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Adapting to Sea Level Rise: Insights from a New Evaluation Framework of Physical Design Projects

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ABSTRACT
Designers and engineers are developing proposals for physical projects to adapt coastal sites to future sea level rise related threats. This puts pressure on local and regional decision makers to develop strategic frameworks for prioritizing, permitting and funding such projects. However, no systematic evaluation tools exist for the full range of these innovative designs. We build on the literature to develop an evaluation framework that synthesizes two different approaches to categorize these proposals and provide insight for coastal managers and decision makers. We apply this framework to physical projects that address sea level rise in their design around the San Francisco Bay Area, a leading region in sea level rise adaptation. We find that these projects demonstrate a shift toward more habitat-focused strategies, which likely marks the beginning of a larger transformation of the coastal zone. According to our five-part evaluation tool, we also find that the projects' scores have improved over time, indicating that state agency work may be helping communities implement more flexible adaptation initiatives. Despite these positive signs, we also find that none of the projects achieved high marks in all five of the evaluation criteria. This finding indicates that there is a critical need for improvement in physical planning for adaptation to higher sea levels and associated impacts. Most importantly, we find that an evaluation framework such as the one used here can provide critical insights into the likely risks and benefits of proposed adaptation projects and their long-term implications for coastal zones.

KEYWORDS
Climate adaptation;
coastal management;
evaluation;
sea level rise;
shoreline designs;
transformation

Introduction

Decision makers at the local and regional scale are under increased pressure to move beyond vulnerability assessments and begin the process of adapting their communities to the threats of sea level rise. This pressure comes from the reality that climate change is accelerating the rate of sea level rise (Nerem et al. 2018), threatening more than 100 million people per year (Nicholls et al. 2007). Dense coastal development places major regional infrastructure at risk from sea level rise (Biging, Radke, and Lee 2012).

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Sea level rise will also elevate water tables along coasts, causing increased flooding from a combination of groundwater emergence and increased discharge rates (Bjerklie et al. 2012; Rotzoll and Fletcher 2013; Wahl et al. 2015).

Decision makers grappling with these future threats use various planning approaches (Carpenter 2020). Scenario analysis, which includes a participatory approach, is a powerful tool to integrate knowledge and scan the future in an organized way (Swart, Raskin, and Robinson 2004). Carl Steinitz developed a robust and flexible process using alternative futures in environmental planning that engages scientific experts, professionals and stakeholders (Ahern 2006; Steinitz 1990, 2012). The adaptation pathways approach (also called the route-map approach) allows planners to establish a desired set of future conditions, map out different sequences of steps (paths) to achieve those conditions, and tipping points that determine when certain paths should be followed (Reeder and Ranger 2011; Walker, Haasnoot, and Kwakkel 2013).

All strategic decision-making processes that balance costs, risks, and rewards require a deep analysis of the landscape context and the potential for physical projects to confer greater resilience. Coastal communities are starting to implement piecemeal physical adaptation projects, creating an urgent need to understand the ability of these projects to enhance resilience (Sutton-Grier, Wowk, and Bamford 2015). For example, the U.S. Climate Resilience Toolkit features case studies from California to Massachusetts in which tidal wetlands, dunes and coastal roads have been realigned locally in response to high beach erosion rates (2015). In this paper, we adopt the broad understanding of physical projects defined by the International Union for Conservation (IUCN)'s concept of Nature based Solutions (NbS): "actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al. 2016).

We propose a synthesis of two different evaluation methods to assess local physical adaptation projects. One method draws on multi-objective optimization theory and considers how a project alters the future transformability of a coastal landscape. The second focuses on the risks included in the design plans for the projects. We subsequently apply this synthetic framework to the San Francisco Bay Area (Bay Area) to test its usefulness as a method of characterizing local adaptation proposals.

Adaptation evaluation framework

Here we focus on physical projects for sea level rise adaptation (see Table 1). The conventional approach to coastal protection has focused on engineered (or 'grey') interventions such as sea walls and levees (Hill 2015; Temmerman et al. 2013). These interventions result in habitat loss and declines in the abundance of aquatic organisms (Sutton-Grier, Wowk, and Bamford 2015). They are also associated with human fatalities and property damage when the infrastructure failed suddenly (Ashley and Ashley 2008). Today there is a growing recognition that nature-based (or 'green') solutions (NbS) can complement these traditional approaches (Hobbie and Grimm 2020). Here we use the IUCN definition of NbS, which is "actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively

Table 1. Overview physical projects for climate change adaptation.

Project Name (#) Source	Physical Context (sq kilometer)	Key Features	Stage
Aramburu (1) Audubon CA (2010)	Island nature preserve (0.9)	• Restore beach habitat • Design beach retention features • Build seal access channel • Regrade slopes	Done—Approved & fully built
Novato Creek (2) SFEI (2015)	Baylands (35.1)	• Restore wetlands • Elevate roadway • Enhance hydrologic connectivity • Improve sediment management	Early—Initial vision is developed
Oro Loma (3) OLSD (2015)	Public infrastructure land (0.2)	• Design lower height levee • Develop ecotone slope • Create hydrologic connectivity	Early—Experimental stage
South Bay Shoreline (4) USACE (2015)	Baylands (17.2)	• Build a levee • Restore wetlands • Improve public access	Late—Mid
San Francisquito Creek (5) SFCJPA (2012)	Baylands (1.1)	• Build floodwalls • Restore levees • Widen fluvial channels • Restore wetlands	Late—Mid
Mission Bay (6) SPUR (2016)	Urban—heavily developed (3.0)	• Multiple design options include: • Levees • Elevating and retreating • New bayward waterfront • Tide gates	Early—Mid
Treasure Island (7) SFPD (2011)	Urban—heavily developed (2.0)	• Raise new development grade • Raise perimeter elevation • Raise storm drain infrastructure	Done—Approved & phase 1 is fully built

and adaptively, simultaneously providing human well-being and biodiversity benefits." In contrast, the term "green infrastructure" is sometimes limited to urban areas (Benedict and McMahon 2002) or is defined as simply "an interconnected network of green space" (Tzoulas et al. 2007). The term nature-based solutions (NbS) more accurately describes the types of physical projects being considered in this paper, where functional ecosystem goals are typically an explicit rationale.

Geographic scale is also an important attribute of adaptation projects. Our evaluation considers community-wide projects that are at least one square kilometer in area, or are the size of the entire relevant landform (i.e., an entire island). These large projects begin to achieve the scale needed to adapt to sea level rise in coastal communities (Hobbie and Grimm 2020). We made one exception, which was to include a unique demonstration project (the Oro Loma Project, #3) for a new type of levee that is combined with a broad salt marsh ecotone, nourished by treated wastewater. We included this project because many regional experts have described this as a preferred adaptation strategy for use along key shoreline locations in the San Francisco Bay Area.

Our emphasis on NbS derives from the pressing need for a deeper understanding of these strategies, which offer a wide range of multiple benefits, from flood reduction and water quality benefits to ecosystem and biodiversity support. Physical infrastructure projects that rely on dynamic landscapes such as marshes and beaches are also receiving increased attention from broader audiences due to large-scale collaborative efforts such as the Federally-sponsored Resilient by Design Competition in the New York metropolitan area, following Hurricane Sandy (Lochhead 2017). Regulatory agencies face an increased need to understand and evaluate these NbS coastal infrastructure projects (Reiblich, Wedding, and Hartge 2017). For example, researchers have identified the California Environmental Quality Act (CEQA) as a procedural opportunity for local governments to evaluate proposed development projects and require them to be resilient to sea level rise (Herzog and Hecht 2013). With an increased focus on NbS physical infrastructure, local, regional, state and Federal agencies need ways to review their transformative potential and assess whether all of the significant risks have been addressed. Ideally, these high-level reviews would contain clear logical reasoning that could inform the strategic directions that project proponents are encouraged to take, before significant design investments are made. For instance, indicating whether seawalls can be built on the landward side of beaches or tidal wetlands if they would seriously impact the health and diversity of those wetlands in the future, as sea levels rise.

Ecosystem services evaluation is one example of a common framework for assessing physical interventions is (Costanza et al. 2000; Granek et al. 2010). This framework builds a bridge between environmental science, engineering, and economic valuation. It has been used in many contexts to assess the effectiveness of plans and strategies for coastal protection (Arkema et al. 2013; Sutton-Grier et al. 2018). For example, in one assessment, a team worked extensively with the government of Belize to model the services provided by corals, mangroves, and seagrasses (Arkema et al. 2015). Extensive field data was gathered to quantify the potential effectiveness of coastal ecosystems as natural protection against flooding (Gedan et al. 2011; Narayan et al. 2016). In one example, a team of researchers analyzed field measurements in sixty-nine coastal habitats globally to understand the relationship between natural habitats and wave height reductions (Narayan et al. 2016).

Practitioners encounter a number of challenges when they apply the ecosystem services framework to decision making. Researchers have found that the complexity of a socio-ecological system can limit the applicability of this framework (Luisetti et al. 2014), since it requires extensive modeling and significant data collection efforts (Arkema et al. 2015; Chu et al. 2014). There are also major challenges in determining the value of ecosystem services in the absence of markets for these services (Luisetti et al. 2014). In the coastal context, wave attenuation and shoreline protection exhibit notable nonlinearities across time and space (Barbier et al. 2008; Gedan et al. 2011; Koch et al. 2009). These challenges make it extremely difficult to generalize the monetary value of physical interventions. Moreover, highly specific assessments of ecosystems services do not shed light on the degree to which a landscape is transformed by a physical project, and how that project might limit the future adaptability of a coastal area.

In contrast to the ecosystem services approach, we propose a more generalizable and strategic framework that characterizes adaptation proposals by how they will transform a site and the implications of that change for future resilience. Our approach builds on engineering design methods for representing a searchable “solution space” when multiple design objectives must be optimized (Mattson and Messac 2005). This method originated in the biological concept of evolutionary landscapes (Wright 1932) but considers the evolution of physical designs within a *n*-dimensional representation of key characteristics, rather than the evolution of organisms. It allows multiple solutions to be compared using multiple variables in a search for an optimal (Pareto) set (Kaisa Miettinen 1999).

Summarized in Figure 1, our framework is based on work originally presented by Hill (2015). A four-quadrant solution space defined by two variables is used to categorize the mix of physical elements along the shoreline of an adaptation proposal. The vertical axis is defined by the percentage of shoreline that is constructed (or proposed) with concrete and/or steel walls, versus the percentage of shoreline that is made up of loose material, such as sand and gravel (landforms). This distinction between

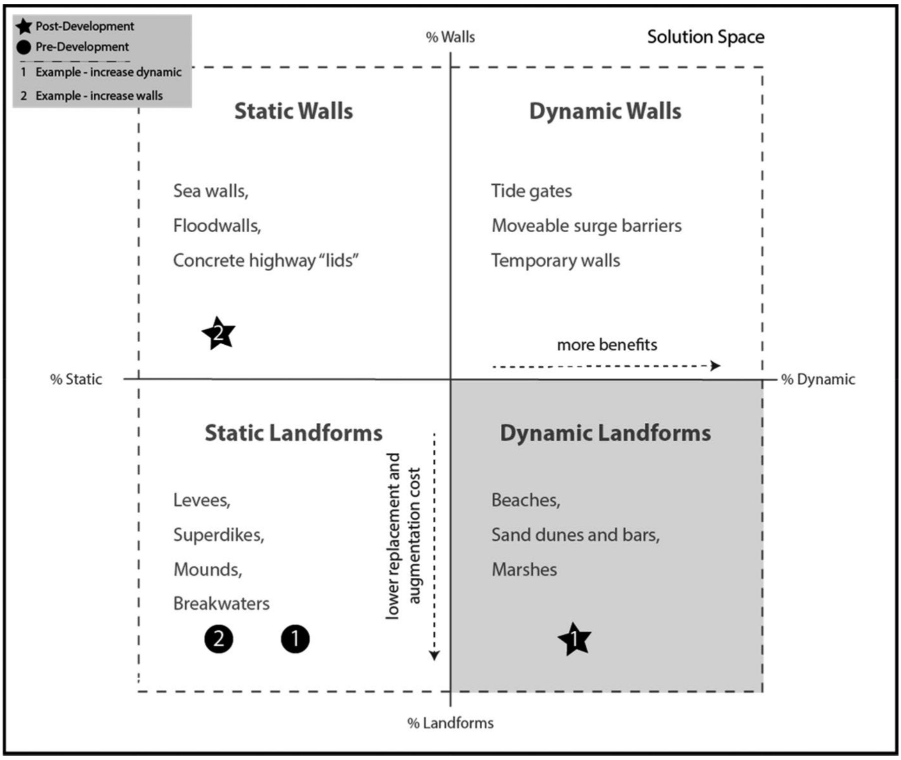

Figure 1. A typology that can be used to describe coastal protective infrastructure at the scale of an individual project, or as a description of the conditions in an entire region. The vertical axis is defined by the percentage of infrastructure that is built with concrete or steel walls versus the infrastructure that is built with landforms such as levees or beaches. The horizontal axis reflects the percentage of shoreline that is dynamic (designed to move) versus static (designed to remain in place). In this paper we use the typology to assess adaptation projects pre and post development. This figure shows an example of this application. Our assessment is shown in Figures 3 and 4.

materials is significant because walls are associated with significantly higher costs (Hirschfeld and Hill 2017; Jonkman et al. 2013) and represent a reduction in future flexibility, since the footings of walls are designed for a limited height. If the designed height of a wall must be exceeded in the future to respond to higher sea levels, the entire structure and its footings must be removed and replaced at significant expense. The horizontal axis of this solution space is defined by the percentage of the constructed (or proposed) shoreline that is dynamic (i.e., able to move, either mechanically or by natural processes) versus static (i.e., fixed in position and unable to move in response to processes). When a dynamic landform such as a tidal wetland is built with loose materials such as sand and silt, it moves in response to the energy of wind and waves. On the other hand, a static landform can be built with loose materials such as gravel that is designed to resist or redirect flooding as a rigid barrier.

The value of this typology is that it expands the choices for adaptation to include a wide variety of potential coastal structures, including both NbS and conventional walls and levees. It also allows decision-makers and designers to reflect on the extent to which a design could provide multiple benefits, such as ecosystem services, at the same time it provides flood protection. Habitat and recreational benefits are more frequently associated with landforms than with walls, for example. Finally, it highlights the relative transformability of different proposals. The bottom two quadrants (static and dynamic landforms) include the coastal structures that are the easiest to relocate or raise, since material can be added or removed without requiring complete replacement. The upper left quadrant – static walls – are typically single-purpose structures that are difficult to transform over time as sea levels continue to rise. These static structures do not provide multiple benefits, such as recreation, wildlife habitat, or other ecosystem services. The upper right quadrant includes mechanical storm surge barriers, which provide flexibility during their operational lifespan but must be removed and replaced if sea level rise exceeds their designed height.

In this paper, we used this typology to categorize specific physical adaptation projects that are proposed or have been built in the coastal zone of the San Francisco Bay Area. We used the typology to compare pre-adaptation and post-adaptation conditions at each project location. This comparison allows us to visualize the change in the landscape represented by the set of physical adaptation projects. We are able to assess the degree to which the set of projects adds (or removes) seawalls in the region, and the extent to which these projects increase or decrease the dynamic behavior of the coastal zone in terms of its position, elevation, or vegetation (Figure 1).

Our second step was to conduct an assessment of the design documents associated with physical adaptation projects, similar to other studies that have used multi-criteria assessments to evaluate plans (Baker et al. 2012; Woodruff 2016). Here we identified a list of key environmental risks that could lead to the failure of Bay Area adaptation projects. We grounded our evaluation criteria in the literature on climate science and adaptation planning through a process similar to Gupta (2010) and Hirschfeld, Hill, and Riordan (2020). We then assessed the extent to which the adaptation projects addressed these potential future risks using a multi-criteria scoring method (Berke and Godschalk 2009; Woodruff and Stults 2016). In Table 2 we show how we clustered the risks into two categories, we explain the nature of the risks, and provide relevant literature.

The first risk category concerns uncertainty about the magnitude of sea level rise within the intended timeframe of the adaptation project (Haasnoot et al. 2013; Kettle 2012). We categorized three methods of representing this uncertainty, which can lead to failure for adaptation projects. In SLR1, a range of magnitudes for future sea level were considered in the project's design (Cayan et al. 2016; Kopp et al. 2014; Reeder and Ranger 2011). SLR2 represents the uncertainty by considering potential magnitudes of sea level rise at both a near-term and a more distant point in time (Lawrence, Bell, and Stroombergen 2019; Stephens, Bell, and Lawrence 2017). SLR3 represents uncertainty by incorporating an explicit process of adaptive management in the design, using thresholds in sea level that trigger new phases of design implementation and new management strategies (Holling 1973; Reeder and Ranger 2011; Walker, Haasnoot, and Kwakkel 2013).

The second risk category is the effect of rising sea levels on unconfined coastal groundwater levels (Werner and Simmons 2009), and on the spatial extent of tributary flooding near the Bay (Lamb et al. 2010; Moftakhari et al. 2017). These two risks are related, since rising groundwater will increase tributary discharge rates (Bjerklie et al. 2012), and extreme precipitation events can increase groundwater levels (Habel et al. 2017; Horton 1933). Both phenomena may lead to flooding on the inland side of a coastal adaptation project, and cause structural failures of landforms such as levees, mounds or berms (Graaf 2012; Sills et al. 2008).

Study area

We used the San Francisco Bay Area (Figure 2) as a case study that allows us to test our evaluation approach using adaptation projects that are designed or already built, and to consider its generalizability to similar urbanized estuaries. California has long been a leader on climate change mitigation (Schreurs 2008). Formal adaptation work began in California with the Governor Schwarzenegger's Executive Order S-13-08, which required state and local agencies to include sea level rise in their future plans (2008). Since then, State agencies have written three guidance documents on planning for sea level rise. The newest guidance was released in 2018, and a related report states that planners should consider up to three meters of sea level rise by 2100 (California Natural Resource Agency and California Ocean Protection Council 2018; Griggs et al. 2017).

The Bay Area is a dynamic region with approximately 7 million residents, making it one of the largest population centers in the United States. The area's economy is characterized by a very high Gross Metropolitan Product, including Silicon Valley's technology industry and Napa Valley's wineries (U.S. Bureau of Economic Analysis 2017). The region is defined physiographically by its estuarine conditions, providing critical habitat for shorebirds along the Pacific Flyway. A historical emphasis on industrial, military and agricultural uses on coastal land eliminated nearly 90% of the Bay Area's wetlands (Callaway et al. 2011). Recent work on habitat creation and restoration helped the region to regain approximately 5,000 ha of intertidal wetlands (~2.2% of the area lost) (Stralberg et al. 2011).

With three major metropolitan centers and typically low-lying shorelines, the Bay Area faces dramatic impacts from sea level rise in both its urban areas and newly-restored ecosystems (Heberger et al. 2012; Stralberg et al. 2011). In the face of these threats, government agencies are actively working to address sea level rise risk through local

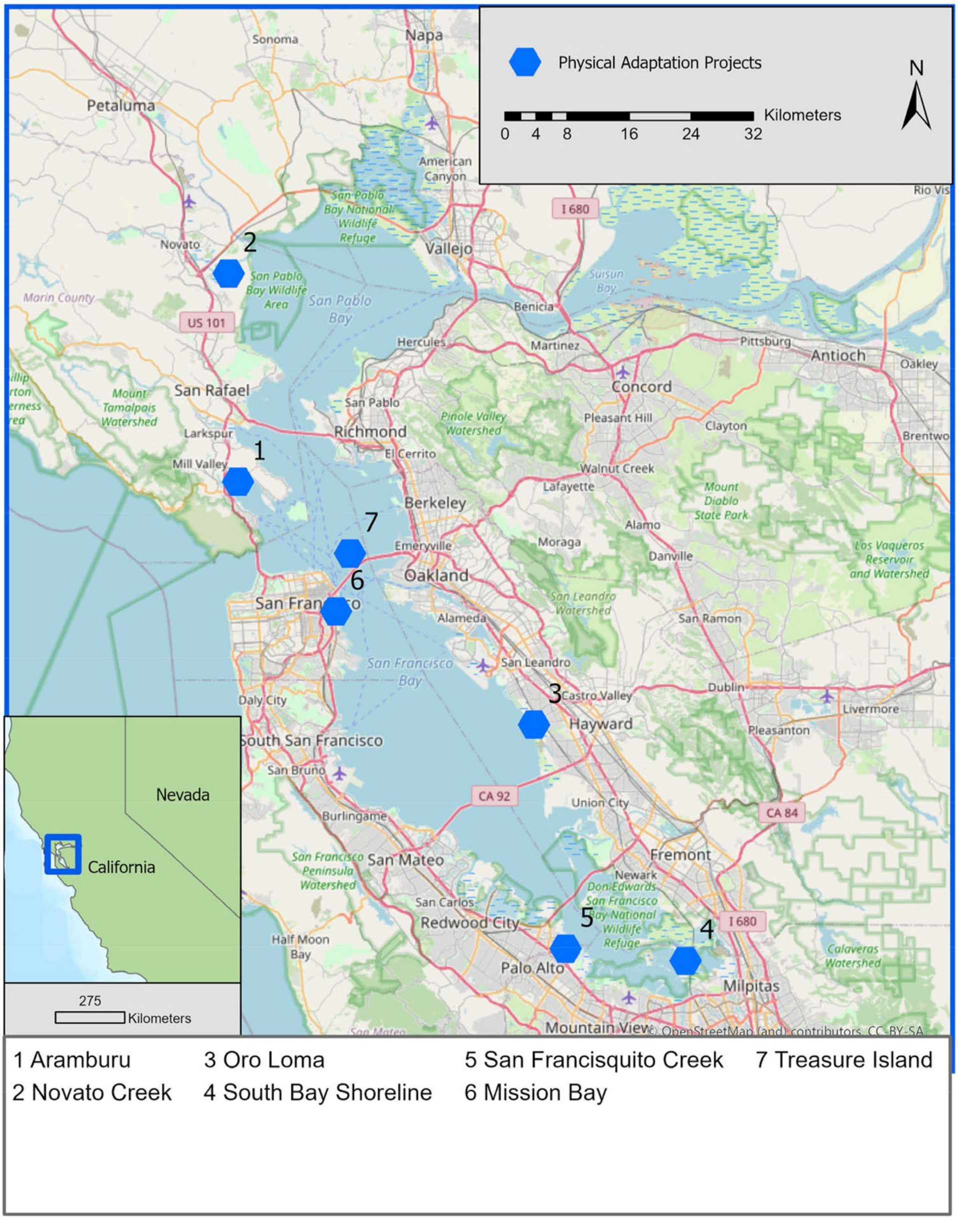

Figure 2. The San Francisco Bay Area and the location of the projects evaluated.

plans, physical projects, and large-scale collaborative efforts such as the Resilient by Design Bay Area Challenge, which was funded by the Rockefeller Foundation and organized by many partner agencies including the Bay Area Regional Collaborative (BARC) ("Resilient by Design" 2018).

Thus the Bay Area serves as a useful analogue for other urban estuaries, such as the Thames Estuary in United Kingdom (Reeder and Ranger 2011), the Elbe in Germany (Nicholls and Klein 2005), and the Chesapeake Bay in the United States (Ezer and Corlett 2012), facing similar threats.

Methods

In 2015, we identified seven physical adaptation projects in the Bay Area (see Figure 2 and Table 1) by searching local government websites and surveying local sea level rise stakeholders. At that time, the projects were described by regional experts as examples of climate adaptation work[1]. The projects were geographically diverse and were distributed across five of the Bay Area's nine counties. They included different stages of development, from a conceptual site plan to built projects. While each project was unique to its particular site, there were also common features. For example, increasing the elevation of existing physical shoreline protections while restoring bayland habitat was a common physical strategy.

This evaluation framework consists of two different approaches. Approach 1 draws on evolutionary landscape theory (Kaisa Miettinen 1999) and is designed to assess a project's transformative nature based on Hill's coastal infrastructure typology (2015). Approach 2 builds on the multi-criteria assessment and scoring method used by Baker et al. to evaluate climate adaptation planning in Australia (2012). In that analysis, the researchers use numerical scores to evaluate the design documents on the project's potential to mitigate multiple risks of climate change. We used a similar approach, but instead of using a broad set of climate change impacts, we characterized two major classes of risk that are directly related to sea level rise and could lead to failure of the adaptation projects. We also selected criteria that could be used for site-based physical adaptation projects, rather than the regional plans analyzed by Baker et al. (2012). We based this evaluation on the physical design specifications described in project reports using geographic information system (GIS) data. We relied on a combination of design specifications and final engineering drawings as descriptions of the components of these projects and their spatial extent.

Approach 1: a project's transformation of the coastal zone

Approach 1 is based on the analytical framework originally presented by Hill (2015). This analytical framework (Figure 1) constructs a solution space for adaptation using two axes that represent design choices that influence project cost, the range of benefits produced, and the transformability of an adaptation strategy over time as sea levels continue to rise. Altered shorelines are categorized as landforms or walls along the vertical axis, and as static or dynamic structures along the horizontal axis. Using a quantitative assessment of the percentage of the shoreline that is wall vs. landform, or dynamic vs. static, projects can be placed in one of four quadrants within the solution space: 1) static walls, 2) dynamic walls, 3) static landforms and 4) dynamic landforms. This characterization allows the relative flexibility of adaptation projects to be compared, where flexibility is characterized as the capacity to raise the infrastructure over time. It also allows the consideration of whether the adaptation project provides multiple benefits, such as recreation or other ecosystem services. For example, the typology treats walls built with concrete and steel as single-purpose structures from an ecological point of view because they typically do not provide multiple ecosystem services, such as recreation, water filtration, or habitat.

We utilized this typology because it offers multiple advantages. First, it captures critical aspects of a complex landscape and simplifies them into a visual and numeric communication tool. Specifically, it helps to assess a proposed alteration of a shoreline by determining the degree to which a wide range of project types can confer multiple benefits and provide future flexibility. Additionally, the typology is flexible and thus can be applied to a range of different projects such as those we are evaluating.

In this research we apply this typology to describe the pre-development condition of each site and to assess the post-development change the project brings or proposes. To apply approach 1 to these specific projects, we used a geographic information system (GIS) vector-based inventory of shoreline infrastructure along the San Francisco Bay, developed by the San Francisco Estuary Institute (SFEI)) (2016). This dataset contains 30-m line segments of linear shore structures (berms, levees, walls, etc.) that occur between mean higher high water (MHHW) and an elevation of 3 m above MHHW. For each 30-m line segment, the dataset describes four characteristics: the type of coastal structure, whether it is accredited as a protective structure, whether it is fronted by natural features (i.e., wetlands and beaches), and its current elevation relative to NAVD88. We also used each project's report to develop a project specific boundary.

First, we used the reclassification scheme shown in Table 3 to align the shoreline data from SFEI to the shoreline typology (Hirschfeld and Hill 2017). Next, each project's boundary was used to clip the SFEI data and generate specific pre-development conditions for each case study. Note that because the Aramburu Project (#1) and the Treasure Island Project (#7) were built prior to the development of the SFEI data, we used Google Earth's historical imagery to generate the data for the pre-development conditions. In the third step we used each project's design specifications to generate new shoreline types to describe the projected post-development conditions. For example, we changed the designation of shorelines from "static" to "dynamic" when projects changed protective structures such as a wall to wetlands. Similarly, when projects added floodwalls, we changed the designation of the shoreline to reflect this as a post-development condition. In the case of the Mission Bay Project (#6), we developed separate analyses for the creek portion (referred to as 6 A) and the Bay shore portion (referred to as 6B) for consistency with the different concepts developed in the project's report. Finally, for each project we calculated the percentage of the total shoreline that is wall versus landform, and the percentage of the total shoreline that is dynamic versus static. These percentages were calculated for both pre-development and post-development conditions.

Approach 2: Risk review using project documents

In this portion of our evaluation, we developed criteria for two types of risk based on a literature review of climate science and adaptation planning through a process similar to Gupta (2010) and Hirschfeld, Hill, and Riordan (2020). As shown in Table 2, we concluded that two of the primary issues that could lead to failure in coastal adaptation projects are the risk of under- or over-estimating the magnitude of sea level rise (Cayan et al. 2016; Haasnoot et al. 2013; Kettle 2012; Reeder and Ranger

Table 2. Categories, evaluation criteria, explanations, and key literature.

Categories	Evaluation Criteria	Explanation	Literature
1. Sea Level Rise	SLR1: Sea level projections	Includes a range of future projections	Cayan et al. (2016) Kettle (2012), Kopp et al. (2014), Reeder and Ranger (2011)
	SLR2: Timeframes	Includes analysis of both near-term and long-term projections	Lawrence, Bell, and Stroombergen (2019), Stephens, Bell, and Lawrence (2017)
	SLR3: Adaptive management	Includes explicit sea level rise adaptive management strategies	Haasnoot et al. (2013), Holling (1973), Reeder and Ranger (2011), Stephens, Bell, and Lawrence (2017), Walker, Haasnoot, and Kwakkel (2013)
2. Hydrology	H1: Fluvial water	Additional risks from precipitation and fluvial processes are considered in conjunction with sea level rise	Erikson et al. (2018), Horton 1933, Moftakhari et al. (2017), Wahl et al. (2015),
	H2: Groundwater	Impacts driven by water table depths are addressed	Bjerklie et al. (2012), Habel et al. (2017), Plane, Hill, and May (2019), Rotzoll and Fletcher (2013), Werner and Simmons 2009

Table 3. Reclassification scheme used to match SFEI data to the analysis framework.

SFEI Class	Landform or Wall	Static or Dynamic
Berm	Landform	Static
Channel or opening	Landform	Static
Embankment	Landform	Static
Engineered Levee	Landform	Static
Shoreline Protection Structure	Landform	Static
Natural Shoreline	Landform	Dynamic
Wetland	Landform	Dynamic
Floodwall	Wall	Static
Transportation Structure	Wall	Static
Water control structure	Wall	Dynamic

2011), and the risk of failing to capture critical hydrologic processes that compound the threats of sea level rise (Bjerklie et al. 2012; Habel et al. 2017; Moftakhari et al. 2017; Wahl et al. 2015).

There are many uncertainties related to sea level rise projections and associated impacts (Kettle 2012). These uncertainties include the range of magnitudes for future sea levels (Cayan et al. 2016; Kopp et al. 2014). The uncertainties also relate to the specific timing of the impacts (Lawrence et al. 2013). Climate adaptation literature, social-ecological systems literature, and landscape design literature all indicate that using adaptive management techniques make designs more robust and flexible for uncertain futures (Folke et al. 2005; Steinitz 2012; Walker, Haasnoot, and Kwakkel 2013).

Both the climate science literature and the adaptation literature recognize the importance of designing shorelines to address the compound impacts of sea level rise (Hill 2013). Researches demonstrate using statistical tools that compound flooding from river flow and coastal water level are a more accurate representation of the future risk cities face (Moftakhari et al. 2017). Others studying the joint occurrence of rainfall and storm surge also highlight the importance of accounting for fluvial flooding (Wahl et al. 2015). Similarly through modeling and empirical data collection recent work demonstrates that rising sea levels increases the risks posed by higher groundwater levels in unconfined coastal settings (Bjerklie et al. 2012; Werner and Simmons 2009). The criteria are also relevant to the state of climate science at the time of development for the projects we studied, since both of these issues have been discussed during the last decade.

Evaluation category 1: Uncertainty about the magnitude of future sea level rise

We used the three criteria below to evaluate whether and how the adaptation projects conceived of sea level rise as a temporal phenomenon that is associated with increasing uncertainty over time (Cayan et al. 2016; Reeder and Ranger 2011). We intentionally did not analyze which sea level rise projection or climate model the project was using, but instead focused on whether and how the uncertainty in the projections was considered. In *SLR 1*, we score the projects based on the degree to which they include a range of future sea level rise magnitudes rather than designing for a single numerical projection of sea level rise, scoring projects higher that prepare for a range of projections. In *SLR 2*, we consider whether each project used multiple timeframes for their design concepts and give higher scores for projects that designed considering near-term (~2050) and long-term (~2100) sea level rise analysis. In *SLR 3*, we evaluate the projects based on whether they explicitly include adaptative management strategies for sea level rise that establish thresholds for design responses as new observations are made over time.

- **SLR 1**: Includes a range of future sea level rise magnitudes accounting for uncertainty
- **SLR 2**: Includes analysis of both near- and long-term projections
- **SLR 3**: Includes explicit sea level rise adaptive management strategies

Coastal flooding as a result of sea level rise is a certain future impact (Hallegatte et al. 2013). However, significant uncertainties remain. The exact amounts of eustatic and relative sea level rise remain unknown (Cayan et al. 2016; Kettle 2012). The timeframes for certain amounts of sea level rise are also uncertain. Additionally, there are many regional and local factors that affect the amount of relative sea level rise a site will experience (IPCC 2014). As a result, we argue that project evaluation criteria should reward adaptation planners for thinking more strategically about how to incorporate flexibility in their designs.

One example of how these criteria can be incorporated into physical projects is by designing such projects based on integrated localized sea level rise data that captures storm surge analysis to create a spatial understanding of the impacts on current infrastructure and land-use patterns, regardless of the source of flooding in a specific event (Ju et al. 2019). Through this modeling, additional vulnerability, risk, and exposure analyses can be integrated into project designs (Baker et al. 2012).

In addition to including ranges and timeframes for sea level rise, local adaptation projects benefit from being developed as part of a larger strategic vision, with an adaptive management plan (Haasnoot et al. 2013). Such plans allow for the development of contingencies and alternatives in response to observations of trends and impacts (Reeder and Ranger 2011; Stephens, Bell, and Lawrence 2017). Adaptive management plans also identify variables and thresholds that would trigger a shift to an appropriate alternative design or management approach. One example is the adaptation pathway framework developed for the Thames Estuary region, including the Thames Barrier (Reeder and Ranger 2011).

Evaluation category 2: Hydrology

Next, we looked at the extent to which the project considered the idea of compound flooding and the interaction of sea level rise with floodwater from freshwater sources (Wahl et al. 2015; Moftakhari et al. 2017; Bjerklie et al. 2012). In *H 1*, we score the projects based on the degree to which they integrate future sea level rise projections with surface freshwater sources. In *H 2*, we score each project on whether the design made use of current and projected water table depths specific to that site.

- **H 1**: Additional risks from precipitation and fluvial processes are considered in conjunction with sea level rise
- **H 2**: Impacts driven by current and projected water table depths are addressed

While coastal flooding from storm surge is a serious concern, compound flooding, which occurs when storm surges coincide with precipitation events, is an even greater threat to low-lying baylands locations. Associated impacts from these fluvial and coastal flooding events include damages to infrastructure and loss of human life (Moftakhari et al. 2017; Wahl et al. 2015). The design of shoreline structures must allow fluvial floodwaters to be discharged if there is no capacity to store that water. Shoreline protection projects must therefore consider ways to allow significant pluvial and fluvial flows to reach the baylands.

Flooding from a rising water table in coastal plains could double the geographic area affected by marine inundation alone (Bjerklie et al. 2012; Plane, Hill, and May 2019; Rotzoll and Fletcher 2013). Associated impacts from rising water tables and a narrowing of the unsaturated space include reduced stormwater infiltration and drainage capacity, saturation of the soil that may increase liquefaction risks in a seismic zone, remobilization of existing soil pollution that could affect human health and nearshore ecosystems, and saltwater intrusion into drinking water systems or underground infrastructure (Habel et al. 2017). A robust sea level rise project should include a localized analysis of groundwater impacts associated with sea level rise.

Project scoring

We assessed six of the seven projects using the above criteria and recorded our results with a multi-criteria scoring method (Baker et al. 2012; Berke and Godschalk 2009;

Table 4. Scoring system used to evaluate projects.

Score	Evaluation Description	Comparison to Baker, et al.
0	No evidence of the criterion in the project	Same evaluation criteria
1	The criterion is mentioned and defined; however the project does not provide any analytical details.	Less strict—allows for terms to be defined
2	The criterion is mentioned along with a moderate level of detail. However, inclusion is exclusively descriptive and does not have any local application or analysis.	Same evaluation criteria
3	The criterion is included and there is some local application using local climate scenario modeling or other local data. However, the information is still mostly descriptive.	Same evaluation criteria
4	The criterion is included and at least two detailed analyses of the criterion are provided in a locally specific manner. This can include using a variety of tools such as vulnerability, exposure and/or risk assessments, maps, fieldwork, GIS analysis and modeling, and local climate scenario modeling	More strict—authors require two analytical aspects of criterion

Woodruff and Stults 2016). We did not assess the Oro Loma Project (#3) using the risk factors because we did not have access to the design plans for the project. We assessed each project according to its performance on a five-point scale (0, 1, 2, 3, or 4) (see Table 4). For example, in one case a score of 1 for the “timeframes” criterion (*SLR 2)* was assigned because the project’s plans briefly recognized the long-term nature of sea level rise but provided no further details or related dates. Two projects received a score of 3 for the same criterion because they provided two specific timeframes and analyzed the ranges of sea level rise that could occur by such dates. For the Novato Creek Project (#2), we dropped the “adaptive management” criterion (*SLR 3*) because the project is in such an early stage of development. For the Aramburu Project (#1) we dropped the fluvial criterion (*H 1*) since the site context does not include significant fluvial processes.

Data and methods access

Our data and detailed methods are available at UC Berkeley’s online data archive (DRYAD). The data contain the original source report, the geographic boundary, the pre-development shoreline conditions, the post-development shoreline conditions, and the evaluations scores for each project. The code and models we used can also be downloaded from this site. These data can be accessed at this URL: https://doi.org/10.6078/D11S3N.

Results

Here we present the findings from (1) our analysis of the physical transformation of the coastal zone, our evaluations of (2) specific ways these projects included uncertainties about the magnitude of sea level rise, and (3) the extent to which each project considered flooding from freshwater sources.

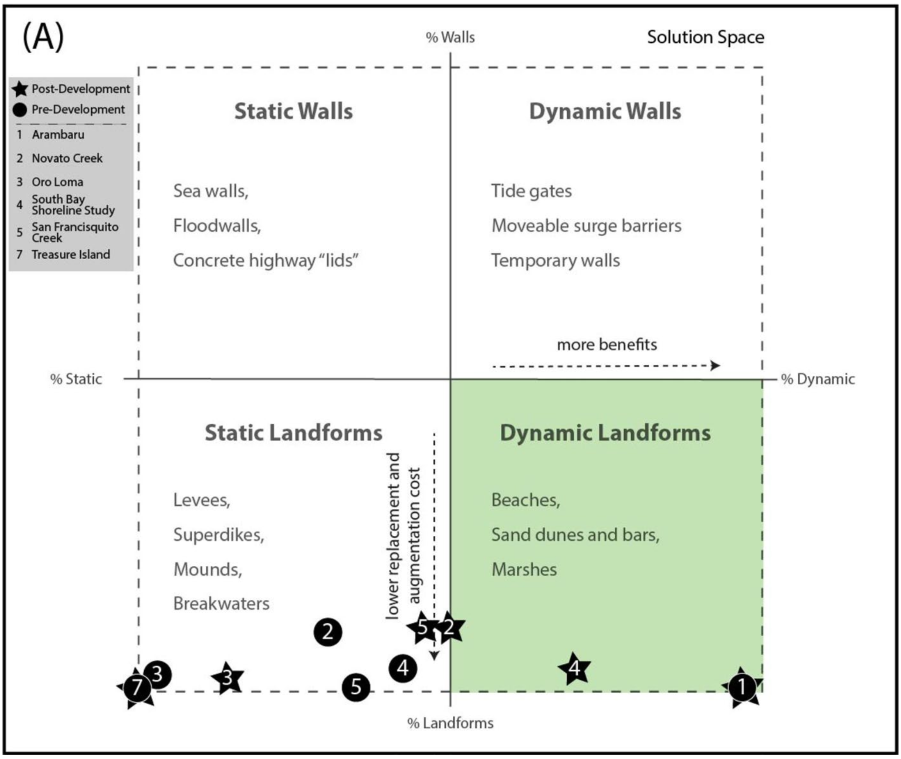

Figure 3. Six projects pre- and post-development are shown using a four-quadrant typology of protective shoreline structures. The vertical axis is defined by the percentage of shoreline that is wall, versus the shoreline that is built with earthen materials, such as sand and gravel (landform). The horizontal axis is defined by the percentage of shoreline that is dynamic (built with material that is able to move, either mechanically or by natural processes) versus static (materials that are fixed in position). This figure shows the six projects that have singular post-development plans. Note that the Aramburu Project (#1) and the Treasure Island Project (#7) do not change from pre- to post-development.

Results from approach 1—the transformation analysis

We used GIS analysis tools to evaluate each project in terms of its component elements (landforms vs. walls) and its potential to provide multiple benefits (dynamic vs. static). Figure 3 shows results for both the pre-development and post-development conditions. The pre-development project sites almost all sit within the static landform quadrant of the typology we used. The pre-development conditions can also be characterized as containing less than 10% walls by shoreline length, with the exception of the Mission Bay Project (#6). The pre-development conditions of the projects are all less than 50% dynamic by shoreline length as well, with the exception of the Aramburu Project (#1). When compared to the Bay-wide conditions, the pre-development conditions are representative of the conditions of the larger region, which is currently comprised of predominantly static landforms (69% of the entire SF Bay edge), typically including an earthen slope or berm with a riprap edge (Hirschfeld and Hill 2017).

To the extent that the projects we evaluated represent the likely post-adaptation condition of the SF Bay edge, we see transformation toward a more dynamic coastal zone. While most individual projects remain in the static landform quadrant of our typology, every project that shows any change shows an increase in the percentage of the coastal zone that is dynamic. Several projects show a minor increase in the percentage of wall present—the San Francisquito Creek Project (#5) has a nearly 10% increase in the proportion of shoreline walls, and the Novato Creek Project (#2) has a 1.5% increase in the proportion of walls. The South Bay Shoreline Project (#4) is a notable exception in that it represents a shift into the dynamic landforms quadrant with a 45% increase in dynamic shoreline edges. The Aramburu Project (#1) and the Treasure Island Project (#7) are also exceptions because in both cases there is no change in their location on the shoreline typology diagram pre- and post-adaptation.

The results for the Mission Bay Project (#6) are shown separately in Figure 4A and B because of the wide variety of post-adaptation conditions that are projected by the multiple plan scenarios included in the project documentation. The figures show that the site's pre-development condition is unique relative to the other sites we studied, because it has significantly more wall as a percentage of shoreline length (30% at the creek and 72% along the shoreline) than the other sites. All three options for a post-adaptation condition would increase the percentage of wall at the site, and only one of the options—the tidal barrier (b)—increases the percentage of dynamic shoreline. Post-adaptation conditions for the Bay shoreline (6B) of the Mission Bay Project (#6) shift in the opposite direction from its proposed creek shoreline. Three of the adaptation design options (a, b & d) significantly increase the percentage of landform along the shoreline. One option—using an elevated street (c)—would move the project into the "dynamic walls" quadrant of our adaptation typology.

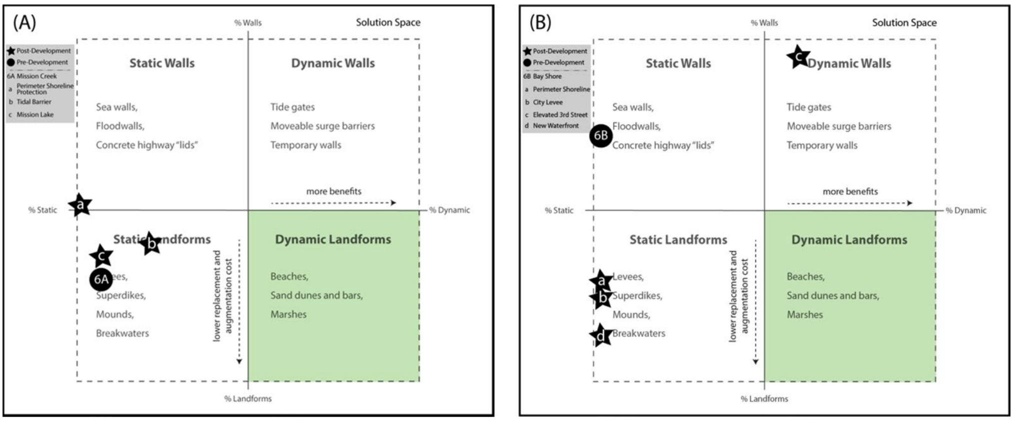

Figure 4. The Mission Bay Project (#6) is shown using a four-quadrant typology of protective shoreline structures. The project is split into two portions. The creek portion is referred to as project 6 A and is shown in Figure 4A. The Bay shore portion is referred to as project 6B and is shown in Figure 4B. Both the creek and the Bay shore have multiple post development options which are represented by the stars and labeled as a-d.

Results from approach 2—physical project design document assessment

Here we used five criteria to evaluate each project, scored on a zero to four scale. Figure 5 shows results for each project using our categories of evaluation criteria: 1) sea level rise (*SLR 1*, *SLR 2*, and *SLR 3*) and 2) hydrology (*H 1* and *H 2*). We show the results as a percent of the highest possible score. The projects received an average aggregate score (i.e., combined score for the two categories) of 45%. The lowest two scores were the Aramburu Project (#1) with a score of 23% and the Novato Creek Project (#2) with a score of 26%. The highest overall score was 70% for the Treasure Island Project (#7). The middle tier projects were the South Bay Shoreline Project (#4), the San Francisquito Creek Project (#5), and the Mission Bay Project (#6) with scores of 45%, 50%, and 55% respectively. The average aggregate scores improve over the years.

Our evaluation categories (sea level rise and hydrology) represent two independent yet critical issues that may determine success or failure in these adaptation projects. Altogether, the projects received an average score of 27% for the sea level rise category. The Treasure Island Project (#7), with a score of 55%, received the highest score in the sea level rise risk category. The Novato Creek Project (#2), with a score of 6%, received the lowest score in the sea level rise category.

The projects received an average score of 18% for the hydrology risk category. The San Francisquito Creek Project (#5) received the highest score in the hydrology category with a score of 30%. The Aramburu Project (#1) received the lowest score with a score of 13%.

Project scores in the sea level rise category show a wider range (6% – 55%) than project scores in the hydrology category (13% – 18%). Project scores in the sea level rise category show a positive trend, with the highest two scores received by the most recent projects (2016). Project scores in the hydrology category show a downward trend, with the lowest two scores received by projects from 2016 (see Figure 5).

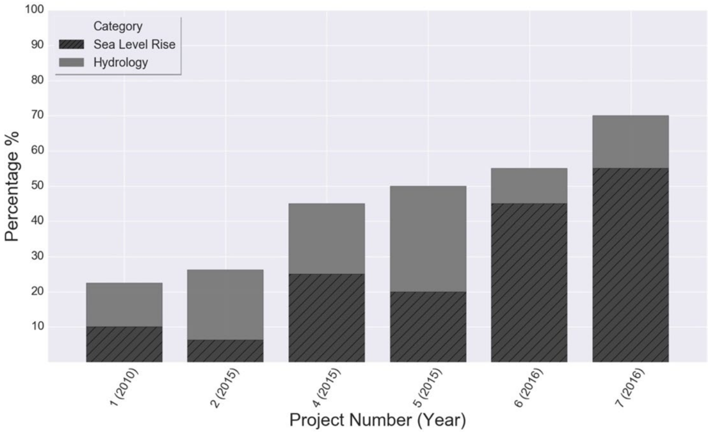

Figure 5. Aggregated project score as a percent of highest possible score. Scores are split into two categories (sea level rise and hydrology) for all projects evaluated. Data shown in order of year.

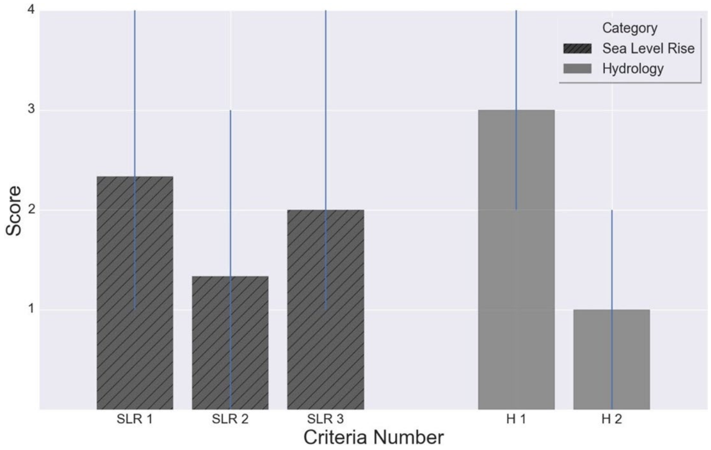

Figure 6. The average and range of scores for each of the five criteria used to evaluate projects. Criteria are clustered into the two categories used for evaluation.

Results for each of the five criteria used in approach 2

Figure 6 shows results for each risk-related criterion, including the range of raw scores and the average of those scores. Our application of the three sea level rise criteria *(SLR 1*, *SLR* 2 & *SLR 3*) produced an average score of 1.9, while our application of the hydrology criteria (*H 1* & *H 2*) resulted in an average score of 2.

Discussion

Studying the first generation of physical adaptation projects in the Bay Area represents a unique opportunity for institutional learning. Systematic evaluation that tracks the design and risk inclusion of adaptation efforts can reveal key insights for future course corrections that ensure robust and appropriate project designs. While other researchers have developed comprehensive systems to measure the sustainability of physical plans for new community developments (Mapes and Wolch 2011) and local government climate adaptation plans (Baker et al. 2012; Woodruff and Stults 2016), no similar evaluation framework exists for physical adaptation to sea level rise specifically. In this paper, we offer two methodological contributions here we reflect on our findings and on the generalizability of these methodologies.

First, we applied Hill's typology (2015) as an analytical framework for characterizing physical adaptation projects for the first time. This allows us to visualize how adaptation projects may transform the San Francisco Bay edge as a system. Our analysis shows a general trend toward the dynamic landforms quadrant of our typology (Figure 3). This is a clear transformation in the sense that shifting from one infrastructure type to another ("gray" to "green") is a distinct technological change (Geels 2002). More importantly, projects within this quadrant offer greater future transformability at a lower cost. Infrastructure that uses landforms (also called "soft" infrastructure) is generally less expensive initially and can be raised or relocated over time without being entirely replaced (Charlier, Chaineux, and Morcos 2005). Similarly, infrastructure that is dynamic typically allows flows of water and sediment to occur. This enables incremental physical changes in complex coastal systems to occur over time, such as the accretion of sediment and biomass in tidal wetlands to keep pace with sea level rise (Mattheus et al. 2010).

Second, we designed an approach to assess the design plans for physical sea level rise adaptation projects in relation to key risks by building on previous work that assessed regional plans (Baker et al. 2012) and adaptation plans (Woodruff 2016). These scores allowed us to better understand the risks included (and not included) in the designing of physical adaptation projects. Our evaluation shows a distinct improvement over time in the sea level rise risk category of the evaluation criteria (*SLR 1*, *SLR 2*, & *SLR 3*), with a mean score of 10% in 2010, 17% in 2015, and 50% in 2016 (see Figure 5). This implies that local capacity to consider the strategic implications of uncertainties around sea level rise is improving. The San Francisco Bay Commission for Development and Conservation (BCDC), in collaboration with other regional agencies, implemented the Adapting to Rising Tides (ART) Program with the goal of building the region's planning capacity ("Adapting to Rising Tides," 2018). Our results suggest this work may have helped to improve local capacity to adapt to sea level rise (Hirschfeld, Hill, and Riordan 2020). Despite this positive trajectory, none of the projects achieved high marks on all five of the evaluation criteria, indicating that there is significant room for crucial improvements. Overall, our results support the conclusion that site-scale designs of coastal structures are unlikely to adequately prepare coastal zones for these future threats until methods for incorporating sea level rise trends and projections into planning and design methods are standardized (Hill 2016).

Case study research, such as this project, uses multiple types of data from a specific region or location (Yin 2013, 2). Case studies have been used to identify patterns in many different disciplines including environmental planning, landscape architecture, engineering and urban planning (Francis 2001). For example, a recent assessment in Hamburg Germany used case study research to understand physical adaptation projects and compare their contributions to local resilience (Restemeyer, Woltjer, and van den Brink 2015). This study shows the power of case study work and its ability to translate the analysis beyond the singular boundary of the site.

As we reflect on our work, we find that these methodologies could be applied in other settings. Approach 1 is based on a typology of coastal infrastructure and typologies are known to be valuable heuristic tools in decision theory (Mees et al. 2014). Researchers in the San Francisco Bay have used this typology to understand missing design strategies (Hill 2013), and the costs of future adaptation (Hirschfeld and Hill 2017). Most recently the typology was applied to coastal adaptation planning in Denmark (Aarhus School of Architecture 2019). In this case the typology was used to understand the relationship between a specific coastal zone strategy and the upland context. Our use of the typology to understand pre and post development could complement this spatial planning use. Combining the two uses would allow the spatial planning approach to have a deeper understanding of the aggregate changes and the extent to which the coastal zone was shifting toward dynamic landforms.

Approach 2 is based on a robust understanding of sea level rise science (Cayan et al. 2016; Kopp et al. 2014; Nerem et al. 2018; Vaughan and Arthern 2007) and the implications for future risks (Biging, Radke, and Lee 2012; Bjerklie et al. 2012; Moftakhari et al. 2017). Therefore, we think the approach is generalizable to other settings and project designers in other regions can use this framework as a template. The three sea level rise evaluation criteria (see Table 2) can be used in other settings. Since the criteria do not stipulate specific sea level rise numbers, they can be adopted to places using localized relative sea level rise information (Nicholls and Cazenave 2010). Evaluators can also adjust or add criteria to match local conditions. For example, places grappling with fire threats struggle with questions of magnitude (Dennison et al. 2014) and timing (Schoennagel et al. 2017) and therefore could shift SLR1 and SLR2 to align with fire threats.

Conclusions

The first-generation physical projects we evaluated are a starting point for sea level rise adaptation in an urban estuary. Important lessons can be learned from an analysis of the characteristics of this first generation of adaptation projects. First, we found that these sea level rise adaptation projects demonstrate a shift toward using more dynamic landforms instead of the static landforms used in the past. This shift could be the beginning of a larger transformation of the coastal zone toward conditions that are more flexible for future adaptation and provide multiple ecosystem services.

Second, we found that consideration of uncertainty about the timing and magnitude of sea level rise and of combined saltwater-freshwater flooding risks improved over time (Figure 5). This suggests that the work of the regional government to improve local capacity had a positive effect. Moreover, this trend suggests that future projects will represent uncertainties about the timing and magnitude of sea level rise more effectively in their design processes. Finally, we found that none of the projects achieved high marks in all five of the evaluation criteria, indicating that there is a critical need for improvement in designing the coastal zone for adaptation to rising sea levels.

Most importantly, this paper illustrates the applicability of our two different methodological approaches. Using a simplified typology to categorize the coastal landscape designs allowed us to observe changes in the coastal zone pre- and post-implementation of adaptation projects. Our flexible multi-criteria framework provided insights into the risks these adaptation projects are taking into account, and their long-term potential within coastal zones. We think these approaches can help ecologists, geomorphologists, designers and planners develop more robust physical interventions that account for the wide range of future sea level rise risks.

Declaration of interest statement

The authors declare no conflict of interest.

Note

1. Note that new designs and projects have been developed since this list was compiled. In the discussion section we address how these models relate to more recent developments.

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