results for feasible dune restoration sites in Dillon Beach (Marin County) and Surfer's Beach (San Mateo County). In the viewer, both locations are noted as feasible for dune restoration projects to reduce exposure to erosion or inundation. However, when determining suitability, one must also consider the proximity of the coastline to a major transportation conduit as Surfer's Beach is a few meters from Highway 1. The importance of this coastal corridor—-amongst other locally relevant factors—shifts the balance towards protection through longer-term means such as the recently updated extent of riprap.

4.2. Viewer reasoning

Local land use planning is inherently spatial, which highlights the value of utilizing a map-based viewer as a means to portray feasibility and suitability considerations for adaptation planning. This decision-support tool provides a means for local planners to consider multiple variables in one comprehensive site. The tool was designed to consider two primary use-cases: First, it can be applied at over large areas (small scale) to identify a subset of strategies that are feasible based on the local context of a site or area and desired outcomes defined by stakeholders. Essentially, this is reflected by the user indicating a strategy of interest, and the viewer then shows the locations where a strategy is feasible. Second, the user can zoom in on a specific city or county (large scale) to screen high-value areas at risk (socially or ecologically) and then identify one or more feasible and suitable adaptation strategies.

4.3. Groundtruthing data and future monitoring

This demonstration connecting spatial and policy analysis methods to address factors that promote the feasibility and suitability for implementation of adaptation strategies could be carried into the future by subsequent researchers. Groundtruthing data to validate the research findings and confirm certain assumptions is an important next step. For example, state agencies and researchers are currently validating the shoreline armoring database that fed into the coastal exposure analysis with InVEST. Additional feedback from local governments can also inform future iterations of this work. In hindsight, a structured, periodic feedback schedule from local governments would have greatly streamlined the process. Similarly, additional resources and time for conducting formalized surveys of prospective end users would have likely improved the analytical outputs and resulting products. Additional wish list items include the appointment of an advisory council, composed of planners and other interested parties, who could have helped hone the findings and products of this study.

This research focused on informing the progression from coastal adaptation planning to strategy implementation along California's coastline. A missing component of this work to date is continued monitoring of the value these resources provide for active coastal adaptation decisions. Monitoring uptake and use can help evaluate these efforts and provide feedback for future iterations of similar work on coastal adaptation in California and beyond. Another aspect of this work that should be monitored is how helpful it is to highlight large sections of coastline as feasible for particular strategies. The model highlights a high proportion of total coastline as feasible for certain strategies, such as seawalls. While these strategies should only be considered with an eye toward their suitability in addition to their feasibility, they should also be recognized as being potentially environmentally damaging compared to certain competing strategies. A suitability analysis would likely heed this disclaimer, and these factors should be recognized from the outset of this work.

4.4. Transferability

This research focuses on identifying factors that influence the likelihood of success of resilient adaptation in different coastal settings. The team has identified a subset of categories that can be mapped to narrow the scope of potential strategies. These decisions were based on engagement experience at multiple scales throughout the state and modified and replicated in other jurisdictions. Transferring this approach to a new geography or political jurisdiction will require a thorough understanding of the spatial and non-spatial enabling and limiting conditions specific to that new geography. Accordingly, initial due diligence will be necessary to build an engagement strategy and subsequent methodology to further define the suitability of specific strategies for a new area.

5. Conclusion

Through the use of spatially-mapped features as a proxy for coastal setting, a methodology to filter adaptation strategy options to a distilled list of relevant options in a given location was developed. This proof of concept approach can be a critical next step in advancing adaptation strategy planning to implementation. Specifically, this statewide assessment revealed where nature-based strategies can help protect the coastline while in other locations, policy-based approaches can help maintain adaptive capacity for future coastal planning decisions.

5.1. Linking spatial science and policy

Local governments often face dual priorities that include the need to protect people and property from the effects of climate change and the need to avoid legal controversies over their citizens' property rights. In order to address the former (planning for the coastal impacts) there is a demand for spatially explicit coastal vulnerability information over a large geographic area. For instance, maps of coastal vulnerability can highlight hotspots that facilitate an iterative dialogue with local planners, business owners, research institutes, and technical experts to ultimately support local communities in their adaptation planning [4]. A place-specific approach can also help avoid legal controversies, especially where public spaces border private coastal properties. Coastal vulnerability models and generalized, spatially explicit zoning data fulfill legal information needs. Local governments generally want to avoid litigation and property rights issues. Understanding in advance where local governments could implement strategies, like conservation easements or initiating large engineered strategies, is helpful.

Spatial adaptation planning can provide a place-specific context and planner-friendly tools to facilitate successful adaptation to climate change [16]. One challenge in linking spatial science to policy relates to the geographic scale of climate impacts as climate adaptation planning often operates at multiple spatial scales. Varying laws and local coastal programs across geographies might require individual local analyses of these issues. Regardless, when possible, the ability to visualize patterns of vulnerable areas overlaid with residential or economically important areas allows for better assessment of community needs. Standardized and spatially explicit data also facilitates coordinated and perhaps standardized regulatory frameworks from different agencies, such as the CCC and the Ocean Protection Council. Spatially explicit information provides the necessary local and legal context that may greatly inform climate adaptation planning that appropriately integrates locally-relevant legal language. In addition, establishing a time horizon for climate adaptation planning is also critical when considering impacts that play out over long temporal scales, as there is often a mismatch between the long-term implications of climate change and short-term climate adaptation planning horizons in coastal communities [4].

5.2. Climate adaptation planning for decisionmaking

Climate adaptation planning is a globally relevant issue, where the local context of adaptation solutions also needs to be considered. Ultimately, the goal here is to advance decision-making through federal and state guidance that is attentive to factors at play at the local scale. This work provides results that can inform climate adaptation planning at local scales in California, with the opportunity to transfer the results and lessons learned to the state, national and international levels. However, climate adaptation planning will primarily remain an issue that individual communities and regions must address at the local scale. Quality decision-making processes depend on having actionable alternatives, clear values and tradeoffs, and meaningful information. This effort aimed to frame the issue of adaptation planning by articulating a subset of alternatives with distilled information to support decisions. The tradeoffs for each decision will need to be weighed at the local-level to ensure that actions reflect the values of the community. In the future, space along the coastline will become increasingly limited due to sea level rise, likely exacerbating the intensity of conflict and the potential for social inequities in coastal access, unless preempted by thoughtful coastal planning [17]. Local governments can engage in climate change adaptation planning with an eye toward reducing social vulnerability as well, by being mindful of possible inequitable economic and social losses in coastal access associated with climate change [17].

5.3. Opportunity for legal or policy changes

This work analyzed these issues under currently existing laws and policies. However, these local, state and federal laws and policies might need to be amended to better facilitate coastal adaptation. While laws are typically not designed for nimble adjustments, there are significant opportunities for policy changes to foster coastal adaptation. Specifically, the Coastal Act might be amended to clarify certain ambiguities in it and to strengthen the CCC's authority to deal with these issues. Similarly, the National Flood Insurance Program (NFIP) could be modified so it no longer incentivizes rebuilding in increasingly precarious locations. The Community Rating System could be a vehicle for such modifications. The promising NFIP program provides incentives for coastal communities to receive credits that reduce flood insurance premiums by proactively reducing vulnerability to flood damage, including actions such as preserving open space or restoring natural habitats. Permitting can also be streamlined for nature-based adaptation strategies to promote these options. Finally, policymakers addressing these issues can design future policies that feature adaptive capacity mechanisms and principles built into them. The research performed through this project can help inform future coastal adaptation policymaking.

Declarations of interest

None.

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