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Transformation in the face of rising sea levels:
Approaches to measuring progress and evaluating strategies

By

Daniella Hirschfeld

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

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in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Kristina Hill, Chair
Professor John Radke
Professor Laurel Larson

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Abstract

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In the face of rapidly rising sea levels caused by climate change, there is an emerging consensus among researchers that transformations are necessary to avoid the most catastrophic of losses. Cities, regions and states are beginning to develop vulnerability assessments and create adaptation plans to address this long-term threat. However, there is no clear way to measure adaptation planning success or comparatively evaluate different strategies. Combining socially relevant knowledge with physical planning practice has the potential to provide deep insights and lead to necessary transformations. This dissertation attempts to disrupt current practice and shift away from path dependencies that lead to the negative cycle of building ever higher walls to protect brittle urban systems. Specifically, this dissertation presents new approaches to evaluating sea level rise adaptation strategies and the key insights gleaned from applying these approaches it the San Francisco Bay and coastal California.

Chapter 1 provides a general overview of the themes covered in this disseration. Chapter 2 of this dissertation is a systematic literature review of over 30 publications in the academic literature on transformational adaptation. Next in Chapter 3, the dissertation uniquely combines two evaluation approaches to understand if seven current physical proposals for sea level rise in the San Francisco Bay are showing signs of a transformation in physical planning. Then in Chapter 4, the dissertation investigates the physical, economic, and regulatory insights that a cost estimate for coastal protective infrastructure (including earthen levees, concrete walls, and wetlands) can reveal. It analyzes 169,000 30-m line segments of linear shore structures and predicts the costs of adaptation under eight different sea level rise scenarios. In Chapter 5, the dissertation applies a newly developed measurement system called the "Regional Planning Fingerprint" to establish regional baselines for the current status of sea level rise adaptation planning. Through each chapter the dissertation establishes new evaluation approaches and associated tools to understand and compare sea level rise strategies and set baselines to measure future progress.

This dissertation helps to advance existing knowledge of changing landscapes, regional adaptive capacity, and climate adaptation planning, particularly as they relate to the urban ecology and environmental planning fields. Through the analysis in Chapter 3, I find clear evidence of localized transformations in the use of dynamic landforms as a design strategy. In Chapter 4, I gained new

knowledge that builds the case that ecologically sensitive sites could be part of future sea level rise adaptation solutions. In Chapter 5, I find that each region is truly unique and by developing localized baseline data, regions can track their own progress toward transformational adaptation.

I submit that the most important contributions of this dissertation are the unique assessment approaches I developed for three different scales—region, city, and site—and the critical insights gained through applying these approaches. One crucial insight gained through this work is the importance of understanding and designing for deeply interconnected places. Another theme that emerged from this research is that key triggers for action are lacking. Chapter 6 fleshes out these insights and presents a research agenda at the critical intersection of climate change adaptation, urban ecology, and environmental planning.

To my children
– Noa J and Shira M

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My completion of this dissertation is thanks to the combined support from many different people and institutions.

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The work in Chapter 5 was part of a larger research project led by Kristina Hill and Bruce Riordon of the Climate Readiness Institute (CRI). The larger project was funded through California State Assembly Bill 2516 (2013-2014) Planning for Sea Level Rise Database Project, which was administered by the Ocean Protection Council (OPC). The project included stakeholder workshops and interviews with over 60 participants from city and county governments, state and federal agencies and other regional partners. I am incredibly grateful to all these people working tirelessly on the ground to increase local resilience to sea level rise.

Additional outside help was used to improve this dissertation. Ben Kossak proofread each chapter this dissertation. His diligence and eye for technical writing vastly improved this document. Tanya Salivon and Harsh Purwar provided assistance with the development of figures in Chapters 2 and 5. Harsh's work in MATLAB and Tanya's work in Adobe Illustrator greatly improved the visual presentation of my work.

Finally, and most importantly I could not have achieved this without the support of my family. My husband Will always encouraged me to be the best I could be and greeted me with a smile on even the worst of days. This dissertation's birth is deeply entwined with the birth of my two children. Noa's early arrival, just two days before qualifying exams, transformed me personally, and Shira was a true motivator as her coming birth inspired me to finish my first real full draft. I hope that this work and my future efforts can transform the landscape and build local resilience for their future.

CHAPTER 1: INTRODUCTION

Today there is mounting empirical evidence that climate change is placing increased pressure on social-ecological systems. Increased rates of change in climatic conditions, such as water temperatures and precipitation patterns, put ecosystems and biodiversity at risk of further degradation and loss (Grimm et al., 2013; Staudinger et al., 2013). Impacts of climate change are also felt directly by human populations. For example, threats from higher land surface temperatures and associated urban heat include mortality and hospital admissions (Corburn, 2009). The practice of planning and environmental management provides an opportunity to address these threats in the near and long term (Wheeler, 2008).

The accelerating rate of sea level rise is one well-documented impact of climate change (Nerem et al., 2018). Impacts from sea level rise are also well-understood, with a long history of study. Millions of people currently living in the coastal zones face significant risks (Nicholls & Cazenave, 2010). Increased flooding from the confluence of higher seas and higher rates of precipitation is one specific risk faced by coastal communities (Wahl, Jain, Bender, Meyers, & Luther, 2015). Other places are threatened by saltwater intrusion into aquifers (Griggs, 2017). Increased rates of sea level rise also threaten critical habitats for fish and birds (Stralberg et al., 2011).

In the context of these threats, planners in coastal communities are starting to work on climate change adaptation planning. According to one database created by the Georgetown Climate Center, there are 65 local or regional plans in the United States that include the issue of sea level rise (Georgetown Law 2018). Other researchers have found that some communities are integrating sea level rise planning into existing planning work, thus making the number of actual plans hard to count (Bierbaum et al., 2013). Despite this planning work, recent research indicates that the quality of climate adaptation planning is low (Woodruff and Stults 2016). Researchers also found climate adaptation efforts to be more one-off occurrences than a coherent set of actions that are needed to address the threat (Bierbaum et al., 2013).

When it comes to climate adaptation, physical solutions are also critical. Designers and engineers play a key role in this regard and are beginning to include sea level rise in proposals for physical plans (Hill, 2015). One database developed by the United States Global Change Research Program features 17 case studies of physical solutions to sea level rise ("U.S. Climate Resilience Toolkit," 2015). Some researchers find that very little climate adaptation work has progressed beyond the initial stages of planning (Carmin, Nadkarni, & Rhie, 2012). Therefore work on physical strategies for sea level rise is still the exception rather than the rule.

There has been very limited work to systematically evaluate different sea level rise adaptation solutions. Much of the work on sea level rise adaptation focuses on the costs and consequences of inaction. This work however does not include thorough benefit-cost analysis that includes the costs of the actual adaptation strategies. Additionally, current analysis does not address the broader set of climate adaptation issues, which include questions of site design, urban planning and regional governance. To address this gap, this dissertation develops evaluation frameworks and applies them to local, regional and statewide climate adaptation solutions to reveal insights into shorezone transformations and opportunities for planning and design intervention.

Theoretical context and relevant literature

In this dissertation, I weave together the fields of urban ecology and environmental planning to deepen our knowledge of resilient social-ecological systems. I emphasize systematic evaluations and draw on various literatures to support this work. I draw on environmental planning to inform my understanding of the need to balance divergent concerns—economy, environment, and equity—in creating sustainable places (Campbell, 1996; Wolch, Byrne, & Newell, 2014). Studies in the field of environmental management and governance help me to understand critical decision making processes and the functions of institutions at a range of different scales (Berkes, Colding, & Folke, 2003; Olsson et al., 2006; Ostrom, 2009). The burgeoning literature on social-ecological systems provides insights into complex systems and the reality that things are in a constant state of flux (Folke et al., 2004; Holling, 1973). Writings in political ecology help to deepen my critical thinking and enable me to see how human-environment interactions are embedded in broader political economy contexts (Heynen, Kaika, & Swyngedouw, 2006). In developing my ideas on transformations in the face of rising sea levels, I also look to the long history of work and academic research on natural hazards and vulnerability (Burby, Deyle, Godschalk, & Olshansky, 2000; Cutter et al., 2008; Godschalk, Beatley, Berke, Brower, & Kaiser, 1998).

In this dissertation, I draw on the research domains described above to inform my research into questions of climate adaptation planning and transformations in the face of sea level rise. Here I emphasize key gaps and ongoing debates to frame subsequent chapters.

Climate adaptation planning

The key concepts and initial calculations of climate change due to greenhouse gas emissions date back to the 1800s with the work of Fourier (Fourier, 1824), Foote (1856), and Arrhenius (1897). Scientists largely ignored this research until Keeling published his studies on CO_2 in the atmosphere in the 1970s (Keeling et al., 1976). Since this time, there has been a proliferation of scientific evidence of the changing climate (IPCC, 2013).

Most of the literature focused on climate mitigation efforts (i.e., initiatives to reduce greenhouse gases) until the early 1990s. The first literature on adaptation came from major government reports (E. L. F. Schipper, 2006). For example, the two-volume report from the Office of Technology Assessment (OTA) recognizes the threat posed by climate change and begins to evaluate the tools and resources available for adaptation (US Congress, 1993). Then in 1995 the second Intergovernmental Panel on Climate Change Report included adaptation for the first time (E. L. F. Schipper, 2006). Around the same time, researchers started to write about adaptation from a planning perspective. James Titus wrote "Strategies for Adapting to the Greenhouse Effect" in which he explicitly recognized that the right early actions on climate adaptation would lead to improved outcomes (Titus, 1990). Several years later, Joel Smith wrote an article that established a process for identifying and analyzing adaptation options (J. B. Smith, 1997).

The practice of climate change planning follows a similar pattern to the theory. At the municipal government level in the United States, planning practitioners started to create climate plans in the late 1990s. It was not until the early 2000s, however, that these plans included climate adaptation (Wheeler, 2008). Today, according to the Georgetown Climate Center, there are 124 local or regional plans in the United States that specifically address issues of climate adaptation (2018).

There are several critical open debates at the intersection of climate adaptation theory and planning practice. First, there is an ongoing question as to what the term itself actually means. In one recent article, researchers highlight the conflicting definitions of four major international organizations working on climate change adaptation (Biagini, Bierbaum, Stults, Dobardzic, & McNeeley, 2014). In the context of this dissertation, I understand climate change adaptation to be the anticipatory processes by which strategies are developed to preserve current value, reduce risks, or realize benefits associated with climate variability and climate change.

Planning is a critical step to developing anticipatory actions. Researchers looking carefully at the current status of climate adaptation planning emphasize that actual progress is limited (Bierbaum et al., 2013; Carmin et al., 2012; Wheeler, 2008; Woodruff & Stults, 2016). In a comprehensive assessment of these early plans, Wheeler determined that they helped to raise awareness and established goals; however they lacked strong actions that could achieve climate mitigation or adaptation objectives (2008). In another more recent assessment, researchers looked at federal, state, and local climate adaptation efforts that were submitted for inclusion in the National Climate Assessment (NCA). The authors found that though plans were written, few plans truly developed a collective set of strategies sufficient to address future threats (Bierbaum et al., 2013). Researchers recently conducted a systematic assessment of 44 major US cities' climate change adaptation plans using plan content analysis to determine the quality of the plans (Woodruff & Stults, 2016). These researchers found the average score to be only 40.6% and the highest score to be only 76.6% (Woodruff & Stults, 2016). Thus there is a clear need to better connect viable strategies with planning processes to ensure their inclusion in the actual plans. Moreover, the evaluation of these strategies should be presented in such a way that enables decision makers to select the most appropriate and implementable solutions for their locations.

A crucial step in connecting viable strategies with actual plans is considering the full range of strategies (Hill, 2015). There is a growing body of academic and grey literature on climate adaptation actions and possible typologies (Biagini et al., 2014). Using a detailed literature review, Smit et al. (Smit, Burton, Klein, & Wandel, 2000) identify the following six broad ways to categorize climate adaptation actions: timing relative to the stimulus, intent, spatial scope, form of the action, degree of change, and the driver of the action. Other researchers who focused on hazards (Cutter et al., 2008), developing nations (Huq, Reid, & Murray, 2003), scale of action (Wilbanks & Kates, 1999), and natural resource protection (Fidelman, Leitch, & Nelson, 2013) find similar categories. In the context of anticipatory planning for sea level rise and social ecological transformations, I use Hill's typology derived from research on evolutionary landscapes that categorizes physical sea level rise adaptation options into four quadrants: 1) static landforms, 2) dynamic landforms, 3) static walls, and 4) dynamic walls (Hill, 2015).

Transformation

Transformation is an old concept that has recently gained attention among researchers and practitioners concerned by climate change (Kates, Travis, & Wilbanks, 2012). Based on a literature search, I find that the number of publications in this area has gone from 1 in 1981 to over 700 in 2017 (see Figure 1.1). This increase is based on the recognition that business-as-usual is no longer a viable solution to the long-term impacts from increased greenhouse gases (GHG) in the atmosphere (Hill, 2016; Kates et al., 2012).

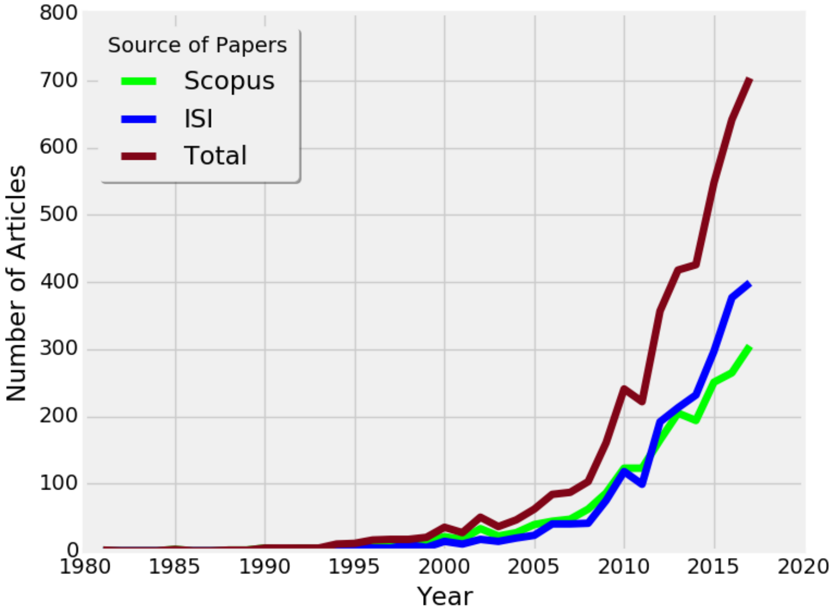

Figure 1.1. Increasing number of peer reviewed publications on transformation and climate change. Based on data from ISI's Web of Science online interface www.isiknowledge.com and from Scopus online interface www.scopus.com.

Transformation has many different definitions as shown in Table 1.1 (O'Brien & Sygna, 2013). Some researchers focus on the scope and scale of adaptation needed (Moser and Ekstrom 2010; Kates, Travis, & Wilbanks 2012). Others focus on the depth of the changes and the extent to which the system has fundamentally changed (Folke et al., 2010; Geels, 2011). Then there are authors coming from the field of political ecology who conceptualize transformation in terms of systems that maintain certain social hierarchies (Heynen et al., 2006; Pelling, 2010). For the context of this dissertation, I consider transformation to be a two-fold concept. First, in Chapters 3 and 4, I focus on the transformation as a cross between transformational adaptation and transformation to sustainability as defined in Table 1.1. In this sense transformation is about a meaningful change of the physical shorezone in terms of both protective infrastructure and ecological systems. Second, in Chapter 5, I look at transformation from the institutional sense exploring opportunities to change local agencies and planning processes to build future resilience. In Chapter 2 I use a systematic literature review to more deeply explore these terms and what we know about transformations.

Table 1.1. Different concepts and definitions of transformation (adapted O'Brien & Sygna, 2013).

Transformation Concept	Definition	Example Reference	Academic Discipline
Transformational adaptation	Large-scale changes made in the context of the changing climate	Kates, 2012	Various
Transformation to sustainability	Deep structural changes in infrastructure and ecological systems	Geels, 2011 Folke, 2010	Various
Transforming behaviors	The role of human agency in transformation processes	Crompton, 2011	Cognitive and social psychology
Social transformations	Transformations of the political, economic and social structures that maintain the system of risk and vulnerability	Pelling, 2010 Swyngedouw, 2010	Sociology, political ecology

Research questions

Transformations of physical settings and of institutions are incredibly challenging. Despite such challenges, there is a pressing need to understand how to strategically design and manage the shorezone to meet future sea level rise threats (Little & Lin, 2017). One step in creating transformative change is evaluating and comparing potential adaptation strategies. This dissertation offers insights into shoreline transformation and appropriate metrics through three major research questions:

1) How does the literature define transformational adaptation? And what knowledge is needed to support these actions?

2) How can we meaningfully compare the potential for transformation offered by different sea level rise adaptation strategies? And can we establish baselines against which future progress can be evaluated?

3) What strategic opportunities for adaptation and shorezone transformation do different evaluation frameworks reveal?

Methods

In this dissertation I primarily develop different evaluation assessment approaches and apply each to specific geographic locations and scales. In the dissertation I use four major methods: meta-analysis, case study research, multi-criteria assessment, and spatial analysis, which I explain further below.

Meta-analysis

A systematic assessment of the peer-reviewed literature provides key insights to researchers. This work enables the identification of existing gaps that allows for new directions in future research. Reviews also enable researchers to rigorously explain existing knowledge and provide summaries of the current evidence for such knowledge (Ford, Berrang-Ford, & Paterson 2011). To conduct a systematic literature review, one must clearly define search terms and clearly explain exclusions and inclusion criteria. Then one can compare research on quantitative and qualitative trends (Fink, 2010).

In Chapter 2 of this dissertation, I build on the themes above using a systematic literature review to identify over 30 peer-reviewed publications specifically on the topic of planned and anticipatory actions to achieve transformational adaptation. In the review I explore the scope, the leading actors, and the knowledge needs for transformational adaptation. Through this work, Chapter 2 identifies some key gaps that guide subsequent work in this dissertation. Specifically, Chapter 2 finds that more knowledge is needed that can help to create paradigm shifts towards adopting alternative landscape designs.

Case study research

Case study research in the field of environmental planning is unique in that it provides insights into both theory and practice. From a theory perspective, case studies can develop new theories especially by developing rules of thumb about landscape and projects at the site or region scale

(Francis, 2001). This analysis can be useful for management professionals since it can provide potential solutions for problems they are facing (Francis, 2001).

Case studies are empirically based efforts to study a current specific event or location in great depth within its existing context (Yin, 2013, p. 2). Case studies require multiple types of empirical data including mapping data, interview data, empirical observations from field visits, and the analysis of existing secondary data such as demographics. Case study research can either be done on a single site or it can be done in a comparative context (ibid).

I use case studies in Chapters 3, 4, and 5 of this dissertation to test the evaluation frameworks developed. In Chapter 3, I use seven physical projects in the San Francisco Bay Area (Bay Area) to test methods for the evaluation of the integration of sea level rise planning into physical designs. In Chapter 4, I use the Bay Area more generally to explore the strategic opportunities a cost estimate can provide. In Chapter 5, I use the state of California as a case study for a new regional evaluation framework.

Multi-criteria assessment

Multi-criteria assessments are used in many disciplines and have a wide range of applications. They have a long history of use in both the policy and planning arenas. These assessments provide a great deal of flexibility, allowing the researcher to identify the most important areas for evaluation. This technique is particularly useful when developing evaluations that expand beyond benefit-cost analysis. However multi-criteria assessments are difficult to design and interpret (Bardach, 2012).

When designing multi-criteria assessments researchers rely heavily on the literature to identify the most important areas for assessment. Through this work researchers develop initial evaluation criteria, which are sometimes grouped into specific categories. These initial criteria are tested through expert evaluation and comparison with existing assessments (ibid).

Chapters 3 and 5 include newly developed multi-criteria assessments. In Chapter 3 the assessment includes two unique categories and five specific evaluation criteria. This assessment is used to look at the quality of sea level rise planning in the context of physical adaptation plans. It helps to determine the degree to which these efforts are transforming over time the Bay Area shorezone. In Chapter 5 the assessment is broken down into 5 categories and 21 specific evaluation criteria within these categories. This assessment is used to explore successes and failures of regional sea level rise adaptation planning in the State of California.

Spatial analysis

Spatial analysis, a critical approach in both environmental planning and geography, is fundamentally about understanding how parts of our world relate to one another spatially. A very old discipline, with maps dating back centuries, it underwent a significant transition in the 1960s with McHarg and Steinitz articulating the need for systematic analysis as part of land use planning (Steinitz, 2008). The transition also involved a shift from maps to algorithms that represented landscapes and explored suitability. This laid the foundation for the shift to computers that led to the development of geographic information systems (GIS) (Chrisman, 2006). The use of GIS has increased significantly over the past 20 years. The proliferation of GIS can be seen in the number of fields of study that now include GIS in their methodologies (Bolstad, 2005).

Spatial analysis and GIS offer many benefits with respect to understanding coastal resilience. First, the methodology is widely adopted, and thus data can be shared and a larger audience can easily understand results. Additionally, researchers have used GIS for other scientific breakthroughs, thus suggesting that it is a valuable tool in scientific discovery (Goodchild, 2010). Finally, GIS is also incredibly flexible and can be used for a wide variety of applications. Thus researchers can use it to combine data from natural and social systems.

Chapter 4 of this dissertation relies heavily on spatial analysis to develop a regional cost estimate for different possible sea level rise adaptation strategies. The analysis utilizes three different spatial datasets including linear shore structures, sea level rise scenarios, and an aquatic habitat inventory. The chapter demonstrates that spatial analysis can reveal key insights into preferable shoreline solutions in terms of both location and adaptive structures.

Research contributions

Through this dissertation, I contribute to three bodies of literature by presenting unique ways to evaluate climate adaptation strategies at three different scales.

It contributes to the climate adaptation literature by applying a unique evaluation framework that consists of two different approaches. This mixed method work allows for a close examination of first-generation physical plans in terms of their ability to transform the shorezone.

It advances the coastal resilience literature in two respects. Firstly, it develops a unique analysis, which unlike research focused on the impacts of inaction explores the costs of different physical adaption strategies, such as levees and sea walls. By looking at adaptation planning from this perspective, it addresses critical issues related to shoreline alignment and realignment. Secondly, by connecting shorelines to habitat zones, the dissertation makes the case that ecologically sensitive sites could be part of future sea level rise solutions.

Lastly, it intervenes in ongoing debates in environmental planning concerning the comparison of progress on climate change adaptation planning. The analysis indicates that a mix of resources and leadership is required for regions to make progress on these complex planning efforts.

Structure of dissertation

This dissertation contains five subsequent chapters. Chapter 2 explores the literature and analyzes over 30 different articles, book chapters, and reviews on transformational adaptation. The chapter identifies possible levers for actions and knowledge that can help to create change.

Chapter 3 focuses on seven physical projects in the Bay Area, which explicitly claim to include sea level rise considerations. This chapter reveals that current work is slowly transforming the Bay Area and creating a more dynamic shorezone.

Chapter 4 investigates the physical, economic, and regulatory insights that a cost estimate for coastal protective infrastructure (including earthen levees, concrete walls, and wetlands) can reveal. It analyzes 169,000 30-m line segments of linear shore structures and predicts the costs of adaptation under eight different sea level rise scenarios.

Chapter 5 introduces my own design for a regional evaluation framework of sea level rise adaptation called the "Regional Planning Fingerprint." Based on the literature, I designed 5 categories and 21 specific evaluation criteria within these categories. The chapter also applies this assessment to six coastal regions in California. This chapter demonstrates a viable approach for establishing a baseline of current work and reveals key opportunities for strategic interventions by state and local planners.

Finally, Chapter 6 presents the conclusions of this dissertation and provides a future research agenda at the critical intersection of climate change adaptation, urban ecology, and environmental planning.

CHAPTER 2: TIME FOR CHANGE: A FRAMEWORK FOR IDENTIFYING THE NEED FOR STRATEGIC KNOWLEDGE

Introduction

There is an explicit call from many scholars and practitioners to engage in active transformations of social-ecological systems in order to avoid catastrophic losses associated with climate change (Heynen et al., 2006; Kates et al., 2012; Pelling & Manuel-Navarrete, 2011). However what such actions look like (Kates et al., 2012; Moser & Ekstrom, 2010), what institutional paradigms are needed to support them (Gupta et al., 2010), who benefits from these actions (Romero-Lankao & Gnatz, 2013), and how they can be implemented (Walker, Haasnoot, & Kwakkel, 2013) remain unclear.

Transformation is an old concept and exists within many different academic disciplines (O'Brien & Sygna, 2013). As noted in Chapter 1 the term has many different definitions (see Table 1.1). In the context of climate change, I am explicitly interested here in transformational adaptation actions, which are defined as large-scale changes made in the context of the changing climate (Kates et al., 2012). I understand transformational adaptation to be an inclusive term that covers both physical changes made to the landscape (as I write about in Chapters 3 and 4) as well as governance or policy changes that can lead to a different way of managing the landscape (as I write about in Chapter 5).

It is also important here to distinguish transformational adaptation from transitional adaptation and incremental adaptation (Roggema, Vermeend, & Dobbelsteen, 2012). Incremental change can be seen as marginal changes where the primary aim is to preserve the essence of an incumbent system (Park et al., 2012). For example when looking at a land use plan, if only 1 or 2 % of the land is altered, that would be incremental adaptation as compared to a plan where 30% of the land was designated to change function. In this second case the plan should be considered to contain transformational adaptation (Roggema et al., 2012). Transitional adaptation, while similar to incremental in that it is also about maintaining the system, is more about coping when a change is thrust upon the system (ibid).

My aim here is to understand climate change adaptation and the ways in which it can be transformational (versus transitional). In that context it's important to understand the term adaptation, which originally came from theories on evolution. The term's use has shifted in the policy context. It can be traced back to 1927, when John Dewey (1927) proposed that "policies be treated as experiments, with the aim of promoting continual learning and adaptation in response to experience over time." A growing body of literature on climate adaptation has developed various typologies over the last few decades (Biagini et al., 2014). However, the literature specifically on the topic of adaptive policies is limited, and there is no set typology of approaches (Walker et al., 2013).

Walker et al. (2013) building on the work of Schipper and Burton (2009) provide the following useful set of four dimensions on which to categorize climate adaptation approaches (Table 2.1): 1) intent, 2) timing of actions, 3) temporal scope of action, and 4) spatial scope of actions. For each they also provide specific options. For example, for the category of intent, the authors include autonomous and planned adaptation options. In light of my interest in intentionally avoided catastrophic losses, I focus on actions that are planned and anticipatory.

Table 2.1. Classification of adaptation actions—my focus in blue (adapted Walker et al., 2013).

Adaptation based on:	**Type of adaptation**		
Intent	Autonomous		Planned
Timing of action	Reactive	Concurrent	Anticipatory
Scope—temporal	Short-term		Long-term
Scope—spatial	Localized		Widespread

This leaves open the question of scope both in the temporal and spatial sense. Several authors have recently explicitly connected anticipatory planned adaptation actions to transformations. The burgeoning literature on social-ecological systems contains many papers on this exact topic (Folke et al., 2010; Moore et al., 2014; Olsson et al., 2006; F. R. Westley et al., 2013). In this literature the authors rely on the following definition from Folke et al. (2010): Transformability is "the capacity to transform the stability landscape itself in order to become a different kind of system, to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable." This definition remains open-ended on the question of both temporal and spatial scope. Thus I look to the literature to tease out an answer to these questions of scope.

When thinking about intentional actions, a key question that arises is, "Who are the actors?" Wesley et al. (2013) focus on the leadership literature and identify various terms for individuals who are critical in terms of "making it happen." O'Brien and Sygna (2013) suggest that there are actors in the practical sphere, political sphere, and personal sphere who shape the operating context and have the capacity to build toward transformative change through transformational adaptation actions. Park et al. (2012) place an emphasis on individual actors working at the level of a specific farm or site. On the other hand, Moser and Ekstrom (2010) focus on governing agents as the ones who can generate real world changes. In all contexts, the literature suggests that this is a multilevel and multiphase process. I use the literature to further examine the types of actor currently being considered (and overlooked) as part of these transformational adaptation actions.

Grappling with these questions can take on many forms. In this chapter I rely on a systematic literature review to rigorously summarize the existing understanding of transformational climate change adaptation actions and potential leverage points.

Systematic literature reviews are used primarily in the medical literature. However, the method was adopted by the social sciences in the 1960s (Petticrew, 2001). Ford et al. helped to bring the practice to the study of climate change adaptation (2011). Others have since used it in many different areas of climate change adaptation. Some have looked at the inter-relationships between adaptation and mitigation through a systematic review (Landauer, Juhola, & Söderholm, 2015). Others used such a review to better understand household-scale adaptation actions (Porter, Dessai, & Tompkins, 2014). Some researchers used this review technique to explore the protective role of coastal marshes in the context of rising seas (Shepard, Crain, & Beck, 2011). In terms of transformation some reviews try to get at the steps in the process (Moore et al., 2014) while others work on understanding the scale of action (O'Brien & Sygna, 2013).

In this chapter I rely on these two earlier reviews by Moore et al. and O'Brien & Sygna that are focused on transformation. Specifically, I look to the literature to develop a clearer understanding of transformational adaptation actions in terms of both the scale of the actions and the processes involved in creating such actions. For both of these matters I tease out an understanding of the knowledge needed to strategically compare options for action.

Review methodology

A systematic literature review is an analysis that focuses on the current knowledge related to a given topic. These reviews are structured to rigorously summarize existing understanding (Fink, 2010; Ford et al., 2011). They are used to locate, appraise, and synthesize evidence on a specific topic area (Petticrew, 2001). They also allow for quantitative and qualitative assessments of the literature (Ford et al., 2011). In this literature review I aim to: 1) deepen our understanding of transformational adaptation, 2) identify potential actors who can trigger actual changes, and 3) explore some of the knowledge needed to create real world changes.

To engage in this literature review I first conducted a key word search in Elsevier's Scopus and Thompson Reuters Web of Science (WoS) citation databases. Although considered comprehensive in the academic world, these databases do not always include books. Also they focus mainly on English-language publications and thus have an Anglo-American bias (Newell & Cousins, 2015). The search terms transform*, adapt*, plan*, knowledge*, and "climate change" yielded 82 results in WoS and 107 in Scopus. I further refined this search by excluding journals in unrelated topic areas (e.g., medical literature) and literature from 2019 and 2018. When combined, 21 duplicates were identified and thus the dataset included 67 unique publications.

These publications were further reviewed to determine if they actually were about intentional transformations in the face of climate change (see Table 2.1). Through this process another 32 publications were rejected on the basis that they did not meet my criteria. Most of the publications that I eliminated from the review fell into three main categories: 1) climate impact assessments, 2) non-intentional actions (e.g., reactions to stimuli) and 3) climate mitigation efforts. Once finalized, this review included 34 unique publications from a variety of disciplines. It included 31 articles, 2 book chapters, and 1 review.

These publications cover many different climate impacts (Figure 2.1). The majority of the publications (59%) look at climate impacts inclusively and do not focus on any one single impact. The other publications focus on a specific climate change impact—15% are concerned with the urban experiences of climate change, 9% are focused on the agricultural sector, and 17% are focused on flooding. It is important to note that some that focus on flooding include sea level rise, while others are set inland and thus only look at riverine flooding.

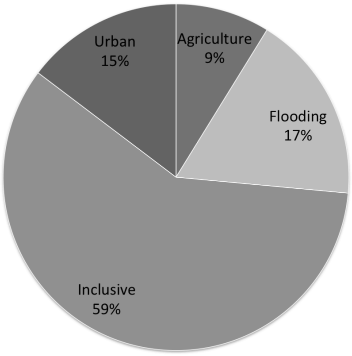

Figure 2.1. Pie chart showing climate change focus of the different papers in this literature review.

To address the conceptual tension noted above, I categorized these papers in terms of spatial and temporal scope. I then identified the specific critical actors—stakeholders, design professionals, urban planners, or resource managers—described in each of the publications. I also listed the knowledge needed and approaches used to enable transformation. Although these resulting categorizations represent a simplification of complex concepts and rigorous analysis, my objective was to provide a general conceptualization based on this literature. Finally, a conceptual schematic of landscape transformation is developed by drawing on this literature.

Results: Reflections on scope, leading actors, and knowledge needs

In this section I present my findings based on analyzing the 34 papers included in this review. I specifically present information on the temporal and spatial scope of the actions considered by these papers. I also provide details on the types of actors that the literature included. I then provide information on the types of knowledge gained through the research and the knowledge needs suggested by these findings. In each section, I go beyond simply presenting the results and reflect on the implications of these findings. In the final section I present a conceptual schematic of landscape transformation developed by drawing on this literature.

The spatial and temporal scopes included in the literature

The question of scope as discussed in the introduction is a two-fold question. Based on the categories offered by Walker et al. (2013) there is a question of the spatial scope and the temporal scope of actions that lead to transformational adaptation. In this review I find that the articles predominantly (nearly 80%) focus on localized actions rather than widespread actions (Figure 2.2(A)). This is surprising as one conceptually would think of transformations as occurring over a greater area (Moser & Ekstrom, 2010; Olsson et al., 2006). However, I take this to have two implications. The first is that transformational change does not necessarily have to be about changes to a large land area. Instead, transformational change is about making a substantial difference in the relevant area of analysis. Therefore, changing a single small site from one land use type to another (e.g., from a predominantly urban form to a predominantly habitat form) is transformational for the site itself. Second, although the researchers focus on a specific locale, their conclusions relate to governance or process and thus actually have broader more widespread implications.

When it comes to temporal scope, in this review I find that the articles mainly (76%) combine short- and long-term actions (Figure 2.2 (B)). In the context of this review I identified short-term and long-term based on key words in the abstracts. In the case of the papers identified as focused on short-term actions, some of the phrases were “current actions” or “rapid responses.” Then papers that I categorized as only long-term are ones that self-identified as such stating that their work was about understanding long-term efforts rather than reactionary responses. Finally, those that I categorized as both used a combination of these phrases suggesting that they were trying to understand short-term actions in connection with long-term actions or results.

It is interesting that papers on transformational adaptation would combine short-term and long-term actions. From a theoretical point of view one would expect to only see papers about long-term actions since these kind of efforts are the only ones considered transformational (Moser & Ekstrom, 2010). Some consider short-term focused work to be transitional (as defined above) and not actually transformational (Roggema et al., 2012). I, however, take the fact that the literature is combining these two timeframes to imply that there is a need to think about the bridge between transitions and transformations. In this regard, planning and the adaptation pathways approach offer us a way to bring together short-term actions with long-term change (Reeder & Ranger, 2011; Walker et al., 2013).

The adaptation pathways approach (also called the route-map approach) is a planning tool that creates long-term transformation through two avenues. Generally, the approach involves establishing a desired future set of conditions, different paths to those conditions, and tipping points that determine when certain paths should be followed (Walker et al., 2013). This enables long-term transformation by laying out short-term steps that can lead to an alternative future (e.g., shifting away from structural flood solutions to involved flood storage) (Reeder & Ranger, 2011). This approach also helps to avoid maladaptive decisions that can lead to catastrophic impacts in the future (Reeder & Ranger, 2011). By building in flexibility through the use of "what if" situations and their outcomes, this approach helps to limit costly investments and misguided decisions (Walker et al., 2013). Some specific examples of the use of this approach are plans for adapting the UK Thames Barrier project to sea level rise (Reeder & Ranger, 2011) and water management planning in the Netherlands (Kwadijk et al., 2010).

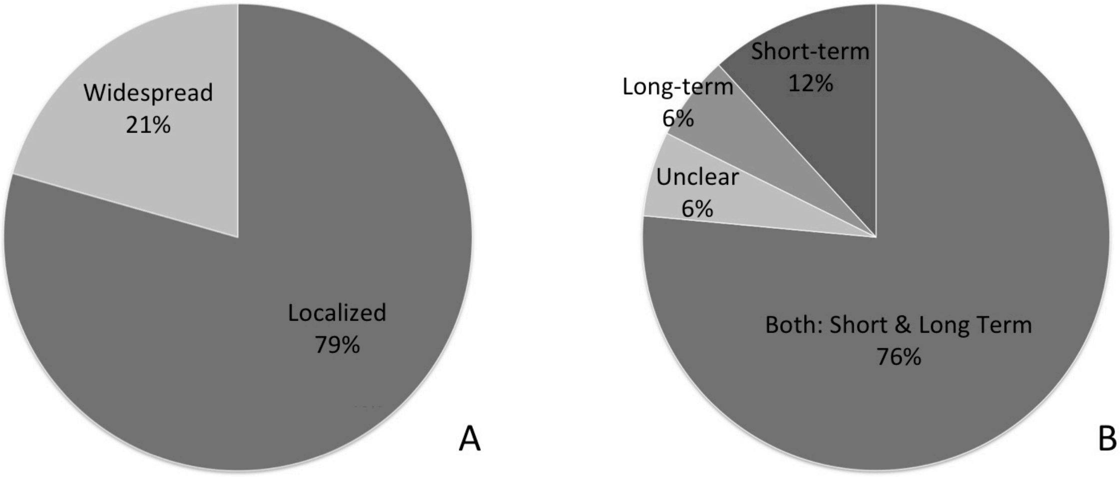

Figure 2.2. Pie charts showing the spatial (A) and temporal (B) scope of the different papers in this literature review.

Actors who initiate or drive change

All but 1 of the 34 papers I reviewed here include specific actors engaging in transformational changes. This literature offers four categories of possible actors: 1) designers, 2) resource managers, 3) stakeholders, and 4) urban planners. In general, when a resource was applicable to more than one code for actor type, I included all relevant codings. As shown in Figure 2.3 (A) 5% of the papers include designers, 28% include resource managers, 29% include stakeholders, and 38% include urban planners. Resource managers is a broad category I used to bring together all those that focus on natural systems and their management. This included, but is not limited to, papers on water resource managers (Baron, Hoek, Kaufmann Alves, & Herz, 2015; de Graaf et al., 2009), forest resource managers (Hagerman, 2016), and conservation managers (Chapin et al., 2010). Stakeholders is similarly a broad category. In the context of this work, I used this grouping to refer to the actions of individuals rather than the actions of professionals.

In looking at this data there are two groups that are noticeably absent or under-represented. First, none of the papers explicitly call our attention to decision makers. However, these actors have critical roles to play and are absolutely necessary to create transformational change (Brown et al., 2014; Hill, 2016). Second, it is surprising that designers are not represented in a larger percentage of the papers. Several authors highlight the critical role that designers play in creating future transformations (Hurlimann & March, 2012; Roggema et al., 2012). It is unclear why the literature reviewed here predominantly omits these categories of actors. It could be due to a narrow set of search criteria or it could be that few academic studies are analyzing the role these actors have on transformations. I argue that going forward these categories—decision makers and designers—should not be overlooked and must be included in future analysis.

Figure 2.3. Pie charts showing the type of actors addressed in the papers in this literature review. Chart A shows the full range of actors in all papers. Chart B shows those papers that focus on actions by individuals versus those that focus on actions by professionals.

In Figure 2.3 (B) I show how the literature primarily (nearly 65%) focuses on the role of practitioners in creating transformational change. The practitioners category here refers to several groupings of actors as captured in Figure 2.3 (A). Specifically, it includes urban planners (e.g.,Wamsler, Brink, & Rivera, 2013), designers (e.g., Roggema et al., 2012), and resource managers (Barnett et al., 2015). In contrast, only 21% of the papers focused on the role of individual actors. These individual actors include farmers (N. A. Marshall, Gordon, & Ash, 2011; Nadine Anne Marshall et al., 2014), grazers (N. A. Marshall et al., 2011), and citizens in certain communities (Ryan, 2016; T. F. Smith et al., 2011). Most striking in looking at Figure 2.3 (B) is the need to better understand the relationships and interactions between the individual actors and the practitioners. This finding substantiates what others have noted regarding a need to understand the multiple levels and the multiple sectors of actors (Berkes et al., 2003; Ostrom, 2009; Steinitz, 2012).

Potential levers that can lead to transformations

I show in Figure 2.4 two different ways to look at and cluster together different levers for transformational change identified in the literature I reviewed. In Figure 2.4 (A) I show the specific action approach the authors identified and explored. In Figure 2.4 (B) I show the knowledge areas the authors identified based on the social, ecological, and technological systems framework from Markolf et al. (2018). For both data sets I coded the literature to more than one category when it was appropriate. For example, Wamsler and Brink (2014) looked at both the planning processes involved in decision making as well as the governance capacity to interface with citizens. Thus I coded this as both a governance and planning approach publication.

As shown in Figure 2.4 (A) 51% propose using planning practices as a way to create transformative change through transformational actions, while 36% propose a focus on governance actions. Additionally, we see that 13% of the papers are unclear on the specific approach. Many of these papers are ones where the primary focus was on individual actors. In this sense these papers are more interested in a transformation emerging from the behaviors of individuals (Bonabeau, 2002; Bousquet & Le Page, 2004). When it comes to governance, the papers included a wide range of specific ways to create needed changes. Some suggested looking at changing institutional capacity (Wagner, Chhetri, & Sturm, 2014) while others were more focused on policy changes at the local and national scale (Chapin et al., 2010). Some of the papers suggested using an adaptive co-management governance approach (Butler et al., 2016) and several papers focus on the potential to mainstream adaptation to achieve transformational adaptation (Wamsler et al., 2013).

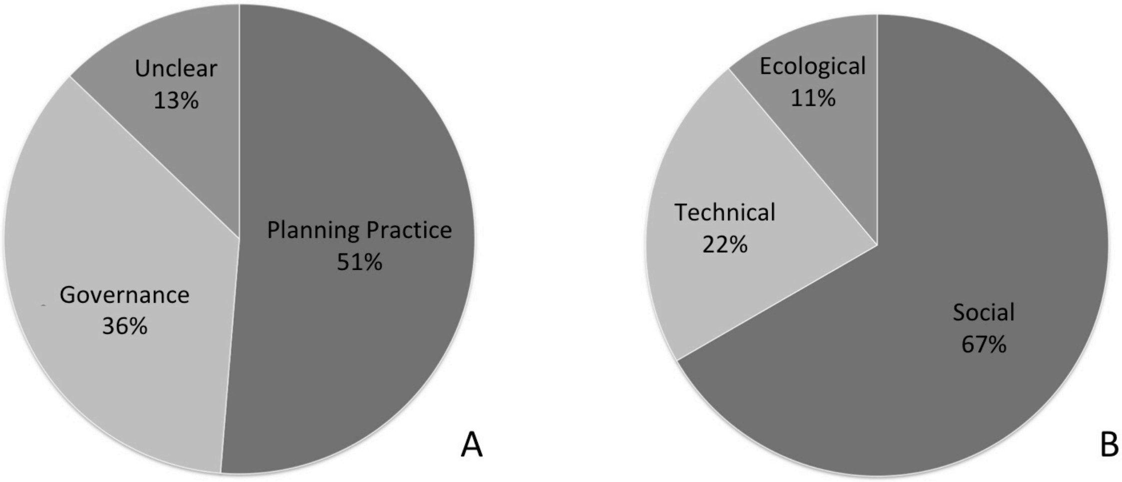

Figure 2.4. Pie charts showing the approach (A) and knowledge area (B) needed to create transformations according to the different papers in this literature review.

Planning is also a broad category that in this case includes many more common planning practices as well as some newer ideas. Among the common planning practices suggested are: using adaptation pathways (Butler et al., 2016), creating networks of actors (Dowd et al., 2014), using participatory planning (Sharpe, Hodgson, Leicester, Lyon, & Fazey, 2016) and using scenario planning (Rickards, Wiseman, Edwards, & Biggs, 2014). Scenario planning in particular is known to be a powerful tool commonly used to understand change impacts and vulnerabilities (Berkhout et al., 2013). One of the newer approaches suggested was the use of emotive-physical storytelling (Ryan, 2016). The focus of this literature on planning practices is not surprising as this is likely a result of the search terms as well as the further culling process I used to focus in on intentionally planned actions. Further, I think it's important to note that these findings match with earlier theories of creating transformations in the landscape (Steinitz, 1990) and urban environments (Timmerman & White, 1997) through physical planning and adapting to climate change through planning (J. B. Smith et al., 1996; Titus, 1990).

I find that 67% of the papers in this review suggest that social knowledge is critical, while 22% focus on the need for technical knowledge. I also find that only 11% focus on the need for ecological knowledge. To unpack these categories, we can look more specifically at what was included in each. For example, papers that were coded for ecological knowledge specifically discussed the need for environmental data (e.g., Wagner et al., 2014). Those that were coded for technical knowledge involved modeling (e.g., Baron et al., 2015), or spatial analysis (e.g., Roggema et al., 2012). The social knowledge category was the broadest and included a wide range of knowledge areas including: local perceptions (e.g., Eriksen, Nightingale, & Eakin, 2015), values (Colloff et al., 2017), and racial histories (Hardy, Milligan, & Heynen, 2017).

This emphasis in the literature on social knowledge and understanding is rather surprising given the long history and focus on improving models and data to make the case for climate change action (E. L. F. Schipper, 2006). I propose that these surprising findings are the result of two things. First, my coding process could in part explain these findings. Many of the papers explicitly highlight the need for local knowledge that I coded as social; however this knowledge could be about key ecological information and thus could actually fit into two categories. The other explanation is that these are newer papers and it could reflect a growing sense that meaningful change in fact requires critical changes in beliefs (O'Brien & Sygna, 2013). Based on this second interpretation, I propose a focus on the types of strategic knowledge building about adaptation strategies that would in fact lead to the paradigm shifts necessary for transformational change.

Discussion: Conception of transformational adaptation

Based on the findings from the literature presented above I propose the conceptual schematic of transformational adaptation in a landscape context depicted in Figure 2.5. The graphic merges imagery from Elin Enfors (2013) who looks at social-ecological feedbacks in a dryland farming context and key theoretical work of Lance H. Gunderson who developed the broad application of the ball and cup heuristic used in this figure (2000). I used Enfors' figure as the initial basis for the central square with a ball evolving through time with the potential to travel down any one of the four alternative paths. I changed Enfors' top four alternatives from a generic set of feedback loop concepts to visuals of landscape types. Shifting to these landscape types highlights the roll of design and the intentional actions associated with creating the landscape.

I also merged a ball and cup heuristic into Enfors' original square. This heuristic was initially depicted by Scheffer et al. in their study of alternative stable states in shallow lake ecosystems (1993). Gunderson further generalized the graphic and applied it more broadly to many ecological systems. In his conceptualization, the ball represents the system in question (grasslands, rangelands, clear lakes, etc.). The valley represents stability domains where a set of conditions help to maintain the system in a certain state. For example, recent work by Larsen and Harvey shows how feedbacks between morphological, hydrological, and biological systems in wetland landscapes operate together to determine the equilibrium pattern (2010). Then the arrows in Gunderson's graphic represent disturbances such as the grazing of grasslands (2000). Finally, the shape of the cup and slopes of the walls relate to a system's resilience (2000).

As I conceive of it, this graphic is intended to show transformational adaptation in a landscape context with a focus on planned and anticipatory actions. By depicting the system's long-term potential in terms of landscape types I capture both the localized changes and widespread changes included in this literature. I further explore these themes in Chapter 3 where I explicitly look at transformational adaptation in terms of site-scale designs (localized) and their implications for the broader San Francisco Bay region (widespread). I also intentionally depicted the system's potential to change through time as a way of conceptualizing a mix of short-term actions and long-term implications. By making a specific change today, actors can change the path and associated dependencies of a landscape. Thus these actors could set a landscape onto a specific trajectory.

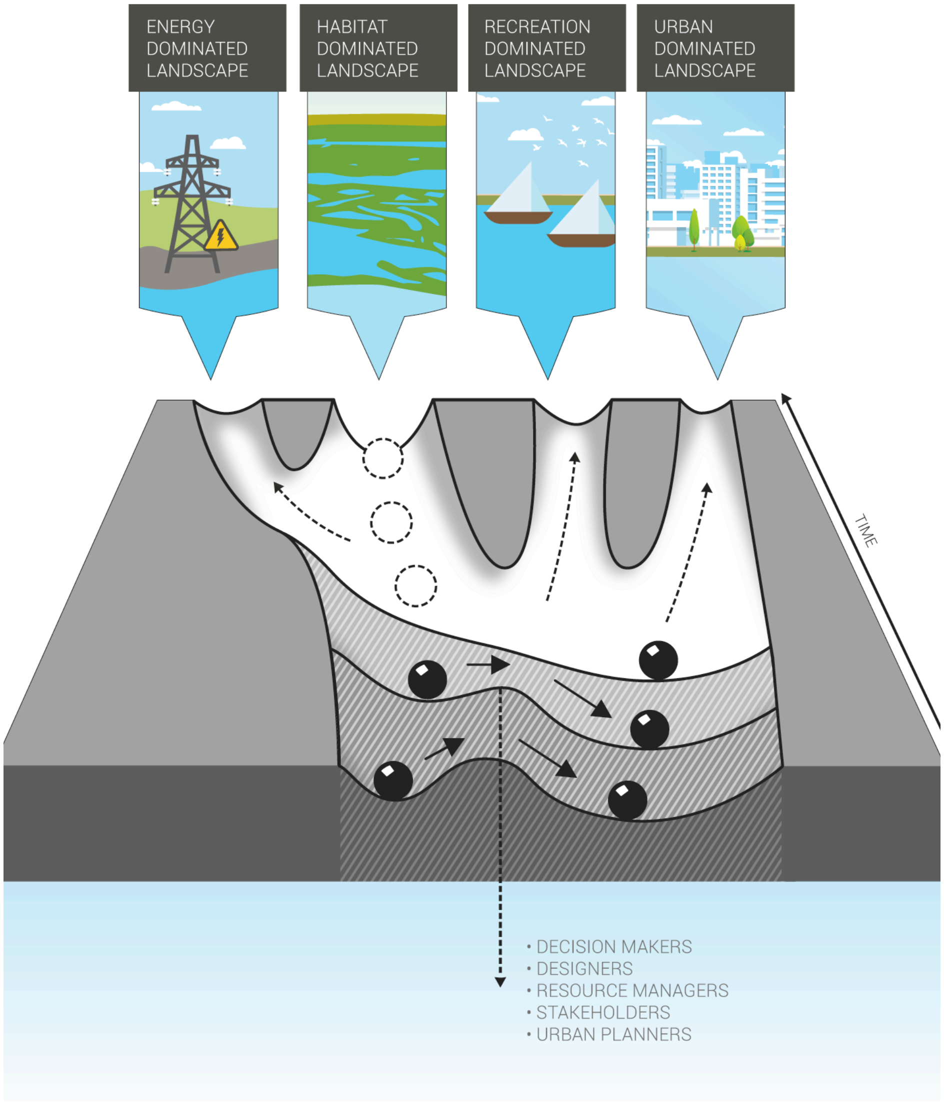

Figure 2.5. This figure is a conceptual graphic depicting my current understanding of transformational adaptation in a landscape context. The graphic merges imagery from Elin Enfors (2013) and Lance H. Gunderson (2000) to show the possibility for certain actors to intentionally shift a landscape in a particular direction.

Thus I connect this literature with earlier theories on alternative futures (Steinitz, 2012) and the adaptation pathways approach to planning (Walker et al., 2013).

As shown in Figure 2.5 it is my understanding that certain actors (e.g., a designer, a professional planner, a decision maker, or a resource manager) have the potential to intentionally shift a landscape in a particular direction. I generated this list of actors based on the literature reviewed here and on prior theory which suggests that designers (Hurlimann & March, 2012; Roggema et al., 2012) and decision makers (Brown et al., 2014; Hill, 2016) also have key roles to play. I further explore the role of these actors in Chapter 5 where the analysis is based on data generated from interviews with urban planners and resource managers. It should be noted that prior theory tells us that while actors have this potential, it's not about one single actor creating such a shift, but about the complex interactions between many actors at different scales working together to create these kinds of changes (Berkes et al., 2003; Ostrom, 2009; Steinitz, 1990). This review highlights the gap in our understanding of these interactions as they relate to transformational changes. Below, and in Chapter 6, I propose key future questions and a related research agenda to help close this gap.

Not directly captured in this figure are the remaining topics of approach and knowledge as described above and captured in Figure 2.4. In terms of approach, I find that recent literature highlights planning and governance as the two necessary approaches to achieve transformational adaptation. These findings support previous theory on the topic of physical planning (Steinitz, 1990; Timmerman & White, 1997) and climate change adaptation (J. B. Smith et al., 1996; Titus, 1990). Through this review I capture a recent shift in the literature recognizing the call for knowledge in the social realm. This realm according to Markolf et al. includes many topics such as economic and financial systems, equity and affordability, codes and regulations, and behavior and decision making (2018). This review leaves open the questions of 1) how to integrate this knowledge type with these specific approaches, and 2) what exactly this type of strategic knowledge looks like. I explore these questions about knowledge needs in all of subsequent chapters through the development and application of different evaluation approaches. I focus on building new knowledge in the area of social realm based on the results of this literature and the call for this particular need.

Conclusions: Summary and next steps

In this literature review I look at recent publications and build on prior theory to develop a conceptualization of transformational adaptation (Figure 2.5) that acts as a guide for my subsequent chapters. Based on this review I see transformational adaptation as happening through the direct action of key players operating at local and regional scales to create short-term actions that build toward long-term change. With these ideas related to transformational adaptation as the foundation, I utilize subsequent chapters to explore different evaluation approaches and shed further light onto the potential levers of change. In this chapter I looked at transformation in the context of many different climate change impacts (Figure 2.1). In the subsequent chapters I focus on sea level rise in particular.

CHAPTER 3: ADAPTING TO SEA LEVEL RISE: EVALUATION OF SEA LEVEL RISE ADAPTATION PILOT PROJECTS

Introduction

Scientific evidence indicates that climate change is accelerating the rate of sea level rise (Nerem et al., 2018). Coastal communities, which are home to millions of people, face significant risks, such as increased flooding from the confluence of higher seas and higher rates of precipitation (Wahl et al., 2015) and saltwater intrusion into aquifers (Griggs, 2017). Increased rates of sea level rise also threaten critical habitat for fish and birds (Stralberg et al., 2011). Designers and engineers are developing physical strategies to adapt coastal sites to some but not all of these future threats. Additionally, some previously designed projects are expanding their scope to include efforts to adapt to future sea level rise. However, no systematic evaluation of such projects exists. Such an evaluation would provide insights into the true potential for these projects to produce much needed transformations and the projects' overall quality.

Given this context, I address the following question: How can physical sea level rise adaptation projects be evaluated? I apply this question to physical projects that include sea level rise in their design at various stages of development in San Francisco Bay Area (Bay Area). I build on the literature to develop an evaluation framework that consists of two different approaches (referred to here as approach 1 and approach 2). I present the data and methods I used, the results from this work, the implications of these findings, and critical conclusions.

Critical context

Scientific evidence indicates that climate change is accelerating the rate of sea level rise (Nerem et al., 2018). Coastal areas are especially threatened since this rise will elevate water tables and cause increased flooding, especially when flood events coincide with extreme precipitation (Wahl et al., 2015). The risks to coastal communities from sea level rise are serious, and the consequences of inaction are dire—threatening more than 100 million people per year (Nicholls et al., 2007).

Coastal threats from sea level rise are exacerbated by a long history of human development in the coastal zone. Poor land use planning and increasing populations in coastal regions place millions at risk (Hill, 2013; Nicholls et al., 2007). Dense coastal development places major regional infrastructure at risk from sea level rise as well (Biging, Radke, & Lee, 2012). Industrial use in coastal regions has a long history of leading to major threats from contaminated sites. Experts estimate that in the San Francisco Bay there are ~200 contaminated sites at risk from future sea level rise (Heberger, Cooley, Moore, & Herrera, 2012). Land subsidence and saltwater intrusion into freshwater aquifers due to mismanagement of groundwater systems are other near shore concerns (Griggs, 2017). Human activity in the coastal zone and associated watersheds has led to habitat destruction with serious declines in habitat area as well as hydrologic integrity (Nicholls & Klein, 2005; Pennings & Bertness, 2001).

Coastal communities, in the context of these threats, are developing climate adaptation strategies and plans. According to the Georgetown Climate Center there are 65 local or regional plans in the United States that include the issue of sea level rise (2018). Some communities are integrating sea level rise planning into existing planning work (Bierbaum et al., 2013). For example, the City andCounty of San Francisco created a method that enables each department to integrate sea level rise into capital improvement decisions (City and County of San Francisco & San Francisco Capital Planning Committee, 2015).

Researchers in the fields of geography and planning are identifying the need for intentional transformations of social-ecological systems to address climate change (O'Brien & Sygna, 2013; Pelling, 2010). In the past five to 10 years, coastal adaptation efforts in California have moved beyond planning to actual implementation in the form of both regulatory changes and physical projects. For example, in California local governments are updating their Local Coastal Programs, which are part of zoning regulations, to include sea level rise considerations (Herzog & Hecht, 2013). In Ventura, California, there is a physical adaptation project that stages a retreat from the shorezone over time, and this community serves as one example of a growing number beginning to address sea level rise through physical projects ("U.S. Climate Resilience Toolkit," 2015).

Here I focus on physical adaptation projects in the Bay Area. In 2015 I, in conference with local experts, identified seven physical projects as leading edge designs for physical adaptation to sea level rise. I then assessed the extent to which these projects are models for physical transformation. This research also considers what lessons can be learned for future physical climate adaption projects. This research reviewed a total of seven projects in the Bay Area, designed or constructed in the past 10 years. This analysis used an evaluation framework that consists of two different approaches. Approach 1, drawing on evolutionary landscape theory, looks at each project's transformative nature based on Hill's coastal infrastructure typology (2015). Approach 2 uses evaluation criteria to describe how each project has considered sea level rise science and the hydrologic connections between fluvial flooding, the water table and sea level rise.

My analysis in this chapter strongly supports the need to increase the usability of the latest scientific understanding of sea level rise dynamics by creating data products and visuals that designers can include in their site plans. My assessment also provides insight into the complexities of dynamic coastal environments, suggesting that while it is important to have improved guidelines, the strengths of any single adaptation strategy ultimately reside in site-specific, contextual analysis and performance-based evaluations. Finally, my research shows that it will be necessary to expand the geographic extent of the projects I have reviewed (i.e., increase the number of locations where projects of this nature are placed) to genuinely prepare for future climate impacts. Based on my work in Chapter 5, this will require a much higher degree of social and political commitment.

Policy context

The United Nations Framework Convention on Climate Change added climate adaptation to its research and policy agenda in the early 1980s. However, climate adaptation has generally been preceded by efforts to mitigate climate change to reduce the magnitude of adaptation requirements (E. L. F. Schipper, 2006). As a result, climate adaptation broadly and sea level rise specifically represent a relatively new area for project designers and engineers.

California, as a state, has a long history as a leader on addressing climate change (Schreurs, 2008). Initially, like at the international level, this work focused on climate change mitigation and on the development of downscaled data on climate impacts (Hayhoe et al., 2004; Moser & Tribbia, 2007). Formal adaptation work began in California with the Governor's Executive Order S-13-08, which requires state and local agencies to include sea level rise in their future plans (2008). Since this executive order, state agencies have written three guidance documents on planning for sea level rise. The newest guidance was recently released, and a related report states that planners should consider up three meters of sea level rise by 2100 (California Natural Resource Agency & California Ocean Protection Council, 2018; Griggs et al., 2017). This guidance does not provide specific directions for strategies at the project and site scale in coastal regions. It also does not include formal standards for evaluating an adaptation project in advance of the anticipated sea level rise itself to determine the likelihood of success.

In addition to state-level guidance, researchers and expert practitioners have identified the California Environmental Quality Act (CEQA) as an avenue for local governments to evaluate projects and require them to address sea level rise (Herzog & Hecht, 2013). CEQA requires state and local government agencies to conduct thorough environmental review of projects. Following these reviews, they can then make discretionary decisions to approve or deny the projects. The recently released California-specific database (resilientca.org) identifies nine cases where CEQA was used to force projects to consider sea level rise. In one specific example, the State Lands Commission included sea level rise requirements prior to approving Chevron Products Company's modifications to its Richard Refinery Long Wharf (Chevron Products Company, 2016). Using CEQA could help communities force projects to include sea level rise; however, communities would have greater recourse with consistent evaluations for project designs.

Despite the absence of specific measures of adaptation success, a number of projects have been described as nationally significant case studies. For example, the U.S. Climate Resilience Toolkit features 17 case studies from all over US that address sea level rise, are coastal in nature, and take specific actions. Among these is a recent project in Ventura, California, where managed retreat was implemented by removing a parking lot and restoring a beach ("U.S. Climate Resilience Toolkit," 2015). Similarly, the Climate Adaptation Knowledge Exchange managed by EcoAdapt features 17 community-scale case studies that address sea level rise and involve planning and development for retrofitting infrastructure. The San Francisco South Bay Salt Pond Restoration Project is one of these examples, with the goal of converting 15,100 acres of industrial salt ponds to tidal wetlands in part to adapt to sea level rise (EcoAdapt, 2018).

In addition to wide variations in goals, coastal adaptation projects that intend to prepare for sea level rise can take place at various geographic scales. This research is focused on community-wide projects that are at least one square kilometer 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. I made one exception, in approach 1, to include a unique demonstration project (the Oro Loma Project, #3) designed to test the potential for a new type of levee that is combined with a broad salt marsh ecotone nourished by treated wastewater as a future climate adaptation strategy. I included this project because many local experts have pushed this solution as the leading strategy to adapt the San Francisco Bay and other developed estuaries to sea level rise.

The regional context

The Bay Area (see Figure 3.1) is a highly dynamic place with 700 million residents, making it one of the largest population centers in the United States. The area also hosts major industries, including Silicon Valley's technology industry and Napa Valley's wineries. The Bay Area is also defined by its estuarine conditions and provides critical habitat for shorebirds along the Pacific Flyway. A historical emphasis on coastal industry and agriculture eliminated roughly 90% of the Bay Area's wetlands (Callaway, Parker, Vasey, Schile, & Herbert, 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).

The Bay Area, with three major metropolitan centers and low-lying shorelines, is facing dramatic impacts in developed areas and in its reconstructed ecosystems from sea level rise (Heberger et al., 2012; Stralberg et al., 2011). In the face of these threats, the Bay Area is actively working to address sea level rise risk through local 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).

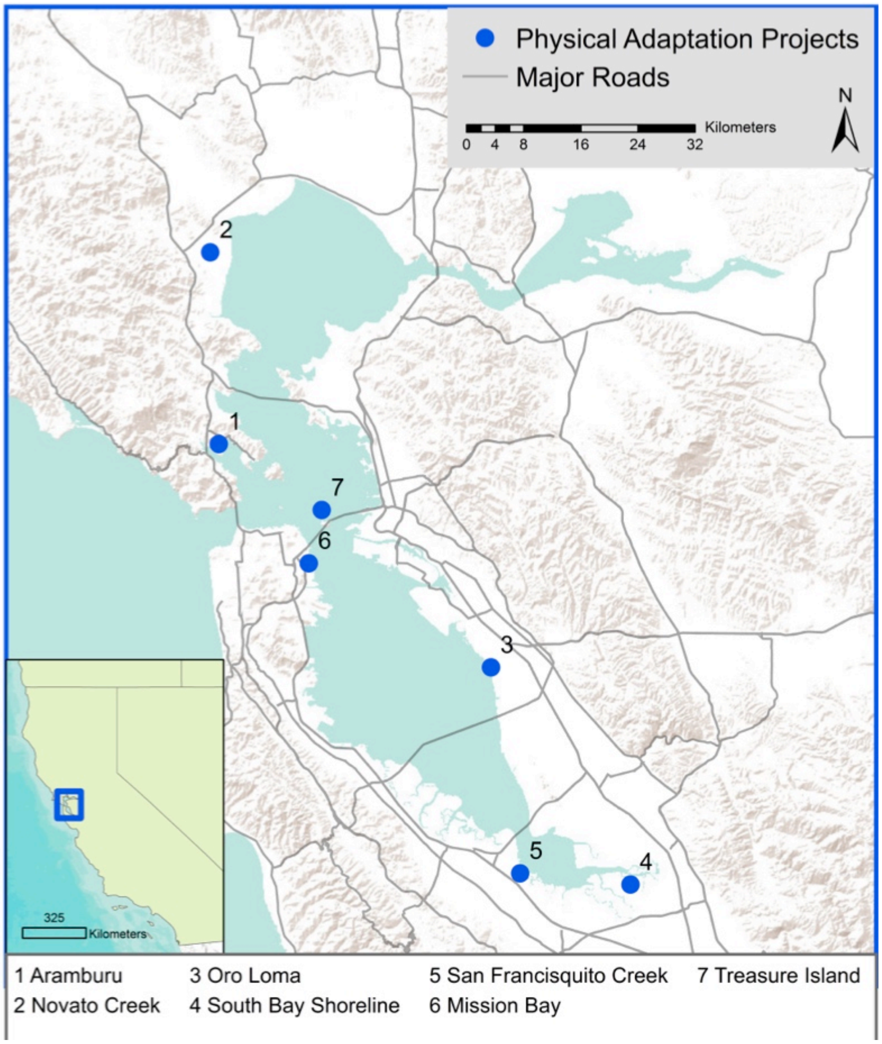

Figure 3.1. The San Francisco Bay Area and the location of the projects evaluated.

Methods

I compiled a list of physical adaptation projects by searching local government websites and surveying local sea level rise stakeholders. In 2015 I identified seven adaptation projects (see Figure 3.1 and Table 3.1) in the Bay Area that were at the time considered by experts to be examples of climate adaptation work and met my community-wide scale criteria noted above[1]. The projects are geographically diverse, representing five of the Bay Area's nine counties. They include four different stages of development, from a conceptual site plan to built projects. While each project is unique to its particular site, there are features that most projects share. Increasing the heights of existing physical shoreline protections while restoring habitat is a common physical strategy.

Table 3.1. Overview of each of the seven projects evaluated.

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

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

This evaluation framework consists of two different approaches. Approach 1 draws on evolutionary landscapes theory 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. In that analysis, the researchers use numerical scores to evaluate local plans on the plan's potential to mitigate multiple impacts of climate change (2012). I used a similar approach, but developed five new evaluation criteria, presented below. These criteria are specifically focused on impacts of sea level rise rather than the broader set of climate change impacts included in the Baker et al. analysis. I designed the criteria to be used for site-based physical adaptation projects rather than the regional plans analyzed by Baker et al. I based the evaluation on the physical design specifications described in project reports, and on geographic information system (GIS) data. I relied on a combination of design specifications and final engineering drawings as descriptions of the spatial extent and components of these projects.

Approach 1: A project's transformation of the shorezone

Approach 1 is based on the analytical framework originally presented in an earlier paper by Hill (2015). This analytical framework, derived from theories of evolutionary landscapes, addresses issues of long-term planning in the context of a changing climate. In this assessment shorelines are categorized as landforms or walls, and as static or dynamic. Projects can then be placed in one of four quadrants: 1) static walls, 2) dynamic walls, 3) static landforms and 4) dynamic landforms. This typology emphasizes flexibility, in terms of the feasibility of raising the infrastructure over time, and the potential for a coastal infrastructure type to provide multiple benefits. For example, the typology treats walls as single-purpose structures that do not provide multiple benefits, such as recreation, wildlife habitat, or other ecosystem services.

I utilized this typology because it offers my research multiple benefits. 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 site and determine the degree to which it can confer multiple benefits and has future flexibility. Additionally, the typology is flexible and thus can be applied to a range of different projects such as those I am evaluating. Finally, this typology allowed me to combine spatial data and project designs as necessary for this analysis.

In this research I 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, I 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 (NAVD88). 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. I also used each project's report to develop a project specific boundary.

First, I used the reclassification scheme shown in Table 3.2 to align the shoreline data from SFEI to the shoreline typology (Hirschfeld & 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, I used Google Earth's historical imagery to generate the data for the pre-development conditions. In the third step I used each project's design specifications to generate new shoreline types to describe the projected post-development conditions. For example, I 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, I changed the designation of the shoreline to reflect this as a post-development condition. In the case of the Mission Bay Project (#6), I developed separate analyses for the creek portion (referred to as 6A) 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 I 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.

Table 3.2. 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

Approach 2: Physical project document assessment

I based my evaluation criteria on a critical review of current best practices in the literature of adaptation planning. The criteria are also based on the state of climate science at the time of plan development (see Figure 3.2).

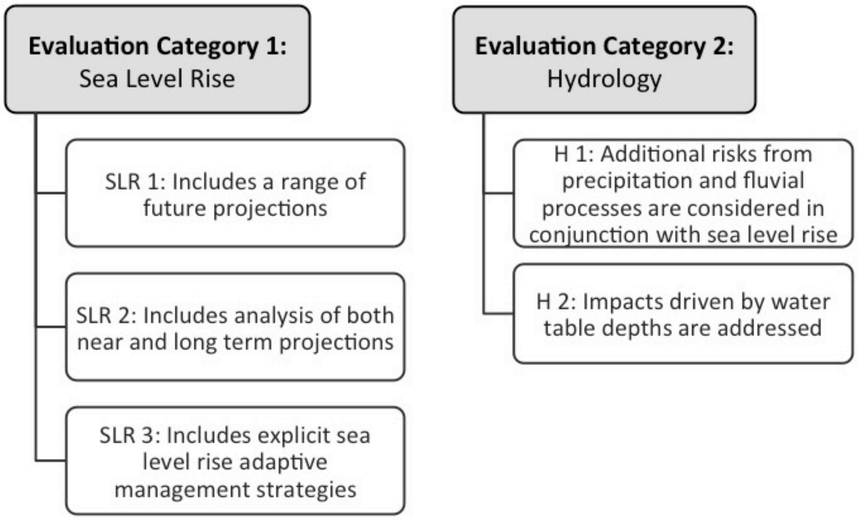

Figure 3.2. Categories and criteria used to evaluate design plans specifications.

Evaluation category 1: Sea level rise

I propose two categories of novel criteria that can be used to evaluate projects that seek to adapt to sea level rise. First, using the three criteria below, I evaluated the specific ways these projects conceived of sea level rise as a temporal phenomenon. Note that I intentionally did not get into which sea level rise model the project was using, but rather focused on the way they used the data. Clearly the model they are using is important, and future research should work to include this analysis. In *SLR 1*, I score the projects based on the degree to which they include a range of future sea level rise projections rather than simply designing for a single numerical projection of sea level rise, scoring higher projects that prepare for a range of projections. In *SLR 2*, I score each project's use of timeframes for design, and give high scores for projects that include both near-term (~2050) and long-term (~2100) sea level rise analysis. In *SLR 3*, I score the projects based on their explicit inclusion of adaptation management strategies for sea level rise that allow changes to design as new observations are made over time.

SLR 1: Includes a range of future projections
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. However, significant uncertainties remain. The exact amounts of eustatic and relative sea level rise remain unknown. The timeframes for certain amounts of sea level rise are still uncertain as well. Additionally there are many local factors that affect the amount of sea level rise a site will experience (IPCC, 2014). As a result, I 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 local projects is by integrating future localized sea level rise data with storm surge analysis to create a spatial understanding of the impacts on current land-use patterns, regardless of the source of flooding in a specific event. Through this modeling, further vulnerability, risk, and exposure analyses can be integrated into project designs (Baker, Peterson, Brown, & McAlpine, 2012; San Francisco Bay Conservation and Development Commission (BCDC), 2017).

In addition to developing analysis that includes ranges and timeframes for sea level rise, projects benefit from being developed as part of a larger strategic vision and including adaptive management (Haasnoot, Kwakkel, Walker, & ter Maat, 2013a). Such plans allow for the development of contingencies and alternatives in response to observations of trends and impacts. These plans also identify data to track and thresholds to look for in order to shift to an appropriate alternative. One example is the adaptation pathway framework developed for the Thames Estuary region, including the Thames Barrier (Reeder & Ranger, 2011).

Evaluation category 2: Hydrology

For my second category of evaluation criteria, I looked at the extent to which the project considered the interaction of sea level rise with floodwater from freshwater sources. In *H 1*, I score the projects based on the degree to which they integrate future sea level rise projections with surface freshwater sources. In *H 2*, I 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 (Wahl et al., 2015). 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. Associated impacts from rising water tables and a narrowing of the unsaturated space include reduced infiltration and drainage capacity, saturation of the soil, remobilization of existing soil pollution, and saltwater intrusion into drinking water systems and underground infrastructure (Habel, Fletcher, Rotzoll, & El-Kadi, 2017). A robust sea level rise project should include a localized analysis of groundwater impacts associated with sea level rise.

Project scoring

I assessed six of the seven projects using the above criteria and recorded my results with a coding system derived from Baker et al. that assigned numeric values to the evaluation criteria (2012). I did not assess the Oro Loma Project (#3) using approach 2 because the designed version is a small-scale pilot project testing a wetland's ability to treat wastewater. For each criterion I assessed each project according to its performance on a five-point scale (0, 1, 2, 3, or 4) (see Table 3.3). For example, I gave one plan a score of 1 for the "timeframes" criterion (*SLR 2)* since the plan briefly recognizes the long-term nature of sea level rise, but provides no further details or related dates. Two plans 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), I dropped the "adaptive management" criterion (*SLR 3*) due to the preliminary stage of the project. For the Aramburu Project (#1) I dropped the "additional risks" criterion (*H 1*) since the site context does not include significant fluvial processes.

Table 3.3. 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

Data and methods access

Our data and detailed methods are available at UC Berkeley's online data archive (DASH). 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 I used can also be downloaded from this site. These data can be accessed at this URL: https://doi.org/10.6078/D11S3N.

Results

Here I present the findings for the adaptation projects from (1) my analysis of the transformation of the shorezone, (2) my evaluation of specific ways these projects included sea level rise, and (3) my evaluation of the extent to which each project considered floodwater from freshwater sources.

Results from approach 1—the transformation analysis

I 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 3.3 shows results for both the pre-development and post-development conditions. The pre-development project sites are almost all located in the static landform quadrant of the typology diagram. These pre-development conditions are all less than 10% wall, with the exception of the Mission Bay Project (#6). The pre-development conditions of the projects are all less than 50% dynamic, 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. The Bay Area predominantly comprises static landforms (69% of the entire SF Bay edge) (Hirschfeld & Hill, 2017).

In the post-development condition, I see transformation toward a more dynamic shorezone. While most individual projects remain in the static landform quadrant, every project that shows any change shows an increase in the percentage of the shorezone 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 proportion of walls, and the Novato Creek Project (#2) has a 1.5% increase in proportion of walls. The South Bay Shoreline Project (#4) is a notable exception in that it actually moves into the dynamic landforms quadrant, and shows an increase of 45% along the x-axis (static/dynamic). 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 typology diagram.

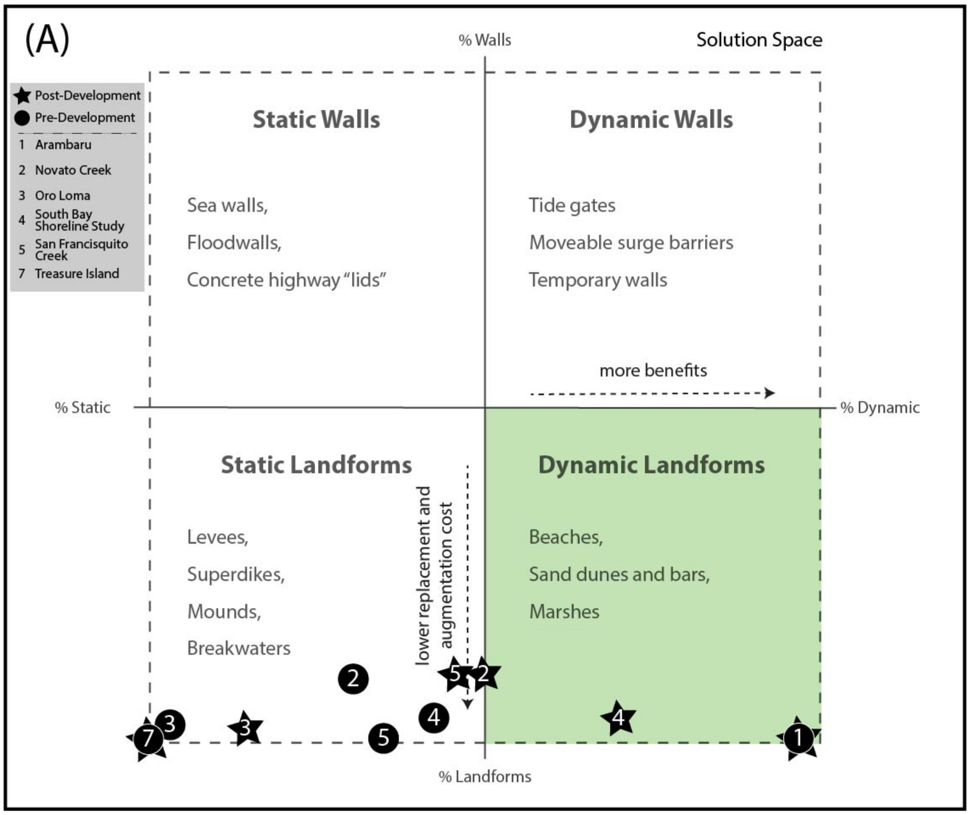

Figure 3.3. Six projects pre- and post-development are shown using a four-quadrant typology of protective shoreline structures. The vertical axis is defined by the percentage of shoreline that is wall, versus the shoreline that is built with earthen materials, such as sand and gravel (landform). The 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.

The Mission Bay Project (#6) results are shown separately in Figure 3.4A and 3.4B because of the wide variety of post- development conditions associated with multiple plan scenarios. The figures show that the site's pre-development condition is unique relative to the other sites. The Mission Bay site has significantly more wall (30% at the creek and 72% along the shoreline) than the other sites. Mission Bay is similar to the other sites in that its shoreline is predominantly static. All three options for a post-development 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-development options for the Bay shoreline (6B) of the Mission Bay Project (#6) shift in the opposite directions from the creek shoreline. Three of the options (a, b & d) significantly increase the percentage of landform along the shoreline. One option—using an elevated 3rd street (c)—would move the project into the "dynamic walls" quadrant of the typology.

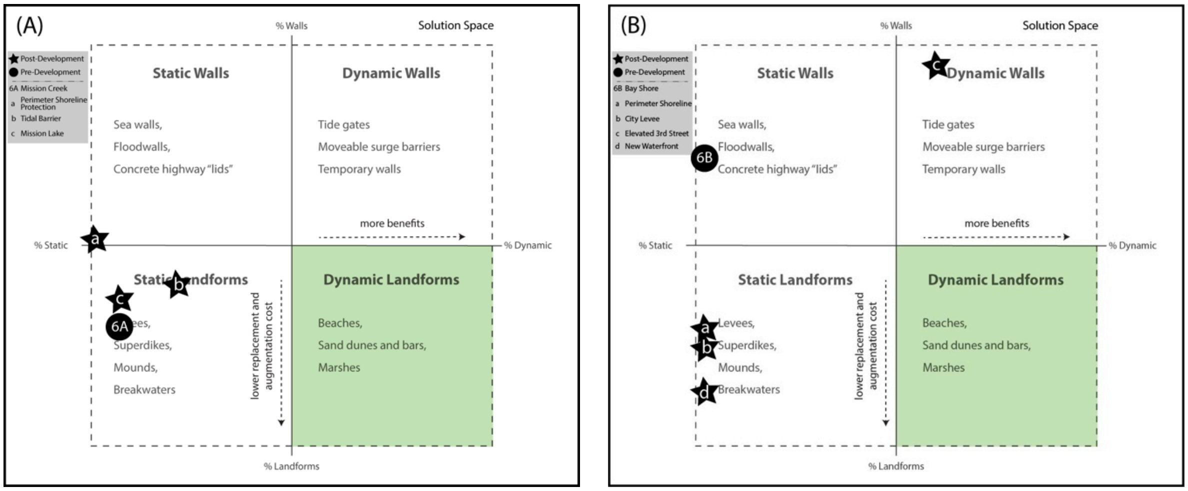

Figure 3.4. The Mission Bay Project (#6) is shown using a four-quadrant typology of protective shoreline structures. The project is split into two portions. The creek portion is referred to as project 6A and is shown in Figure 3.4A. The Bay shore portion is referred to as project 6B and is shown in Figure 3.4B. This project also has multiple post development options which are represented by the stars and labeled as A–D.

Results from approach 2—physical project document assessment

Here I used five criteria, scored on a zero to four scale, to evaluate each project. Figure 3.5 shows results for each project using my two categories of evaluation criteria: 1) sea level rise (*SLR 1*, *SLR 2*, and *SLR 3*) and 2) hydrology (*H 1* and *H 2*). I show the results as a percent of 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 total project scores improve over the years.

Our evaluation categories (sea level rise and hydrology) represent two critical topics that may determine success or failure in these adaptation projects. 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 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 category. The San Francisquito Creek Project (#5), with a score of 30%, received the highest score in the hydrology category. The Aramburu Project (#1), with a score of 12.5%, received the lowest score in the hydrology category. Project scores in the sea level rise category show a wider range (49%) than project scores in the hydrology category (18%). Project scores in the sea level rise category show a positive trend, with the highest two scores received by projects developed in 2016. Project scores in the hydrology category show a downward trend, with the lowest two scores received by projects developed in 2016 (see Figure 3.5).

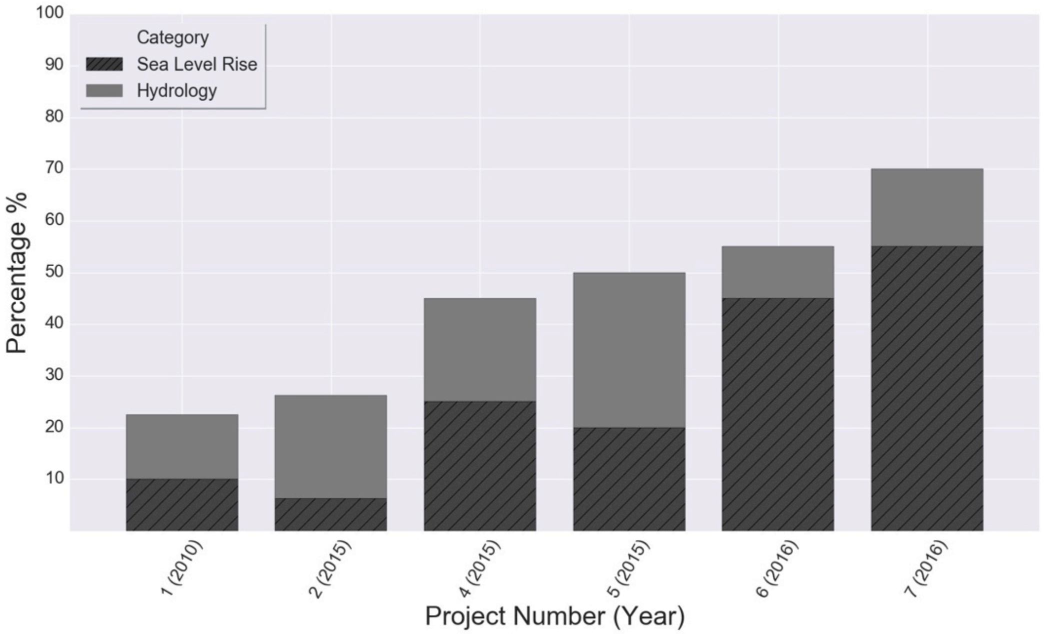

Figure 3.5. Aggregated project score as a percent of highest possible score. Scores are split into two categories (sea level rise and hydrology) for all projects evaluated. Data shown in order of year.

Results for each of the five criteria used in approach 2

Figure 3.6 shows results for each criterion including the range of scores received and the average of the project scores. The three sea level rise criteria *(SLR 1*, *SLR* 2 & *SLR 3*) received an average score of 1.9 and the hydrology criteria (*H 1* & *H 2*) received an average score of 2.

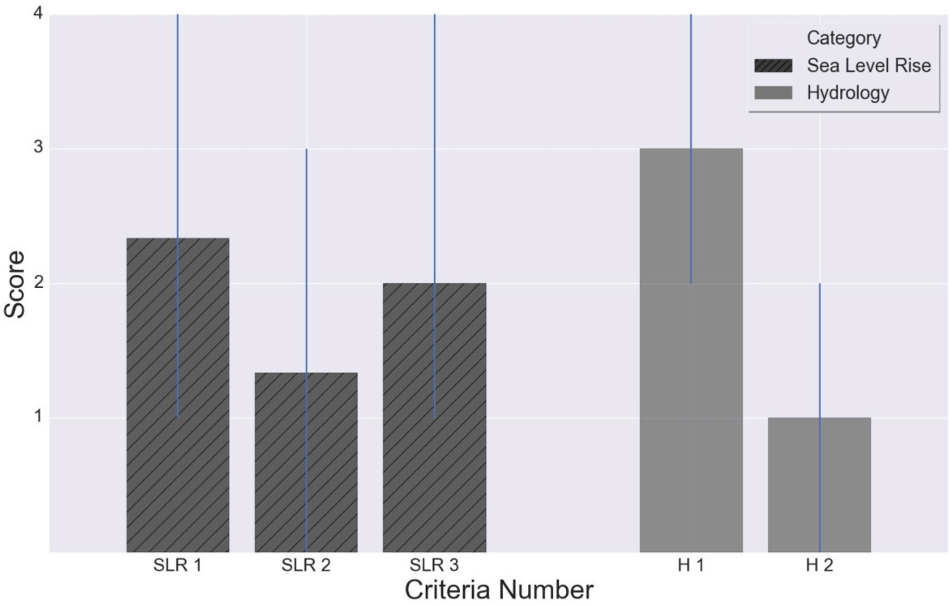

Figure 3.6. The average and range of scores for each of the five criteria used to evaluate projects. Criteria are clustered into the two categories used for evaluation.

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 quality of adaptation efforts is necessary to reveal key insights and to ensure that robust and appropriate project designs are developed over time. While other researchers have developed comprehensive systems to measure the sustainability of physical plans for new community developments (Mapes & Wolch, 2011) and local government climate adaptation plans (Baker et al., 2012; Woodruff & Stults, 2016), no similar evaluation framework exists for adaptation to sea level rise specifically. In this chapter, I offer two methodological contributions from which I reflect on key theoretical questions.

First, I applied Hill's typology as an analytical framework (2015) to actual physical project examples for the first time. This allows me to visualize how projects are transforming the San Francisco Bay edge as a whole. Thus I am able to do a comparison of possible solutions for specific sites. For example, Figure 3.4A reveals that in urban settings static landforms and dynamic walls are part of the contemporary design solution sets, but dynamic landforms are not considered. Dynamic landforms offer more ecologic and social benefits and thus these benefits are lost by leaving out this particular solution set (Zedler & Leach, 1998).

Second, I designed approach 2 to assess plans for physical projects to adapt to sea level rise that builds on previous work assessing regional plan evaluations (Baker et al., 2012). I see this as an effective tool that can be used to evaluate the extent to which desirable adaptation-planning elements are reflected in actual projects. Project designers and planners in other regions can use this framework as a template by adjusting the criteria to match local conditions or include other climate change topics. For example, similar criteria could be applied to projects intended to adapt to predicted increases in fluvial flooding associated with changing rain patterns.

In this section, I provide an in-depth look at the insights I glean from the two different approaches. Additionally, I reflect on these two evaluation approaches to provide ideas for future research possibilities.

Insights from approach 1—a slow shift

The analysis of shorezone transformation through approach 1 shows a general trend toward the dynamic landforms quadrant. This is a clear transformation in the sense that shifting from one infrastructure type to another is a distinct technological change (Geels, 2002). More importantly, this particular quadrant offers greater future transformability. Infrastructure based on landforms (often called soft infrastructure in planning practice) requires fewer monetary resources and is easy to change over time (Charlier, Chaineux, & Morcos, 2005). Similarly, infrastructure that is dynamic allows flows (such as of water and sediment) to occur. This type of infrastructure thus enables physical changes of complex systems (such as keeping pace with sea level rise) to happen as needed (Mattheus, Rodriguez, McKee, & Currin, 2010).

However, a close reading of specific projects raises concerns about the Bay Area's trajectory and about the potential for multi-functional landscapes in highly urbanized settings. In Figure 3.3 I show that almost all of the projects move their specific sites towards the dynamic landforms quadrant. The Treasure Island Project (#7) is an exception to this, since the project did not actually change the nature of the shoreline edge. However, these projects only represent 4% of the total San Francisco Bay shoreline. Therefore questions remain as to the applicability of these solutions for other locations in the San Francisco Bay. Specifically, the projects reviewed here are typically located in the most amenable contexts for this change (i.e., less developed sites with more natural bay edges). Even in this favorable physical setting, some projects added walls. The Novato Creek Project (#2) and the San Francisquito Creek Project (#5) show increases in wall length (1.5% and 9.7% increases respectively). While the projects that show the greatest movement toward dynamic landforms (the Novato Creek Project (#2) and the South Bay Shoreline Project (#4)) are set in current baylands locations with limited urban development. In contrast, the majority of the San Francisco Bay is more urbanized than these project's locations.

There is a long history of wetland degradation and loss in urbanized areas (Dahl, 1990). More recently, planners and designers are working to incorporate green infrastructure into the urban fabric (Wolch et al., 2014). Saltwater wetlands in coastal areas remain a challenge in the context of this general shift. These natural systems are highly complex and require significant land areas to function properly (Zedler & Kercher, 2005). Therefore, the fact that these projects are predominantly not set in urban areas raises a concern that the dynamic landforms shift may not occur throughout the Bay Area. It remains unclear whether planners and designers working in urban settings intend to include multi-benefit strategies that allow more flexibility for adaptive management over time, such as wetlands, beaches and dunes.

To further address this question, I reviewed the final projects developed through the Resilient by Design—Bay Area Challenge competition. Every one of these projects includes the use of dynamic landforms as part of the site designs. In one example called "Islais Hyper-Creek," the team proposes restoring the area's underlying natural watershed as a major new park in a highly industrial part of the City of San Francisco. Additionally the project includes strategies to strengthen specific logistical and port infrastructure to be flood resistant. In another example called "The Estuary Commons," the team developed a network of ecological restorations to improve natural system health and social and economic relationships. The team also made sure to stitch together the neighborhood and the shoreline, creating a more robust urban setting ("Resilient By Design," 2018). When I combine this brief assessment of projects from the design competition with the transformation observed in Figure 3.3, I see the beginnings of a slow shift for the Bay Area to a more dynamic landform-based edge partnered with urban strategies that create robust places able to tolerate flooding.

Insights from approach 2—lessons from specific evaluation criteria

The scores for the sea level rise category are unexpectedly low considering that the six projects evaluated were considered local Bay Area models of sea level rise adaptation in the San Francisco Bay. The projects typically identify a target amount of sea level rise used in site-scale planning; however, many of the projects do not represent the known uncertainties by including a range. Similarly, it is rather surprising that some of the projects do not even mention timeframes let alone acknowledge a longer time horizon (i.e., past the year 2050). The highest scoring projects, the Mission Bay Project (#6) and the Treasure Island Project (#7), do incorporate rigorous analysis of different amounts of sea level rise and consider multiple timeframes.

Scientists are starting to develop new models that look at widespread concurrent flooding associated with sea level rise and precipitation (Lamb et al., 2010; Wahl et al., 2015). Academics in the Bay Area building on this work have developed locally relevant models and applied them to natural gas transmission infrastructure (Radke et al., 2017) and the transportation fuel sector (Radke et al., 2018). Additionally, there is increasing scientific knowledge about the dynamics of coastal transition zones (i.e., the area influenced by terrestrial runoff and coastal waters) and how climate change will influence this zone (Schile et al., 2014). However, despite this increased knowledge, there remain relatively few plans and designs that treat these locations as integrated systems. Therefore, it is surprising that my "additional risks from precipitation and fluvial processes" criterion (*H 1*) has the highest average score (see Figure 3.6). The relatively high score for H 1 may be due to the fact that many of these sea level rise adaptation projects are being added to regional efforts already working to address fluvial flooding. Therefore many of the projects already considered a watershed scale, and these projects had planning mechanisms in place to consider designs for stormwater infrastructure integrated with future sea level rise projections.

While some studies used integrated assessments that merge adaptation planning and management of groundwater resources, these analyses are relatively new (Minciardi, Robba, & Sacile, 2007). Therefore, it is not surprising that the projects I evaluated scored lowest on the water table criterion (*H 2*) (see Figure 3.6). Ignoring water table depths in coastal adaptation designs can have a profound impact on their success. While trying to prevent sea water from reaching developed land surfaces, these designs may not prevent saline groundwater from leading to flooding by emergence of fresh groundwater, and from reduced infiltration and drainage capacity (Rotzoll & Fletcher, 2012). Physical plans that omit this dynamic interaction will also not address the increased risks of contaminant mobilization and transport from rising water tables (Green et al., 2011). Maps of depth to the water table are now available for most of the San Francisco Bay Region (Plane & Hill, 2017). Additionally, the team behind the development of "The Estuary Commons" design, which was submitted as part of Resilient by Design—Bay Area Challenge competition, explicitly considered groundwater ("Resilient By Design," 2018). Though they were the only team to do so, this is a sign that groundwater can be included in future landscape design and physical planning. There are now efforts underway by the United States Geological Survey (USGS) to incorporate groundwater into future risk assessments (Ludwig et al., 2018).

This research shows a distinct improvement over time in the sea level rise 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 3.5). The implication of these results is that the local capacity to include and consider 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 capacity ("Adapting to Rising Tides," 2018.). These results suggest that their work has helped to improve local capacity to adapt to sea level rise. 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. Arguably, until sea level rise trends and projections become embedded in a standardized manner within the design of physical projects, site-scale designs of coastal structures are unlikely to adequately prepare shorezones for these future threats.

Study context and potential future research

I acknowledge that each project was designed and developed in a broader context that includes goals beyond simply preventing coastal flooding from sea level rise. Indeed, the majority of these projects are not exclusively adaptation projects. For example, the Aramburu Project (#1) is primarily designed to improve the habitat functions of the island and the San Francisquito Project (#5) was designed as part of a larger effort to address fluvial flooding. In this chapter, my aim is to explore how adaptation to projected future sea levels is being integrated into other environmental and shoreline design work. Building on this aim I reflect below on the contextual limitations I faced and on the future research this work would serve as a foundation for.

The results from approach 1 are only a first step in understanding shorezone transformations, which are highly complex and require both social and ecological changes. This evaluation focuses on the protective structures themselves and on the degree to which these projects indicate a transformation within the specific site's boundaries. This research did not look at the broader location and the potential that the plans included complementary strategies on the landward side. For example, some of these projects are paired with elevation changes in streets, buildings, and stormwater systems. Elevating the landscape (rather than the protective structures) would be an appropriate additional or alternative future strategy. Further analysis of how coastal protective infrastructure can be paired with adjacent land uses and ecosystems could provide greater insight into the future transformability of these sites (Hill, 2015). Additionally, an operational landscape unit (OLU) perspective could be taken and these sites would be seen as just a small part of their larger context (Beagle et al., 2018; Verhoeven, Soons, Janssen, & Omtzigt, 2008).

Approach 2 is subject to criticism from other researchers since there is a certain level of subjectivity in all qualitative scoring methods. Specifically there could be a bias toward evaluating these projects harshly due to an expert's overconfidence (Morgan, 2014). For example, I based the evaluation on the scientific understanding that was available at the time (e.g., that sea level rise can have impacts on the water table depths); however, it has not necessarily been standard practice in the design, planning, and engineering professions to include this recent science. Therefore my scores for criteria H 2 could be lower than is appropriate. Despite this criticism, there is a precedent in using expert opinion to generate scores for multi-criteria assessments of this nature. Moreover, some argue that biases have been exaggerated (Kynn, 2008). In this study, the same person scored all of these projects to increase the reliability of the scores. Other experts checked the scores to validate the final numbers.

This research is limited by the fact that there are currently very few physical plans for adapting sites to sea level rise. Additionally, the work is further limited by the fact that these projects are at different stages of development (Table 3.1). Therefore, with such a small N, the data presented here are not statistically robust. However, the ideas in this work can serve as a model for future research as the number of projects grows. Additionally, this project could be repeated to further track through time the quality of sea level rise adaptation plans. The research could also be expanded to develop different evaluation criteria more appropriate to each stage of the planning process (Steinitz, 1990).

This research also does not capture change over time, a critical piece to long-term transformations (Kates et al., 2012; Feola, 2015). Future research will need to better incorporate modeling about how salt marsh wetlands will thrive or fail over time as the seas rise (Fagherazzi et al., 2012; Schile et al., 2014). Time-based research could also consider the different critical types of feedback between the shorezone and the urban fabric. One example of a crucial feedback that could be considered is the false sense of security that homeowners experience and the associated investment in their homes when protected by a levee. These expensive homes then put increased pressure on the continued investment in that infrastructure leading to further path dependence (Di Baldassarre et al., 2013). Designs that consider the shorezone and the urban fabric in an integrated matter can help to avoid these issues of path dependence. Finally, future research into the implications of the changes over time should consider the degree to which these initial sea level rise adaptation projects could act as seeds for ideas and innovations in future sea level rise adaptation planning (Geels, 2002).

Conclusions

These first-generation physical plans are a starting point for sea level rise adaptation in an urban estuary, and important lessons can be learned from this analysis. First, I find that these sea level rise adaptation projects demonstrate a shift toward dynamic landforms. This shift could be the beginning of a larger transformation of the shorezone toward conditions that are more flexible and provide multiple benefits. However, projects that adapt shorezones to sea level rise must consider a broad range of strategies, and further research is needed to determine if these efforts could successfully transform the shorezone for extreme scenarios of sea level rise.

Second, I find based on approach 2 that the scores for the physical plans improved over time (Figure 3.5). This may indicate that the work of regional government agencies to improve local capacity has been effective. Moreover, this trend suggests that future project will represent sea level rise uncertainties more effectively in their design processes. Finally, I find 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 physical planning for adaptation to higher sea levels and associated changes in the water table.

CHAPTER 4: ADAPTING TO SEA LEVEL RISE: STRATEGIC INSIGHTS FROM REGIONAL COSTS

Introduction

Flooding and its associated consequences for human development are a major threat to coastal communities (Aerts et al., 2013; Brody, Zahran, Maghelal, Grover, & Highfield, 2007). These impacts are exacerbated by human development in flood-prone areas (Hill, 2013; Nicholls et al., 2007). Scientific evidence shows that climate change is intensifying these risks by accelerating relative sea level rise, elevating water tables in coastal areas, and increasing the incidence of extreme precipitation (IPCC, 2013; Rosenzweig et al., 2011; Wahl et al., 2015). Estuaries provide a uniquely valuable setting for human settlement, but these urban regions are very vulnerable to sea level rise. Specifically, sea level rise in estuaries will result in landward movement of both the average and storm-driven high water lines; landward migration of the salinity gradient in surface and groundwater; changes in sediment transport and deposition; and coastal "squeeze", resulting in a loss of inter-tidal wetlands as well as damage to conventional urban districts and infrastructure (French, 2006; Nicholls et al., 2007). Globally, some urban estuaries are already grappling with these threats, including the Thames Estuary (Reeder & Ranger, 2011) and the Wash region of the United Kingdom (Doody, 2013), the Elbe in Germany (Nicholls & Klein, 2005), and the Chesapeake Bay in the United States (Ezer & Corlett, 2012). The San Francisco Bay urban region is also constructed in an estuary context, and presents an opportunity to gain insights about various physical adaptation strategies for shoreline realignment by estimating their adaptation costs and systematically varying key drivers of those costs. It is likely that some of these strategic insights will be applicable to other urban estuary regions.

Recent research shows that in the San Francisco Bay area, increased urban flooding and wetland habitat loss are among the greatest concerns. Currently, there are 140,000 people at risk from a 1 percent chance flood (commonly referred to as a 100 year flood), and with 1.4 m of sea level rise this number increases to 270,000 (Knowles, 2009). Estimates suggest that without adaptation actions, the cost of the impacts to buildings alone would be $49 billion from a 1 m rise in sea level under a 1 percent chance storm (Heberger et al., 2012). The current projections for marsh habitat along the Bay edge are similarly dramatic. Model projections suggest that sea level rise will produce significant losses of high marsh, which is particularly valuable habitat in the region (Stralberg et al., 2011). In an effort to address these threats, the State of California adopted a new law to require the incorporation of climate change into local planning (California Natural Resource Agency & California Ocean Protection Council, 2018), and is in the process of updating its guidance to local communities. As part of the State's process, the California Ocean Protection Council Science Advisory Team released

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This chapter is based on work previously published as: Hirschfeld, D., & Hill, K. (2017). Choosing a Future Shoreline for the San Francisco Bay: Strategic Coastal Adaptation Insights from Cost Estimation. *Journal of Marine Science and Engineering*, *5*(3), 42. https://doi.org/10.3390/jmse5030042 a report indicating that planners should consider up to 3 m of sea level rise by 2100 (Griggs et al., 2017). This report is based on the probabilistic assessment approach of Kopp et al. (Kopp et al., 2014). Addressing the threats of climate change will require complex system-based approaches that allow decision makers to gain a strategic understanding of relationships between environmental trends and adaptation pathways (Brown et al., 2014; Hill, 2016). Adaptation planning guidance calls for the need to address critical strategic questions (Bierbaum et al., 2013). For example, thresholds of change in system states may be used as decision points that initiate the shift from one adaptation pathway to another pathway (Reeder & Ranger, 2011). Similarly, a vulnerability assessment could trigger further analysis and ultimately a change to a set of adaptation actions (Haasnoot, Kwakkel, Walker, & ter Maat, 2013b).

Despite this need, certain key planning questions remain unanswered for developed estuaries such as the San Francisco Bay. In particular, while it is clear that the shoreline position will tend to move inland unless humans intervene with new infrastructure, it is not clear what variables planners should use in making shoreline realignment decisions that maximize the benefits of investments in walls, levees, dunes, and wetlands. A recent survey of local government officials identified the need for cost benefit analysis guidance to help them adapt to climate change (Nordgren, Stults, & Meerow, 2016). Efforts underway in the San Francisco Bay area suggest that raising existing structures is likely to be the most common response to current and predicted flooding (Hirschfeld, Hill, & Plane, 2017; San Francisquito Creek Joint Powers Authority, 2016).

In this study, we attempt to answer the question: how do different aspects of a cost estimate for coastal protective infrastructure (including earthen levees, concrete walls, and wetlands) reveal strategic opportunities for adaptation? We specifically explored physical, economic, and regulatory issues related to the adaptation costs for such infrastructure.

In the subsequent section, we provide details on the data and methods used in our analysis. We also present our results for the entire San Francisco Bay Area, with a focus on identifying the cost estimates for specific types of coastal infrastructure. We then present a discussion of these results as they relate to strategic planning questions and propose further analysis. Finally, we provide key conclusions from our work.

Materials and methods

The first challenge of describing a regional shoreline is the selection of categories that organize the diversity of existing conditions in a way that is useful to adaptation decision making. Our research is guided by the analytical framework originally presented in an earlier paper by Hill, which is summarized in Figure 4.1 (Hill, 2015). This framework was derived from concepts related to evolutionary landscapes. Shorelines are categorized as either landforms or walls, and either static or dynamic. The typology emphasizes transformability, in terms of the feasibility of raising the infrastructure over time, and the potential for a coastal infrastructure type to provide multiple benefits. For example, the typology treats walls as single-purpose structures that do not provide multiple benefits, such as recreation, wildlife habitat, or other ecosystem services. We use this typology to describe the current condition of the San Francisco Bay Edge, and to assess the potential costs of adapting to future sea level rise threats.

Our initial observation, from a review of the currently planned and built projects in the San Francisco Bay region, is that the legal, economic, and political challenges of land use change will drive public agencies to respond by seeking to raise existing shorezone structures. Therefore, we designed our cost estimation method to calculate the physical project costs associated with raising the height of existing structures at various positions within the shorezone.

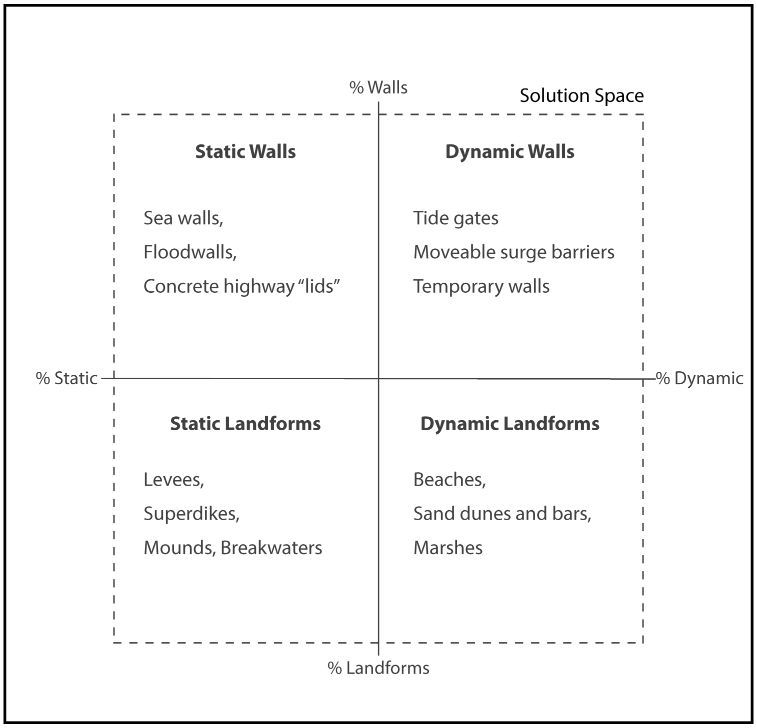

Figure 4.1. This four-quadrant diagram presents a typology of coastal protective shoreline structures (Hill, 2015). The vertical axis is defined by the percentage of shoreline that is wall, versus the shoreline that is built with loose materials, such as sand and gravel (landform). The horizontal axis is defined by the percentage of shoreline that is dynamic (able to move, mechanically or by natural processes) versus static (fixed in position). We used this typology in our study because it allows us to differentiate among coastal structures by their approximate initial construction cost, the cost of raising the structures over time, and the variety of ecosystem services they can offer. Structures in the upper right quadrant are typically the most expensive, and structures in the lower right can offer the widest range of services.

Data sources

Our analysis is based on the following two groups of data: (1) shorezone conditions and future sea level rise projections, and (2) cost estimation data. Three individual data sets, which are publicly available, underlie our characterizations of the shorezone and its inundation under different sea level rise scenarios. The first dataset is a geographic information system (GIS) vector-based inventory of shoreline infrastructure along the San Francisco Bay, developed by the San Francisco Estuary Institute (SFEI) (San Francisco Estuary Institute (SFEI), 2016). This dataset contains over 169,000 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 (NAVD88). These line segments include complex embayment shapes, resulting in large variations in the measured length of the Bay shoreline. 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.

SFEI also developed the second dataset (San Francisco Estuary Institute (SFEI), 2009). This is a vector-based GIS inventory of aquatic features called the Bay Area Aquatic Resource Inventory (BAARI). It includes features such as wetlands, open water, and riparian areas.

The third dataset (United States Geological Survey (USGS)., 2014) is a product of the Coastal Storm Modeling System (CoSMoS) (Barnard et al., 2014), developed at the US Geological Survey (USGS). Staff at the regional flood-mapping project by Point Blue, called Our Coast, Our Future (OCOF) (http://www.ourcoastourfuture.org), provided the data. This dataset provides water heights relative to NAVD88 under 40 different scenarios: 4 storm surge (mean water level, annual high water level (i.e., King Tide), and 20 year and 100 year storm-driven water levels) and 10 sea level rise scenarios (0–200 in increments of 25 and one extreme scenario of 500 cm).

The second group of datasets we used allowed us to develop a regional estimate of raising coastal protective infrastructure. First, we developed a database of unit costs after an extensive review of the costs of engineered structures relevant to the San Francisco Bay region, which is summarized in Table 4.1. Due to limited data, we do not present cost estimates for dynamic landforms, such as wetlands, or dynamic walls, such as tide gates. Next, we created a dataset of parcel-scale land costs, collected using a web data-scraping method developed by Chris Muir (2017) for use with online real-estate data (https://www.zillow.com/). This method enabled us to download all of the data for the San Francisco Bay Area. All of our data can be accessed as described in the Section below called Data and Methods Access.

Table 4.1. Sources and range of associated unit costs converted to thousands of 2016 USD$.

Cost Range: Thousands of 2016 $ (per Linear Km per M of Elevation)	Design Type	Study Type and Source
\$5.3–\$13.2	Landform	SF Bay: Engineering Study (USACE, 2015)
\$3.9–\$12.4	Landform	Academic Publication from Planning Work (Jonkman, 2013)
\$2.5–\$5.5	Landform	SF Bay: Technical Report (Lowe, 2013)
\$0.400–\$33.0	Wall	International Technical Report (Linham and Nicholls 2010)
\$5.8–\$18.3	Wall	Academic Publication from Planning Work (Jonkman, 2013)
\$24.5–\$495.5	Wall	SF Bay: Engineering Study (GHD-GTC Joint Venture, 2016)

Shorezone and shoreline positions, sea level rise, and cost assessments

In this first section of our study, we sought to determine where sea level rise will likely cause saltwater flooding, how much higher the existing coastal structures would have to be to prevent exceedance by rising water levels, and how much it might cost to raise the existing structures around the entire San Francisco Bay edge. We identified three baseline scenarios of shoreline re-alignment for the sake of making cost comparisons.

In the shorezone and sea level rise assessment portion of our work, we took three specific steps. First, we used the reclassification scheme shown in Table 4.2 to align the shoreline data from SFEI to our shoreline typology. Additionally, we used Google Earth and site visits to identify small walls not previously detected by SFEI. Second, we conducted a rapid assessment of water exceedance levels by calculating the difference in height between the floodwater and the structure. We subtracted the height of every shoreline segment in the SFEI data from the USGS CoSMoS model's projected future water levels. In the third step, we generated in GIS three potential shoreline alignments for cost comparison. The most bayward line, referred to here as "Shoreline A", was mapped using SFEI's shoreline infrastructure data. We used the "Bayshore_Defense" category, with the values "First line of shoreline defense" or "Wetland on Bay shore" to designate "Shoreline A". We designated the other two shorelines using an intersection of SFEI's shoreline infrastructure data and the BAARI data to distinguish the saltwater and freshwater habitat zones (San Francisco Estuary Institute (SFEI), 2009). The shoreline referred to as "Shoreline B" uses SFEI's mapping of saltwater habitat. The shoreline referred to as "Shoreline C" is the most landward of the three we designated, and is located on the landward side of freshwater wetland habitat as mapped by SFEI.

Table 4.2. 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[1]	Landform	Static
Natural Shoreline	Landform	Dynamic
Wetland	Landform	Dynamic
Floodwall	Wall	Static
Transportation Structure	Wall	Static
Water control structure	Wall	Dynamic

[1] This class included some smaller walls that we reclassified based on Google Earth and site visits.

Next, we calculated potential costs based on our review of unit costs specific to projects in the San Francisco Bay Area, and supplemented these data with cost calculations from the literature where needed. In Table 4.1, we show the range of unit costs for the two different protective infrastructure types considered in this project: landforms and walls. In this table, we present the information from five different technical and academic publications converted into the same units: thousands of 2016 USD$ for each linear kilometer, and for each meter of raised infrastructure height (GHD-GTC Joint Venture, 2016; Sebastiaan N. Jonkman, Hillen, Nicholls, Kanning, & van Ledden, 2013; Linham & Nicholls, 2010; Lowe, Battalio, & Brennan, 2013; United States Army Corps of Engineers, 2015).

Using this information, we compared four different approaches to calculating an approximate cost of raising the existing coastal structures: (1) simple without parcel costs, (2) simple with parcel costs, (3) complex without parcel costs, and (4) complex with parcel costs. The "simple" approaches (#1 and #2) used a linear relationship when calculating the cost of raising the height of a levee or a wall. Based on the work of Jonkman et al. (Sebastiaan N. Jonkman et al., 2013), we anticipate that the size of levees will increase approximately linearly for relatively low levels of sea level rise (0.5–1.5 m), as shown in Figure 4.2 and Table 4.3. However, as levee height is raised beyond 1.5 m, the relationship between height and cost is influenced more by the volume of the material in the levee. In our "complex" cost estimation approaches (#3 and #4), we applied a levee-growth cost factor that incorporates the geometric component of levee size, as shown in Table 4.3. In Approaches 3 and 4, we also used a more complex approach for estimating wall costs that incorporates the additional requirements of a seismically active region. We assumed that walls could be retrofitted if they need to be raised 0.5 m or less. Beyond 0.5 m of additional height, we assumed that the loadings on the wall would require it to be rebuilt.

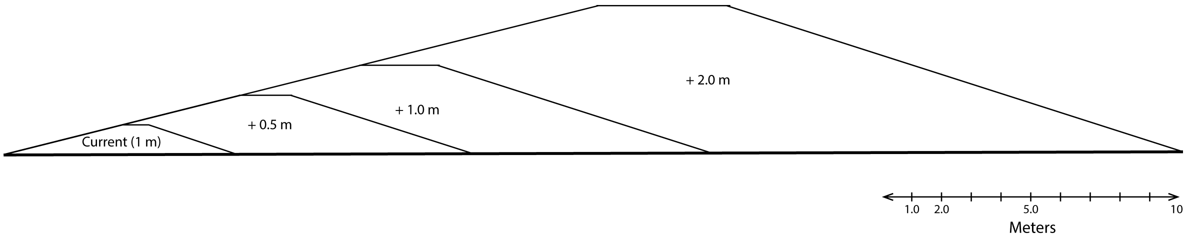

Figure 4.2. Cross-section of a levee depicted under different sea level rise scenarios.

Table 4.3. Implications for levee design under different sea level rise scenarios.

Sea Level Rise Scenario (m)	**Levee Dimensions** [1]		
	Height (m)	**Width (m)**	**Cross-Sectional Area (m²)**
0	Basis = 1	Basis = 7.9	Basis = 4.4
0.5	2	15.8	17.6
1.0	3	23.7	39.6
2.0	5	39.5	110.0
5.0	11	86.9	532.4

[1] Based on levee design with a seaward ratio of 1:4 and a landward ratio of 1:3. The relationship between sea level rise and levee height assumes that wave breaking is depth limited.

We hypothesized that land costs are likely to be a major driver of the cost of higher levees, since more land must be acquired as the width of the levee increases to support its height (see Table 4.3) (Sebastiaan N. Jonkman et al., 2013; Linham & Nicholls, 2010). To calculate this cost, we obtained parcel-scale market cost estimates from an online real estate database (https://www.zillow.com/) on two separate dates, and calculated the average land costs for all parcels in each county. Prior research in the field of urban economics has shown these estimates to be accurate (Huang & Tang, 2012; Mian & Sufi, 2009). We increased these base costs slightly to reflect costs associated with eminent domain purchases in the American legal context. We then multiplied these average costs by the number of parcels needed to accommodate higher levees for each sea level rise scenario. This parcel calculation was applied to both the simple and complex levee approaches resulting in Approaches #2 and #4.

In Table 4.4, we present the final numbers we used for these four different cost estimation approaches. We used the median value of the data we found in the literature for either landforms or walls to define our "typical" unit cost. We used the high and low cost number from the literature for our range. The cost of purchasing land to address the width of the levee varies based on county, shoreline, and sea level rise scenario. In Table 4.4, we provide the range; however, the actual numbers can be accessed as described in the Section below called Data and Methods Access.

Table 4.4. Cost estimates by infrastructure type and analysis approach.

Cost Approach	Static Landforms Typical (Range)	Static Walls Typical (Range)	Land Cost (Billions of 2016 USD$)
(1) Simple, without parcels	$8.0 (±$4.0)	$218.0 (±$75.0)	NA
(2) Simple, with parcels			1.4 to 22.0
(3) Complex, without parcels	Raising >3 m: Times 3	Raising >0.5 m: Times 4	NA
(4) Complex, with parcels	Raising >1.5 m: Times 2	Raising <0.5 m: Times 0.5	1.4 to 22.0
	Raising <1.5 m: Times 1		

Data and methods access

We made our datasets and detailed methods available through UC Berkeley's online data archive, known as DASH. The first dataset contains the water exceedance calculations for the three different shorelines we describe, as well as the full shorezone dataset, and can be accessed at this URL: https://doi.org/10.6078/D1W30C. The second dataset contains the cost calculations for the three different shorelines we describe, as well as the full shorezone dataset, and can be accessed at this URL: https://dx.doi.org/10.6078/D1KK59. Additionally at each URL the code and models we used can be downloaded. Finally, the three publicly available datasets used can be accessed from their original sources.

Results

Description of the current shorezone and alternative future shorelines

Using Hill's classification system (Hill, 2015), we defined four broad types of coastal infrastructure: (1) static landforms; (2) dynamic landforms; (3) static walls; and (4) dynamic walls. We evaluated all 169,000 30-m shoreline segments within the shorezone, all as described in Table 4.2. Each shoreline segment was only classified as a single one of the four types, and our analyses of the shorezone (as an area within which structures are placed or already exist) capture dual protection scenarios. In this area, we found that the San Francisco (SF) Bay shorezone is predominantly comprised of static landforms (69% of the entire SF Bay edge). The remainder contains 18% dynamic landforms, 12% static walls, and less than 1% dynamic walls. These structures, which comprise the set of existing structures, are not necessarily connected to each other, and are often not certified as effective flood protection structures.

In order to define organized future "shorelines" from this set of existing structures and compare their estimated costs, we defined three alternative shoreline positions relative to today's MHHW. We used ecological boundaries to generate our Shorelines A, B, and C, as described in the Methods Section. If flood protection structures are built along the most bayward line, Shoreline A, the structures would eliminate saltwater wetlands. The most landward future shoreline in this study, Shoreline C, would allow the beneficial flooding of wetland habitats by saltwater to continue, while still protecting most of the developed land. The wetlands that remain exposed would likely require additional sediment to keep pace with sea level rise (Stralberg et al., 2011). Shoreline B is defined by the boundary between saltwater wetland vegetation and freshwater wetland vegetation, and lies between Shorelines A and C.

The map in Figure 4.3 shows these three alternative future shorelines for the SF Bay, which we used as the basis for our cost comparisons. In places with limited wetland vegetation, such as the

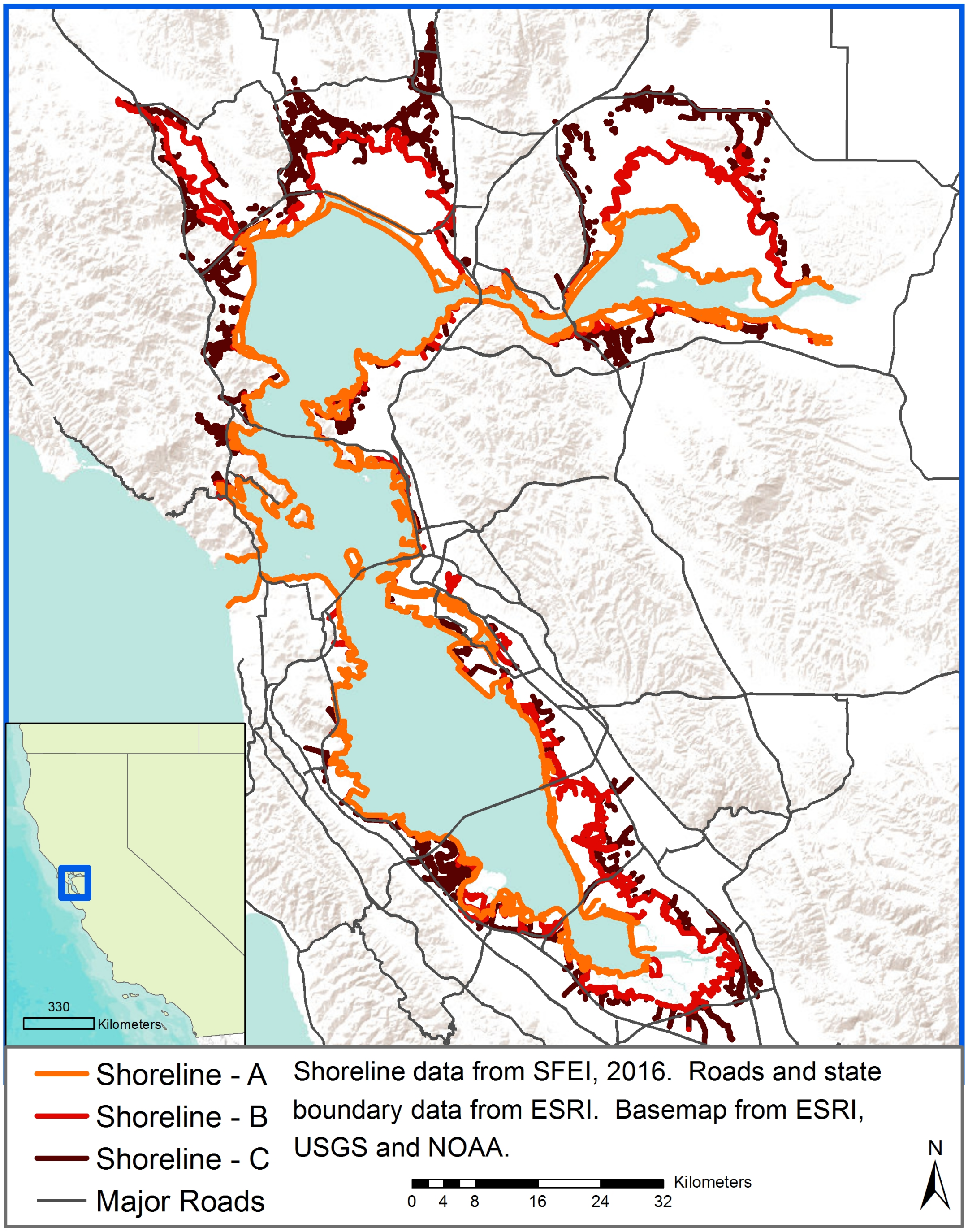

Figure 4.3. Map showing the full San Francisco Bay study area and the location of the three different shorelines—A, B, and C—we designated for comparative analysis purposes.

Central Bay, the three shorelines converge. However, in portions of the Bay with expansive wetland vegetation and more gradual slopes, such as San Pablo and Suisun Bay, the three shorelines are very different.

These alternative shoreline alignments are different both in length and in the percentage of the different shoreline types we have defined. As shown in Figure 4.4, the more landward shorelines are longer. Shoreline C, which is the most landward, is 2154 km long; Shoreline B, which is at the boundary of freshwater and saltwater wetlands, is 1340 km long; and Shoreline A, at approximately the MHHW line, is 967 km long. Figure 4.4 also shows the composition of each shoreline in terms of our four shoreline types. Shoreline A is unique because of a more even split between the two landform categories, static and dynamic. Dynamic walls are 0.1% of all three shorelines and thus do not appear in the figure.

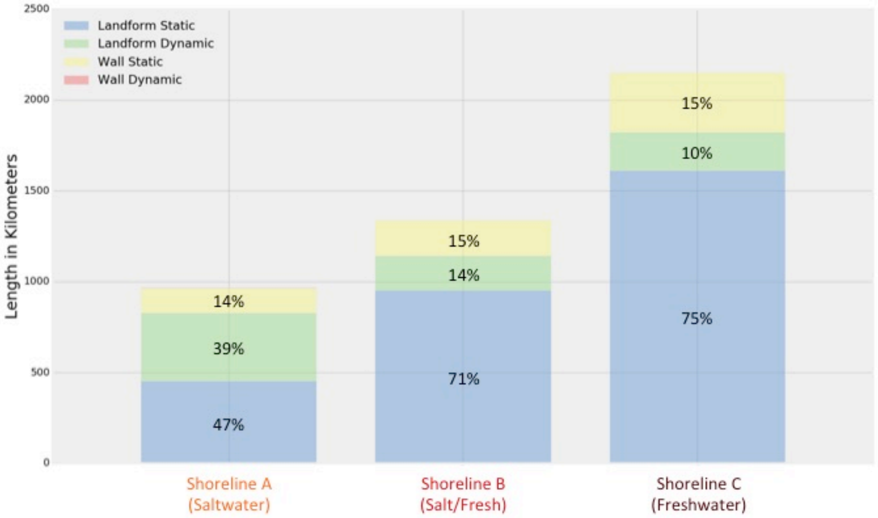

Figure 4.4. Chart showing each of the three shorelines A, B, and C. For each, the bar chart shows their total length, the length of each of the four coastal infrastructure types, and the percentage of each coastal infrastructure type. Note that dynamic walls are less than 1%, and therefore cannot be seen clearly in this figure.

Rapid assessment of water exceedance levels

Here, we used the CoSMoS projections of future water levels (Barnard et al., 2014) to evaluate the potential costs of raising current coastal protective infrastructure to meet future sea level rise scenarios. We calculated the water height exceedance level by calculating the difference in height between the projected water levels and the structure for all four types of shoreline structures in our defined shorezone. Figure 4.5 shows the summary median values for four different sea level rise scenarios, without including storm surges. Note that in Figures 4.5 and 4.6, we present the "no-storm-surge" condition. We do this to separate the impacts of a permanently higher mean sea level from the impacts of temporary storm events, in which floodwaters recede when the event is over. Both types of flooding are important, but the adaptation cost and response to each might be different. All four types of shoreline structures see an increase in exceedance as sea levels rise; however, dynamic landforms (typically wetlands) face the greatest amount of water level exceedance as sea levels rise.

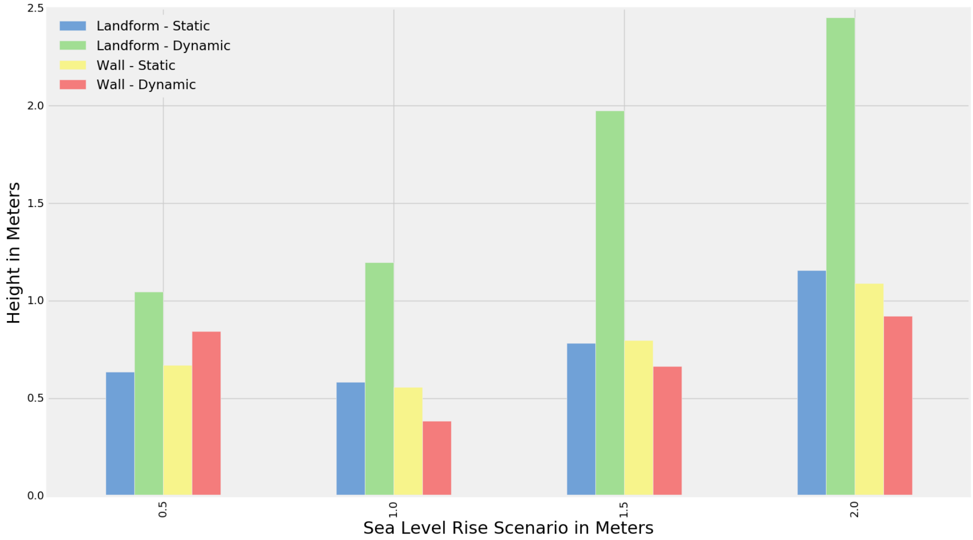

Figure 4.5. Figure showing the median height of the water that would exceed the top of the four types of protective infrastructure—static landforms, dynamic landforms, static walls, or dynamic walls—with sea level rise scenarios between 0.5 and 2 m.

Next, we calculated exceedance heights for each of the three specific shorelines we designated for cost comparison purposes: Shorelines A, B and C. Figure 4.6 shows the exceedance heights for the no-storm-surge condition under four different sea level rise scenarios. Here, we see an overall trend of an increase in exceedance as sea levels rise for all three shorelines.

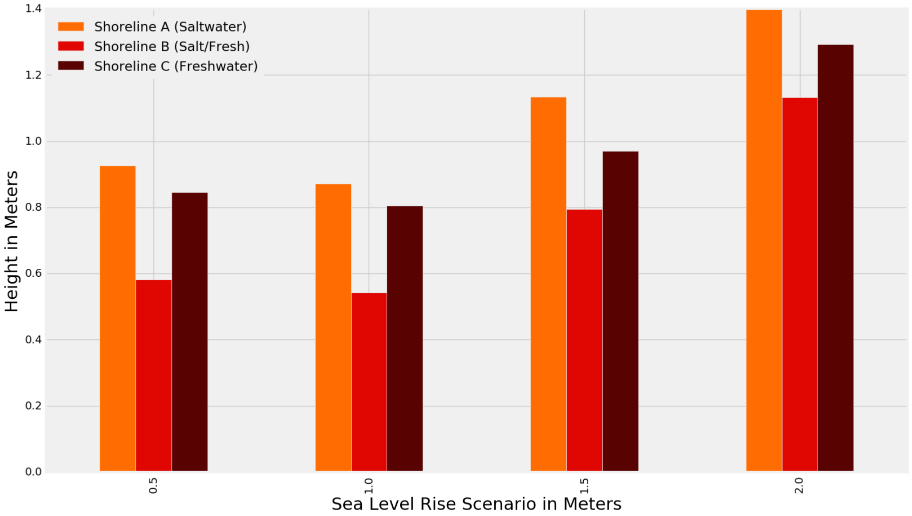

Figure 4.6. Figure showing the median height of the water that would exceed the height of thousands of line segments that represent the top of the three shorelines—A, B, and C—with sea level rise scenarios between 0.5 and 2 m.

Comparing cost estimation approaches

Here, we present our cost estimation results based on the different cost estimation approaches described in the Methods Section and summarized in Table 4.4.

Figure 4.7 shows our results from applying all four cost estimation approaches to Shoreline B, which sits on the boundary of saltwater vegetation and freshwater vegetation. This figure shows the total regional cost for the no-storm-surge condition under four different sea level rise scenarios. All four of the cost estimation approaches we used indicate that the costs of raising walls dominate the total cost estimate, constituting between 70 and 90 percent of the overall cost.

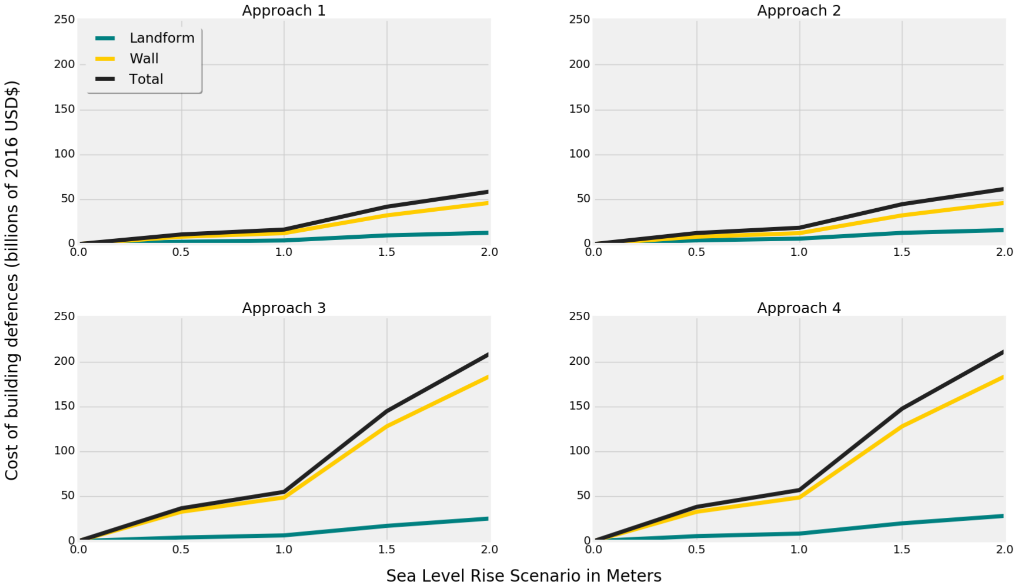

Figure 4.7. Figure comparing the four different cost calculation approaches for Shoreline B in billions of 2016 USD$. The two approaches on the left side (#1 and #3) do not include land purchase costs for the landform cost calculation, whereas the two approaches on the right side (#2 and #4) include a land purchase cost. The upper two approaches (#1 and #2) use a linear calculation for landforms and wall cost calculation, whereas the two approaches on the bottom (#3 and #4) have a more nuanced approach to levee and wall cost calculations. Each subplot shows landform, wall, and total costs in billions of dollars starting at no sea level rise and extending to 2.0 m of sea level rise.

Cost increases are relatively moderate below 1 m of relative sea level rise, but increase much more rapidly beyond that. We found the average cost increase among all four approaches to be $37 billion 2016 USD$ in order to raise existing structures to prevent overtopping from 0 m of sea level rise to 1 m of sea level rise. In contrast, we found the average increase to be $99 billion 2016 USD$ for the total costs of raising the structures to prevent overtopping caused between 1 m and 2 m of sea level rise. The cost of adapting to the first meter of sea level rise is predicted to be $62 billion 2016 USD$ lower than the cost of adapting to the second meter of sea level rise. In addition, Figure 4.7 shows that using a cost estimate that reflects changes in levee volume, and that uses wall replacement thresholds appropriate for a seismic region, has a large impact on the total cost

(Approaches #3 and #4), whereas adding the cost of purchasing land (Approaches #2 and #4) produces a smaller impact on total costs.

Figure 4.8 shows the impact of land purchase costs alone (i.e., excluding wall costs) on all three shorelines by comparing our cost estimates from Approaches #1 and #2. Adding the estimated cost of purchasing private land increases the cost of adaptation. However, the impact of the land purchases is much greater for Shoreline C, which is the most landward of the shorelines. For Shorelines A and B, the difference between including estimated land costs and not including land costs is $1.3 billion 2016 USD$ at the lowest, and $3.02 billion 2016 USD$ at the highest. For Shoreline C, the longest and most landward shoreline, including land costs produces a difference between $7.8 and $11.2 billion 2016 USD$. The reason for this difference is that Shoreline C contains significantly more private parcels that would need to be purchased, compared with Shorelines A and B.

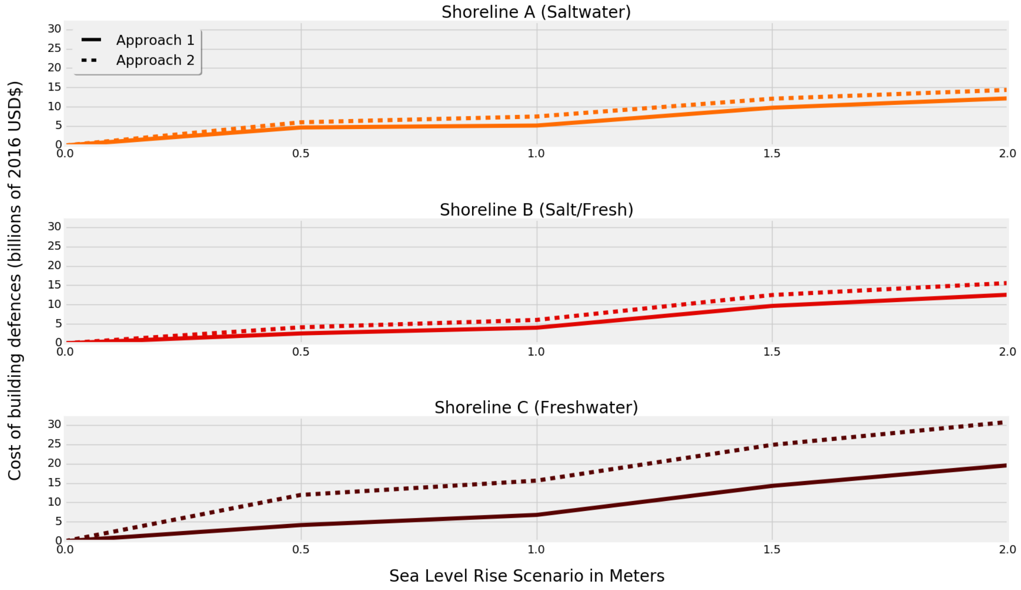

Figure 4.8. Figure comparing the impact of the land purchase costs across the three different shorelines—A, B, and C—in billions of 2016 USD$. Approach 1 (shown as a solid line) does not include land purchase costs, whereas Approach 2 (shown as a dashed line) includes a land purchase cost. Each subplot shows only the landform costs in billions of dollars.

Finally, we wanted to test the sensitivity of our cost estimation approach to traditional structural requirements for freeboard, defined as the distance between the normal water line and the top of a flood protection structure. While there are important functional reasons for these requirements, different types of infrastructure (wetlands vs. levees, for example) may use different engineering standards (Williams & Ismail, 2015). The design of resilient urban districts that tolerate some flooding can also reduce freeboard requirements for some types of shoreline structures.

Figure 4.9 shows the sensitivity of our cost estimation method to additional freeboard by displaying five different freeboard scenarios. For Shoreline B, we initially examined four different sea level rise scenarios with no storm surge and no freeboard. Then, we calculated the cost impact of requiring up to 1 m of freeboard, in increments of 0.25 m. This calculation uses Approach #3, which includes volume-based and seismically influenced cost calculations, but does not include land purchase costs. Figure 4.9 shows that requiring more freeboard has a large impact on overall costs. In our final modeling of estimated costs, presented in the next section, we used a freeboard of 0.61 m (2 feet) to represent current Federal Emergency Management Agency (FEMA) requirements (HDR Engineering, Inc, 2015).

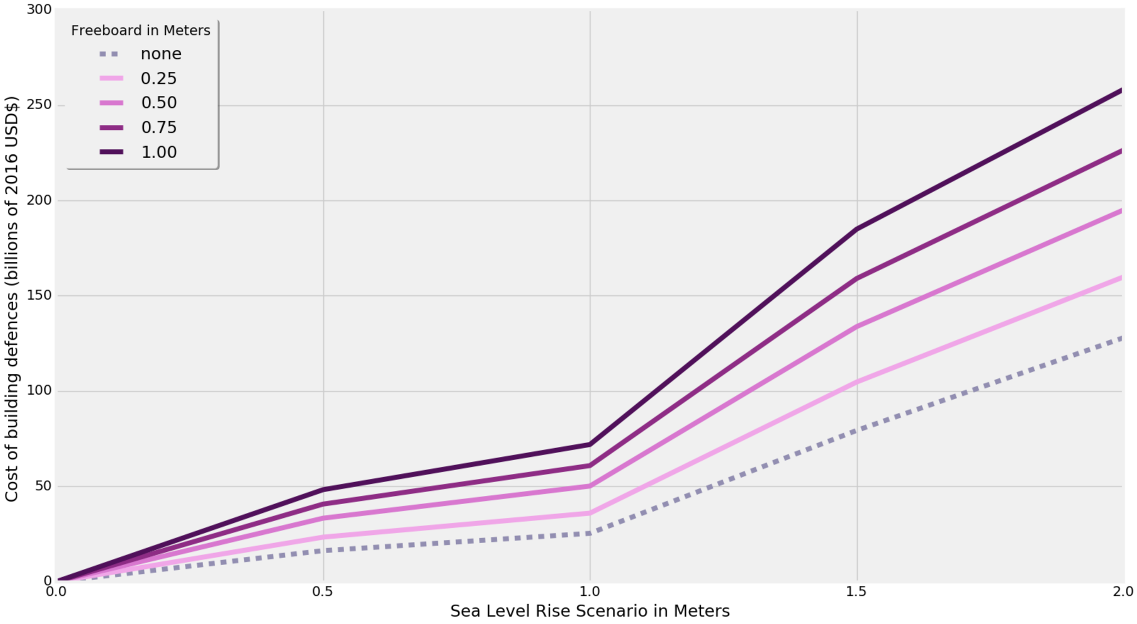

Figure 4.9. Figure showing the impact of different freeboard heights on the total cost for Shoreline B in billions of 2016 USD$. This calculation is based on Approach #3.

Overall cost estimates

In this section, we present our final cost estimates for the full Bay-wide scale of physical shoreline adaptation within the constraints of our assumptions. All of the results here reflect the application of our methods using Approach #4 (complex with land costs), with the freeboard requirement set at
0.61 m as noted above.

Table 4.5 and Figure 4.10 show a comparison of the three different shorelines we designated: A, B, and C. For each shoreline, we show a typical cost, which is based on an intermediate value from the data summarized in Table 4.1. The range is based on the distribution and the high and low end of the data summarized in Table 4.1. This comparison shows that Shorelines A and B are similar to each other, while Shoreline C stands out as significantly more expensive to protect.

Table 4.5. Estimated costs for raising coastal protective infrastructure to meet future sea level rise scenarios for the three designated potential shorelines in billions of USD$.

Sea Level Rise Scenario	**Shoreline A (Saltwater)**			**Shoreline B (Salt/Fresh)**			**Shoreline C (Freshwater)**		
	Range Low	**Typical**	**Range High**	**Range Low**	**Typical**	**Range High**	**Range Low**	**Typical**	**Range High**
0.5 m	$24	$39	$53	$25	$38	$51	$43	$63	$83
1.0 m	$33	$51	$70	$37	$57	$77	$69	$103	$137
1.5 m	$81	$126	$172	$95	$148	$200	$157	$240	$323
2.0 m	$116	$182	$248	$136	$212	$287	$217	$335	$453

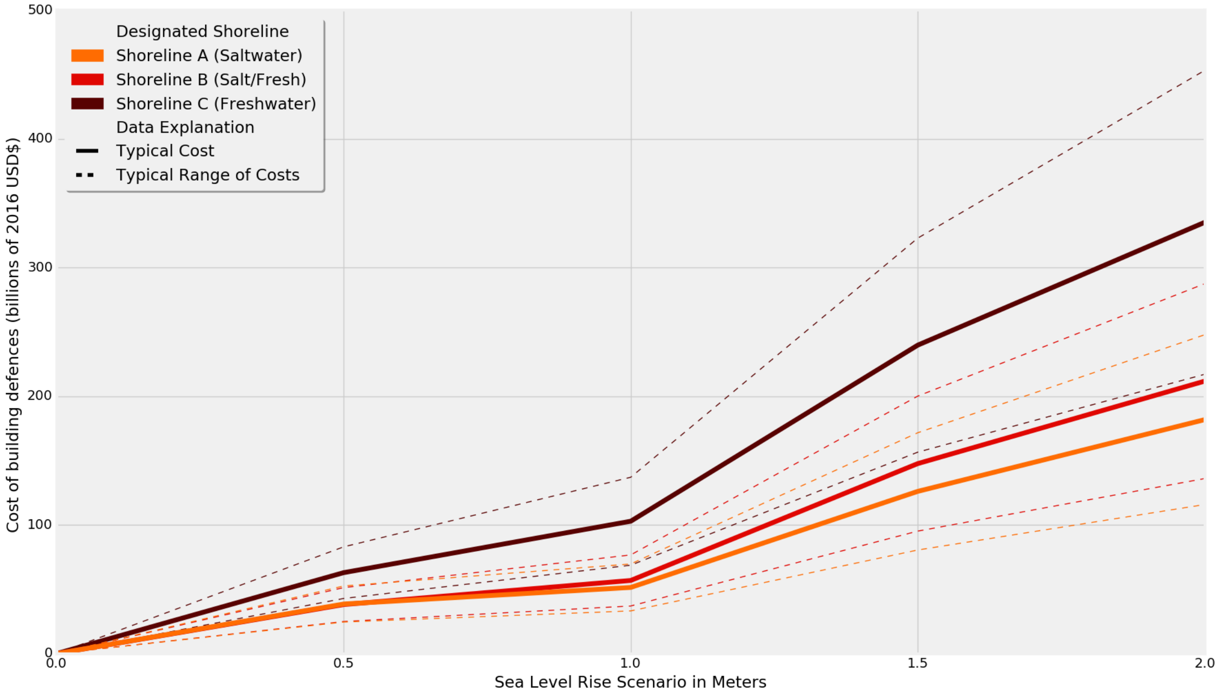

Figure 4.10. Figure comparing the average and the range of potential costs to raise the protective infrastructure along each of the three different shorelines. Costs are based on current infrastructure type—landform or wall—being raised to meet future water levels in a no-storm-surge condition and sea level rise scenarios. The cost estimates are done using Approach #4 and are shown as billions of 2016 USD$.

We also compared the Bay-wide costs of raising coastal infrastructure high enough to prevent flooding from new sea levels combined with a storm surge scenario (the 100-year or 1% storm surge). We display the "storm-vs.-no storm" comparison for our cost estimate for Shoreline B in Figure 4.11. In a 1-m sea level rise scenario, the cost goes from an average of $56.8 billion 2016 USD$ in a no-storm-surge condition to $98.9 billion 2016 USD$ in a one-percent chance storm condition. It is significant to note that raising infrastructure to prevent flooding from temporary storm events along with sea level rise is almost twice as expensive as raising the same structures to prevent flooding from permanent sea level rise only, while adapting to temporary flooding on the landward side.

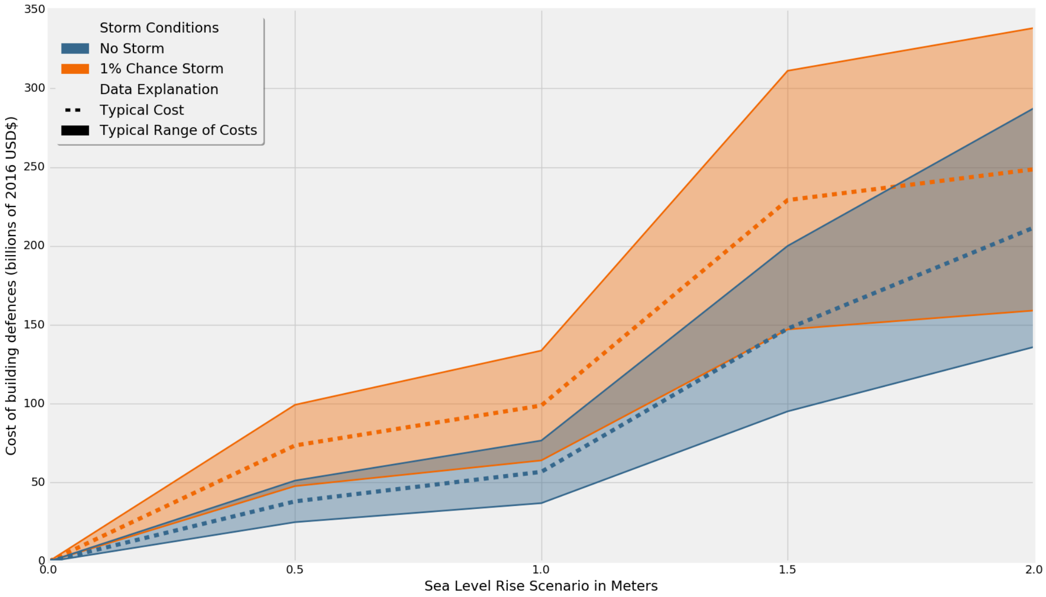

Figure 4.11. Figure showing the average and the range of potential costs under two different design scenarios for Shoreline B. The lines in blue show a scenario that assumes protective infrastructure would be designed to address only future sea level rise and not storm events. The lines in orange assume that protective infrastructure would be designed to address the 1% chance storm event as well as sea level rise. Costs are based on current infrastructure type—landform or wall—being raised to meet future water levels for sea level rise scenarios between 0 m and 2 m. The cost estimates are done using Approach 3: complex cost approximations without parcel values and are shown as billions of 2016 USD$.

Discussion: Strategic implications of results

Implications for alternative shorelines and design strategies

Coastal planning and engineering practitioners often suggest that the vulnerability of a shoreline can be reduced by shortening the overall length of the shoreline (Hillen et al., 2010; S.N. Jonkman, Kok, van Ledden, & Vrijling, 2009). Our results show a lower cost for the shortest shoreline in Figure 4.10. However, our research raises specific concerns about this strategy. While we do find that the longest line (Shoreline C) represents significantly more cost to adapt to future sea level rise, the other two shorelines (A and B) are likely to be similar to each other in cost despite their different lengths. If we weigh these costs against the value of ecosystem services provided by the intertidal zone, the middle shoreline (Shoreline B) appears to be optimal. In San Francisco Bay today, site managers and public agency planners are proposing projects to raise coastal structures along this middle shoreline (our Shoreline B) (San Francisquito Creek Joint Powers Authority, 2016; United States Army Corps of Engineers, 2015).

Prior research suggests that raising wall infrastructure types will be an order of magnitude more expensive than raising the landform infrastructure types. Our results, as shown in Figure 4.7, support this conclusion. Figure 4.7 shows that the cost of raising the height of existing walls, which currently make up only 15% of Shorelines B and C, has a significantly greater impact on total cost than the cost of raising landforms. If we re-calculate our estimated cost for Shoreline B using only walls, the total cost increases by 7.5 to 8.9 times the cost of a combined landform-and-wall coastal shoreline. From a cost perspective, landform-based shoreline infrastructure may be a better investment over time. Switching to wall-based adaptation where there are no walls today introduces the risk of locking future generations into a much more expensive strategy.

There is significant debate both in the literature and in practice as to the ideal height of protective shoreline infrastructure, and the associated amount of temporary flooding that urban development would need to accommodate. On the one hand, reduction in risk is critical and protective infrastructure should be designed to prevent disastrous flooding events. On the other hand, researchers using models find that exposure to some flooding can reduce overall vulnerability (Di Baldassarre et al., 2013), and may even promote the development of more resilient urban districts (sometimes called "floodable development"). Planners in the SF Bay region are currently trying to determine an appropriate height for raised structures in locations where the cost of providing coastal protection is outweighed by the multiple benefits that the protection provides (GHD-GTC Joint Venture, 2016; United States Army Corps of Engineers, 2015). Figure 4.11 shows that designing infrastructure to protect against infrequent, extreme flood events would be significantly more expensive than protecting against the permanent landward movement of the mean water line. While protecting against the 10- or 20-year storm may make financial sense, designing urban districts that are adapted to temporary flooding may be a better way to share costs and risks. Our results present important strategic implications for the design of vulnerability studies, and for setting goals in adaptation plans. If planners seek to accept some flooding while protecting against permanent inundation, physical plans might include floodable urban districts (Restemeyer, Woltjer, & van den Brink, 2015). Adaptation costs could then be shared and optimized in new ways.

Actual adaptation strategies are likely to be complex in their spatial patterns and mix of structures. Previous land use is likely to influence realignment (French, 2006). Rivers will contribute additional flooding problems, exacerbated by the increased incidence of extreme precipitation (Wahl et al., 2015). Coastal structures will also have upstream impacts. In other regions, even movable barriers, such as tide gates, have been shown to produce negative impacts on upstream wetlands and fish populations (Elkema, Wang, & Stive, 2012; Giannico & Souder, 2005; Gordon, Arbeider, Scott, Wilson, & Moore, 2015; Louters, Mulder, Postma, & Hallie, 1991). These, and a host of other specific considerations, would need to be taken into account when selecting a site-specific adaptation strategy. Further research is required to address all of these unique challenges. However, we hope that our work can highlight the cost-specific limitations of a regional strategy that relies on walls and static landforms, such as levees and terraces.

Benefits and limitations of our cost estimation method

The ability to easily calculate the costs of protective infrastructure needed to address sea level rise would be a powerful tool for state and regional agencies, coastal planners, and local officials. The rapid assessment approach we present in this study is especially useful where relatively accurate regional datasets are available. Additionally, our method allows planners to customize key policy components, such as the desired freeboard height, to conduct sensitivity analyses. This may also allow our approach to be used in other geographic regions with different wave energy regimes, and therefore different structural design requirements. Our approach currently does not account for other major project costs, such as conducting required planning studies, managing soil contamination, and maintaining project contingency reserves. In addition, we have not included the capital, operations, and maintenance costs of pumps that will be required to remove stormwater when levees or other structures block the flow of runoff and tributaries, and to lower future groundwater levels. These very significant costs can also be estimated, but would require hydrologic flow data and groundwater modeling along shoreline segments to approximate the volumes of pumping that will be required.

Potential future research

Three important questions for future research arose during this project. One is whether and how coastal protective infrastructure can be paired with adjacent land uses and ecosystems to provide the greatest combined level of resilience (Hill, 2015). Specifically, areas with high groundwater and riverine settings will require significant analysis to ensure that precipitation-based flooding and storm surge are both accounted for in designs and plans. Studies of possible pairings would allow planners to evaluate specific sites and develop a strategy for districts within regions.

Second, our results provide only the first step in the kind of full cost benefit analysis that is required for proper adaptation planning. The costs associated with potential damages as well as the significant impacts to physical assets and human populations will be a key factor in determining the levels of protection required. Moreover, estuary regions must consider how adaptation will affect ecosystem services, and seek to achieve greater connectivity for species and habitat. Without this advance planning, key functions can be completely lost as new or raised shoreline structures block hydrologic flows, wetland migration, and the movement of animals. Our research represents only a first step in estimating the costs of protective infrastructure using different spatial shoreline positions. It is essential to compare these costs to the value of assets that would be protected, including the value of key ecosystem services.

Finally, this study raised the question of whether it will be possible to identify thresholds associated with sea level rise and other drivers of coastal flooding. What thresholds in rates or magnitudes of processes would create unsafe conditions for occupying coastal developments? What thresholds might push coastal adaptation onto different adaptation pathways, for example, away from protection and towards realignment? Our method provides a starting point for exploring these questions from a cost perspective. The method would be enhanced by incorporating both additional capital and planning costs, as well as secondary costs such as those associated with the operation and maintenance of pumps. Including operations and maintenance costs would enrich the current method and provide for an evaluation that could identify different preferences among the alternative strategies.

Conclusions

Strategic physical design implications

Given our assumptions about replacement thresholds, walls are significantly more expensive than levees and should only be used as a last resort approach to protection. Building them may create liabilities rather than assets for future generations, who will bear the costs of removing or replacing them. In general, creating structures that can fail catastrophically is unlikely to contribute to resilience over multiple decades when the rate of environmental change is accelerating, creating a greater likelihood of failure. Moreover, walls are typically single-purpose structures that do not provide benefits of recreation, carbon sequestration, and other ecosystem services. Walls, even movable barriers such as tide gates, produce negative impacts on upstream wetlands and fish populations (Elkema et al., 2012; Giannico & Souder, 2005; Gordon et al., 2015; Louters et al., 1991).

When it comes to identifying an appropriate shoreline, our work suggests that defending the shortest shoreline may not be the best adaptation solution. Based on our approximation of the relative costs, Shoreline B (at the boundary between saltwater habitat and freshwater habitat) may be preferable to the shortest possible shoreline in this study (Shoreline A). Shoreline B has similar costs, but produces multiple benefits from ecosystem services. Shoreline C, which was the most expensive overall, also raises issues of unique flooding problems that occur where freshwater or brackish tributaries meet a saltwater body. Freshwater flooding driven by rainfall can combine with rising groundwater and saltwater flooding to create extreme flood conditions. These points of intersection among flows may require the realignment of shorelines, with the relocation of urban districts and infrastructure. Or, they could be locations where new strategies for human occupation of the shorezone are tested, between Shoreline B and Shoreline C. Floating concrete roadways, stormwater ponds, floating urban blocks, and freshwater habitat could form a mosaic of new development strategies that protect existing sewage treatment plants, which are often located at the intersections of fresh and salt water. This is a geographic zone that needs extensive further study in order to avoid the expansion or introduction of maladaptive strategies.

Strategic regulatory implications

We suggest that shoreline adaptation would be more successful if the shoreline structures continue to allow flooding in extreme events. While there is significant debate both in the literature and in practice as to the ideal design height for shoreline protective infrastructure, our results show clearly that creating requirements to design coastal structures with certain freeboard heights or storm surge expectations has a large impact on costs. Freeboard heights and other storm-specific design requirements should be set to reflect the intended purpose of the shoreline infrastructure, and its specific context within the shorezone. If coastal structures are designed to allow some overtopping without structural failure, higher sea levels can be allowed to produce temporary flooding from storm events. Periodic, temporary flooding can drive urban development to become more resilient by being re-designed to accommodate some floodwaters (Di Baldassarre et al., 2013; Restemeyer et al., 2015).

Strategic economic and overall approach limitations

Most importantly, this paper illustrates the clear benefits of using a simplified typology to categorize shoreline types and calculate initial cost estimates. Working with a combination of Python and GIS enables our approach to handle very large datasets that are crucial for a large regional area. Moreover, our unit cost approach allows us to explore and compare different components of adaptation costs. Specifically, we find that the land purchase costs for levees contribute less to the overall regional cost than expected. Additionally, we see that triggers for replacing walls are a key driver of the total regional costs. We think this approach shows great promise for helping regional planners address critical strategic climate adaptation questions.

CHAPTER 5: ADAPTING TO SEA LEVEL RISE: EVALUATION THROUGH THE REGIONAL PLANNING FINGERPRINT

Introduction

Climate change and associated impacts are placing pressure on institutions and the professionals working within them to become more proactive and to plan for more extreme impacts in distant futures (Gupta et al., 2010; Reiblich, Wedding, & Hartge, 2017). These pressures are leading to explicit calls from many scholars and practitioners to engage in transformational adaptation (as defined and discussed in Chapter 2) (Kates et al., 2012). These pressures hold true in terms of managing the resilience and developing physical plans for both ecosystems (Stein et al., 2013) and social systems that support human livelihoods (Folke et al., 2005). There is mounting evidence that government action is increasing (Bierbaum et al., 2013; Carmin et al., 2012). Despite a growing recognition of the need for climate adaptation action, current efforts are found to be more one-off unique occurrences than a collective coherent set of actions that are needed to address the threat (Bierbaum et al., 2013). There is also limited work at the regional scale despite the pressing need to collaborate across jurisdictional boundaries (Juhola & Kruse, 2015). Thus there is a need for a framework to measure current progress of regional climate adaptation efforts and to identify opportunities for future improvements.

Against this background, in this chapter I address the questions: 1) How can regional efforts to prepare for the long-range impacts of climate change and the need for transformational adaptation be evaluated? And 2) what insights can be gleaned from this evaluation? I apply these questions to the issue of sea level rise adaptation and report on the findings from a yearlong assessment of regional sea level rise planning work by city and county governments in California. I build on the literature to identify categories and evaluation criteria and show how these can be represented in a Regional Planning Fingerprint, an analytical tool I developed to evaluate regions. I present the data and methods I used to apply this analytical tool to regions in California, the results from this work, the implications of these findings, and the final conclusions.

Exploring the decision making landscape

Planning generally and climate adaptation planning specifically is about changing the unknown future and charting a place's path toward a desired set of outcomes (Abbott, 2005; Hurlimann & March, 2012; Walker et al., 2013). To achieve climate change adaptation practitioners such as planners, designers and resource managers face many challenges, including uncertainties arising from modeling (Hayhoe et al., 2017; Kettle, 2012) and the planning processes themselves (Abbott, 2005).

This chapter was part of a larger research project led by Dr. Kristina Hill of University of California, Berkeley and Bruce Riordon of the Climate Readiness Institute (CRI). The larger project was funded through California State Assembly Bill 2516 (2013-2014) Planning for Sea Level Rise Database Project, which was administered by the Ocean Protection Council (OPC).

Researchers in the diverse fields of public policy and social-ecological systems management offer ideas on building robust and flexible futures through planning andmanagement decisions (Folke, Hahn, Olsson, & Norberg, 2005; Olsson, Folke, & Berkes, 2004; Walker et al., 2013). In this section I explore the specific uncertainties faced when planning for sea level rise, the tools planning offers to move forward in light of deep uncertainty and the role regions play in creating robust social-ecological systems.

Modeling the future and associated uncertainties

Uncertainty, while omnipresent, is also a complex and elusive topic (Mack, 1971, p. 1). It can be said that uncertainty arises when individuals or groups perceive that they lack the knowledge relevant to a particular purpose (Abbott, 2005). According to Holling (2001), uncertainty, due to surprises, is an inevitable part of both human and natural systems. He further notes, "We can also work to mobilize evidence that can distinguish among competing explanations so that multiple lines of evidence begin to define what is known, what is uncertain, and what is unknown." Thus in the context of working to transform systems in light of climate change, we should start by examining the models and what we do (and do not) know from them.

Climate models and issues of uncertainty

Socio-economic and physical scenarios are powerful tools commonly used to understand change impacts and vulnerabilities (Berkhout et al., 2013). Representative Concentration Pathways (RCPs) and General Circulation Models (GCMs) form the backbone of future projections used in climate change adaptation planning (Hayhoe et al., 2017; Kotamarthi, et al., 2016). Utilizing information from RCPs, GCMs generate global weather variables such as precipitation, wind, pressure fields and temperature (Barnard et al., 2014; Radke et al., 2018). For local and regional planning efforts, this data is further downscaled (Hayhoe et al., 2004; Pierce, Cayan, & Thrasher, 2014). However, these data resources include tremendous uncertainty and result in a wide range of predictions, thus presenting specific challenges to climate adaptation planning (Hallegatte, 2009; Kettle, 2012; Walker et al., 2013).

RCPs are time- and space-dependent trajectories of concentrations of greenhouse gases and pollutants resulting from human activities including changes in land use. They are a quantitative description of concentrations of the climate change pollutants in the atmosphere over time as well as their radiative forcing in 2100 (Moss et al., 2010). RCPs are the latest generation of scenarios used by the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment report (van Vuuren et al., 2011). These scenarios replace the previous emissions-focused scenarios, such as those covered in the Special Report on Emission Scenarios (SRES) used in the 3rd and 4th IPCC Assessment reports (Nakićenović & Intergovernmental Panel on Climate Change, 2000). RCPs are highly informed descriptions of how the future could be in terms of socio-economic changes, technological changes, and greenhouse gases concentration changes (Moss et al., 2010).

Based on a series of expert meetings, there was a selection of representative scenarios to be used in climate models. These meetings led to the development of four scenarios of the radiative forcing associated with the additional incident energy (W/m^2) caused by anthropogenic climate change—RCP2.6, RCP4.5, RCP6.0 and RCP8.5. Each concentration pathway could be achieved through different policy interventions and socio-economic conditions (Moss et al., 2010). For example, RCP 8.5, which represents three times today's CO2 emissions by 2100, could be achieved through some combination of rapid increase in methane emissions, increased use of croplands, a higher world population, lower rates of technology development, and heavy reliance on fossil fuels (Bjørnæs, 2013). Then modeling teams further developed spatially and temporally explicit related data products. These products included emission and concentration of greenhouse gases, air pollution, and land use and land cover change (van Vuuren et al., 2011). These model outputs were then used as key inputs into GCMs (Hayhoe et al., 2017; Kotamarthi et al., 2016).

GCMs are three-dimensional models that simulate many aspects of the climate system based on first order physics principles (Kotamarthi et al., 2016). These models generate time-based simulations of our climate including the temperature of the atmosphere and the oceans, precipitation, winds, clouds, ocean currents, and sea-ice extent (Pachauri, Mayer, & Intergovernmental Panel on Climate Change, 2015). These models are based on radiative forcing present in the atmosphere (Kotamarthi et al., 2016). There are many models running around the world at different research institutions. These models are extensively tested against historical observations to determine the accuracy of their simulations. Through such testing researchers have been able to improve these models over time (Bony et al., 2006). Additionally, researchers are continuously working toward more complex models that capture more detail. One such improvement has been to build a better understanding of the interactions between oceans and the atmosphere (Hayhoe et al., 2017). Outputs from these models then become a building block for mitigation and adaptation decisions.

There are many issues leading to uncertainties in the climate models. One critical problem in climate modeling is the area of feedbacks, defined as those processes that either amplify or dampen the climate response to an external perturbation, such as increases in carbon in the atmosphere. Researchers have successfully improved GCMs since their original inception in 1969. Specifically teams have used observational, numerical, and theoretical studies to improve the collective understanding of physical mechanisms involved in climate system feedbacks (Bony et al., 2006). However, despite these improvements, uncertainties in the models and their outputs remain.

It is also challenging to use the climate model outputs in local and regional planning. Specifically, the outputs from GCMs are on the order of 100 square km. This is a disconnect from the scale needed to inform decision making related to many climate adaptation strategies (Pierce et al., 2014). Researchers address this scale difference using two different downscaling techniques—dynamical and statistical (Hayhoe et al., 2004). In the first, dynamical, researchers use regional climate models, similar in design to global climate models. In this approach the domain boundaries are set by outputs of the GCM and the localized physical rules are used to create smaller scale outputs. In the second approach, statistical, historic relationships between large- and small-scale conditions are used to extrapolate future simulation outputs at needed smaller scales (Pierce et al., 2014). Researchers have applied both techniques in California to generate regionally relevant data that can be used to inform planning.

Details in sea level rise modeling

Sea level rise is expected to progress at an accelerated rate over the coming century (Nerem et al., 2018). Global, or eustatic sea level rise, projections are based on contribution from five different components: thermal expansion of ocean waters, melt from glaciers, addition of surface water to oceans and contributions from the large ice sheets on both Antarctica and Greenland (Cayan, Kalansky, Iacobellis, & Pierce, 2016). Each component includes uncertainty in terms of amounts of water as well as the rate at which that water would enter the ocean system. The uncertainty calculations are based on the total quantity of water the component can contribute and how well the components' response to perturbations in the climate system is understood (Cayan et al., 2016). The greatest uncertainty comes from the contributions from the Greenland and Antarctica ice sheets. The range for these contributors is the greatest because the ice mass loss dynamics are complex and probably non-linear thus making them the hardest to model (Vaughan & Arthern, 2007).

In California an expert panel worked with a team of scientists to generate projections that can be used to guide planning decisions. The panel and the researchers agreed on using a probabilistic sea level rise projection methodology developed by Kopp et al. (2014). This method generated time-dependent probability distributions based on a Latin hyper-cube sampling method of each of the different components listed in the paragraph above that contribute to sea level rise. One key assumption of this process is that the components are independent of each other (Cayan et al., 2016). For the California projections the panel also agreed to modify the method and use the recent results from DeConto and Pallard (2016) for the contribution from the Antarctic Ice Sheet. Ultimately long-term sea level rise projections were developed using different GCMs and different emissions scenarios.

Relative sea level rise, which more accurately captures local conditions, includes short-term sea level fluctuations combined with these long-term projections. Local fluctuations result from ocean and wind dynamics, tectonics, and ice sheet fingerprinting (Cayan et al., 2016). Storm surges (Allan, Komar, & Ruggiero, 2011), interactions with topography and shoreline infrastructure (Holleman & Stacey, 2014), and El Nino Southern Oscillation events (McPhaden, Zebiak, & Glantz, 2006) are among the physical processes that cause water to accumulate or disperse along a coast. Tectonics includes large-scale sinking and uplift of plates due to glacial isotactic adjustment, as well as local processes that might cause a specific location to subside or uplift (Simms et al., 2016). The same expert panel guided the development of short-term fluctuation for California based on long-standing tide gauge records. The team then combined the short-term fluctuations with the long-term sea level rise projections to develop a dataset of hourly sea level projections (Cayan et al., 2016). Researchers and planners in California subsequently used both long-term sea level rise data (Barnard et al., 2014) and short-term hourly projections to develop further localized data (Radke et al., 2018).

There remain a number of different uncertainties related to sea level rise projections and associated impacts. According to Kettle (2012), these uncertainties can be clustered into six different categories: measuring and monitoring sea levels, determining trends in sea level change, predicting future sea level rise, predicting shoreline change, modeling coastal elevations and quantifying impacts. In addition to these uncertainties, there is the uncertainty about how sea level rise will interact with other changes in water systems such as changing precipitation patterns (Wahl et al., 2015) and changes in groundwater (Habel et al., 2017).

When we revisit Holling's point of needing to define what is known, what is uncertain, and what is unknown in terms of sea level rise, I think it's critical to highlight that we actually know a tremendous amount. We know both from historic tide gauge data and from detailed models that eustatic sea levels are rising (Cayan et al., 2016). Additionally, there is mounting evidence that the rate of rise is increasing (Nerem et al., 2018). What is uncertain is the rate of relative sea level rise and the maximum height of water at specific locations (Kettle, 2012). We also find that what is unknown are the actions that social systems will take and the specific impacts that will occur in any given location (Hayhoe et al., 2017).

Going beyond the models—additional sources of uncertainty

Modeling and data make up only one lens into issues of uncertainty. Ruth Mack, who worked in the area of public administration and economics, proposed the following four categories to aid in the understanding of uncertainty: internal dynamics, external influences, human factors/strategies, and chance (1971 p. 67–69). Internal dynamics are causal relationships including physical and social forces that are intrinsic to the system. The external influences are those physical, economic and social forces that could influence the situation in the future but are not part of the system being addressed. Thus for example this could include the international agreements that will ultimately influence carbon emissions and thus the rate of sea level rise. Human factors and strategies include the social choices at both the individual and organizational level. Finally chance encompasses those one-off random events that cannot be accounted for (Mack, 1971). Researchers in the field of complexity note that this final category may be more a flaw in our understanding of the other three and may emerge from cross-scale interactions rather than truly being completely random (Holling, 2001).

Abbott, writing in the field of planning, further distinguishes between the system's uncertainties, as defined above by Mack, and the uncertainties within the planning process. He identifies three process-specific uncertainties in the planning literature: knowledge of the external environment, knowledge of the appropriate value judgments, and knowledge of future intentions and actions by people and organizations (Abbott, 2005).

Ultimately, from these additional uncertainties, we can consider climate adaptation planning as occurring in a place of deep uncertainty, which is defined as "the condition in which analysts do not know or the parties to a decision cannot agree upon (1) the appropriate models to describe interactions among a system's variables, (2) the probability distributions to represent uncertainty about key parameters in the models, and/or (3) how to value the desirability of alternative outcomes"(Walker et al., 2013).

Decision making under conditions of uncertainty

Planning as a discipline is built around making choices in the context of uncertainty (Abbott, 2005; Walker et al., 2013). Therefore, the literature offers a number of ways to move forward despite deep uncertainty. Carl Steinitz in his work on alternative futures and environmental planning developed a robust and flexible process for assessing a landscape and for engaging scientific experts, professionals and stakeholders (Ahern, 2006). Others, writing on hazards and risk, propose the following three frameworks for dealing with decision making in the context of uncertainty: 1) optimal utility 2) the precautionary principle, and 3) robust decision making (Lempert & Collins, 2007). Their work suggests that robust decision making, which essentially captures the essence of the precautionary principle, indicates that robust decision making is an ideal framework for addressing situations of deep uncertainty.

Recent work looking at climate adaptation planning highlights a family of planning approaches that are all designed to be robust in the context of deep uncertainty. Members of this family all derive from the ideas of "Assumption Based Planning," which was developed by the RAND Corporation in the late 1980s. Additional approaches include Robust Decision Making, Adaptive Policymaking, Adaptation Tipping Points and Adaptation Pathways, and Dynamic Adaptive Policy Pathways (Walker et al., 2013). The basic idea behind all of these approaches is to focus on the planning process itself. During the process, planners should define alternative plans and identify the conditions, often called signposts or triggers, under which the plans should be revised (Walker, Rahman, & Cave, 2001).

The study of social-ecological systems and their management is also founded on the idea that there is inherent uncertainty in any system (Holling, 2001). Thus this literature also provides insights into ways forward despite uncertainty. Folke et al (2005) offer four key ideas on creating adaptive governance of social-ecological systems during periods of abrupt change. First, there's a need for improving our understanding ecosystem dynamics. Second they suggest that we need to develop management practices that build knowledge of different ecological system and allow for continuous learning. Third they say that building adaptive capacity to deal with uncertainty and surprise is critical. The fourth piece to building resilience is supporting flexible institutions and social networks in multi-level governance systems. In addition to this list, Olsson et al (2004) note that the collaboration of a diverse set of stakeholders operating at difference social and ecological scales is key to managing social-ecological systems to build resilience.

Here I bring together these diverse fields to develop indicators that could be used to track a region's efforts to prepare for the long-range impacts of climate change and the associated transformational adaptations that are necessary. Specifically I aim to assess if a place has the capacity to engage in various forms of robust planning including Assumption Based Planning (Walker et al., 2013) and Alternative Future Planning (Steinitz, 2012). This work also has an eye toward a region's capacity to embrace physical plans such as those described in Chapters 3 and 4 to address the pressing need for climate change adaptation. The details of how I develop these indicators and the final assessment tool are covered in subsequent sections.

Focusing on regions when exploring adaptive capacity

Today's world is increasingly interconnected, and managing socio-ecological systems to build resilience is a complex endeavor (Ostrom, 2009). This complexity necessitates that all levels of government have a key role to play in planning for climate change impacts and developing appropriate adaptation measures (Tribbia & Moser, 2008). Local governments are often called on to address land-use needs (Burby et al., 2000; Reiblich et al., 2017) and manage local infrastructure (Meerow, 2017). National governments work to monitor adaptation efforts and can promote action through legislation (Adger, Hughes, Folke, Carpenter, & Rockström, 2005). Internationally there is work to develop agreements between nations to mitigate climate change and to create funding mechanisms to aid in adaptation (E. L. F. Schipper, 2006). Today there is increasing interest among scholars and practitioners on understanding the role that regions play in adapting to climate change (Juhola & Kruse, 2015).

One pressing issue is the precise definition of a region. Nicholls and Mimura (1998) in their work on sea level rise define a region as "a geographically continuous area containing more than 1 nation state." In more recent work on specific spatial tools needed to design adaptation strategies, the authors consider a region to be sub-national. For them a region "comprises multiple land use activities, infrastructure and settlements" and has a range of local stakeholders (Eikelboom & Janssen, 2013). For the purposes of this dissertation, I rely on Forman's (1995) landscape ecology–based conception of a region. As he explains, a region is a broad geographical area that is bound together by a common macroclimate and sphere of human interest. Specifically he sees regions as being tied together by transportation, communication and culture. Based on his definition, regions also are ecologically diverse.

Regions are bound together by both the opportunities and the pressures for collaboration (Lebel et al., 2006; Schmid, Knierim, & Knuth, 2016). Pooling together key resources gives a region greater strength and enhances its ability to adapt long-term to climate change. Specifically, regions can pool together financial resources enabling them to overcome the threat that climate change protection costs could overwhelm their capacity (Nicholls, 2011). Regions also benefit by bringing together shared experiences and using them to build a case for climate action (Nicholls & Mimura, 1998). Another key area for collaboration is the possibility to integrate research efforts and use regional models to inform the planning processes (Rosenzweig et al., 2011).

Researchers in the field of climate change adaptation find that crossborder pressures on regions necessitate collaboration (Schmid et al., 2016). One potential set of crossborder issues is physical changes including the interruption of sediment supply (Schile et al., 2014) and changes in flood frequency (Wahl et al., 2015). Other regional issues are socioeconomic changes including changes in vulnerability (C. Burton & Cutter, 2008; Cutter, Boruff, & Shirley, 2003) and the forced migration of residents in increasingly risky locations (P. R. Berke & Campanella, 2006). Regions also typically share infrastructure networks, such as transportation networks and energy networks, that require collaborative planning to address future impacts from climate change (Radke et al., 2018, 2017).

In reviewing the literature, I find that regions are considered the appropriate scale for some specific climate adaptation work. First, some researchers identify regions as the crucial scale for spatial climate adaptation measures (Adger, 2007; Roggema, 2009). Regions are also key in terms of making strategic planning and design decisions (Hirschfeld & Hill, 2017). Regions are known to play a critical role in connecting local jurisdictions to state agencies by giving a voice to specific local needs (Nordgren et al., 2016). Understanding and enhancing regional adaptive capacity would allow us to better test if a region is prepared to engage in all of these different climate adaptation actions and build resilience (Juhola & Kruse, 2015; Lebel et al., 2006).

In addition to scholarly interest in regions, practitioners at state and local scales are interested in understanding the role of regions. This particular project was guided by the State of California's Ocean Protection Council (OPC) as part of the agency's ongoing sea level rise planning work. OPC's sea level rise work is done in the broader context of the State of California's climate adaptation planning work. As part of this work and the development of California's Fourth Climate Change Assessment, the state worked to develop specific regions for planning and analysis purposes (Bedsworth, Cayan, Franco, Fisher, & Ziaja, 2018).

Towards a conceptual framework

Human actions are accelerating the pace of climate change placing significant stress on ecosystems (Stein et al., 2013). Institutions charged with protecting those systems and human livelihoods are also under increasing pressure to address future threats (Folke et al., 2004; Ostrom, 2009). City and county governments across the United States are developing plans to address these threats (Bierbaum et al., 2013; Woodruff & Stults, 2016). However there is currently no strategic approach to evaluate this work (Gupta et al., 2010). This chapter develops a flexible multi-criterion framework for evaluating the current status and potential future success of a region's ability to proactively address long-term threats such as sea level rise. In this section I describe the steps I used in consultation with Dr. Kristina Hill and Bruce Riordon to develop the framework, introduce the categories and evaluation criteria of my analysis approach, and present the Regional Planning Fingerprint.

Five categories of evaluation

The literature indicates that regions play a key role in long-term adaptation success, but does not provide a systematic framework to assess these regions. Based on my identification of this evaluation gap, I used a method similar to Gupta et al. (2010) to create an assessment framework for analyzing a region's ability to address long-term climate impacts. I adopted the following six-step methodology to develop this framework. First, I reviewed the literature in different related disciplines (resource management, organization studies, political science, hazard mitigation, and climate change adaptation) to identify the most important aspects institutional structures needed for regional success. Second, I used a crosswalk mapping technique where I connected specific characteristics identified in the literature to practical guides used in climate adaptation planning. This process ultimately led to the development of the five categories of assessment listed below and in Table 5.1. Third, I further reviewed the literature to design the 21 specific evaluation criteria within the five categories listed in Table 5.1. Fourth, I developed explanations for each evaluation criterion (see Table 5.1). Fifth, I tested these categories and evaluation criteria through interviews with experts in climate adaptation planning. Finally I, as part of the Climate Readiness Institute (CRI) team, conducted an initial assessment of regions in California (as described in the subsequent sections) working on sea level rise to determine the applicability of this evaluation framework.

The fundamental conclusion from this process is that the regions able to proactively adapt are those with institutions and structures that (1) have adopted actions into existing planning requirements; (2) have a strong institutional capacity; (3) use high quality research to make informed decisions; (4) use an inclusive planning process that engages vulnerable communities; and (5) have the ability to collaborate at a regional scale. Within these five categories I developed 21 evaluation criteria. In Table 5.1 I present the categories and evaluation criteria and explanations of the criteria, and connect them to the literature. In the subsequent paragraphs I also provide further details on each category and the associated evaluations criteria.

Adopted actions

Slow onset problems like climate change require significant preparatory efforts to ensure that society is ready to address future challenges. Planning structures offer one avenue to develop these preparations (Crawford & Davoudi, 2009; Hurlimann & March, 2012). Most researchers find that mainstreaming climate adaptation into existing planning structures provides local benefits such as efficiently using scarce resources (Carmin et al., 2012). To ensure success these plans must be high quality and appropriately designed to the local context (Woodruff & Stults, 2016).

In the context of sea level rise, researchers have found specific benefits from mainstreaming both general policy language and specific actions into existing planning frameworks (Burby et al., 2000; Dovers & Hezri, 2010; Godschalk et al., 1998; Reiblich et al., 2017). Establishing high level policy goals that include future climate changes can set the tone for future community visioning and planning (Dovers & Hezri, 2010). Thus here I analyze if communities have added sea level rise into the safety element of a general plan (AA1). Researchers specializing in hazard mitigation have found that if local governments make good land-use planning decisions, their communities are less likely to suffer losses of lives and property in the context of natural hazards (Burby et al., 2000; Godschalk et al., 1998). In the context of planning in California, I use two measures of local success in this area—the inclusion of sea level rise language in local hazard mitigation plan (AA2) and development limits set through the Local Coastal Program (AA3).

Table 5.1. Score categories, evaluation criteria, explanations and key literature.

Categories	Evaluation Criteria	Explanation	Literature
1. Adopted Actions	AA1: General Plan	Adopts sea level rise language into the safety element of a general plan	Carmin et al. (2012), Dovers & Herzi (2010)
	AA2: Hazard Mitigation Plan	Integrates sea level rise language into assessment and actions required through the hazard mitigation plan	Burby et al. (2000), Godschalk et al (1998)
	AA3: Local Coastal Program	Sets limits on development or the design of development in local zoning documents	Burby et al. (2000), Reiblich et al. (2017)
	AA4: Regional Plan	Adopts a formal regional plan to address sea level rise	Hegger et al. (2012), Toimil et al. (2017)
2. Institutional Capacity	GC1: Grant funding	Brings in funds specifically to help with climate change adaptation planning or implementation	Aylett (2015), Carmin et al. (2012), Gupta et al. (2010)
	GC2: Internal staffing	Adds staff to increase capacity to conduct sea level rise work	Aylett (2015), Gupta et al, (2010)
	GC3: Development of new funding	Analyzes or develops new funding sources to conduct sea level rise work	Baker et al. (2012)
	GC4: Localized cost analysis	Develops cost estimates for different specific strategies to address sea level rise	Nordgren et al. (2016)
	GC5: Champions	Has local champions among the region's elected officials	Westley et al. (2011)
3. Research Quality	RQ1: Vulnerability assessments	Develops comprehensive vulnerability assessments	Füssel and Klein (2006), Smit and Wandel (2006)
	RQ2: Model and mapping tools used	Uses rigorous models that have been locally calibrated and tested	Baker et al. (2012)
	RQ3: Secondary impacts	Addresses key impacts of sea level rise considered	Nicholls & Kebede (2012)
	RQ4: Development of baseline data	Collects and tracks needed data to detect thresholds	Kwadijk et al. (2010), Walker et al., (2013)
4. Planning Processes	PP1: Public engagement strategies	Employs a range of different public engagement strategies	Burton & Mustelin (2013)
	PP2: Use of polling	Uses public opinion polling to gauge public knowledge and beliefs on sea level rise	Hegger et al. (2012)
	PP3: Vulnerable communities identified	Identifies socially-vulnerable populations in sea level rise assessments	Corburn (2009), Cutter
	PP4: Voice for vulnerable communities	Includes socially-vulnerable populations in the planning and decision making around sea level rise	Corburn (2009)
	PP5: Inclusive citizen science	Includes socially-vulnerable populations in citizen science research activities	Corburn (2009)
5. Regional Collaboration	RC1: Collaborative structures	There is a collaborative structure that brings together stakeholders for address sea level rise	Mills et al. (2014), Schmid et al. (2016), Serrao-Neumans et al. (2014),
	RC2: Formal agreements	There are formal partnership agreements for collaborative sea level rise work across jurisdictional lines	Participants added
	RC3: Permit procedures	Has a structure in place to facilitate permitting among multiple agencies	Participants added

Authors and practitioners note that there are specific benefits associated with planning conducted at the regional scale (Lebel et al., 2006; Schmid et al., 2016). One specific benefit relates to the management of shared resources that cover multiple jurisdictions (e.g., sediment, bayland habitat). In the context of such resources, regional planning allows for collaboration and better outcomes for such resources (Toimil, Losada, Camus, & Díaz-Simal, 2017). Regionally planning also helps to ensure that singular jurisdictions do not inadvertently make poor decisions that are maladaptive for the region (Barnett & O'Neill, 2010; Magnan, 2014). For example, building flood protection can lead to human settlement in flood prone locations and shift the frequency and magnitude of flooding from one location to another (Di Baldassarre et al., 2013). Thus I included evaluation criterion AA4: Adopts a formal regional plan to address sea level rise, which is used to determine if there is a formal regional plan for addressing the risks associated with sea level rise.

Institutional capacity

Solutions to sea level rise will require the active participation of the coastal communities directly impacted by increased flooding and other sea level rise associated impacts. These jurisdictions, charged with protecting the constituents' homes and lives, will continue to be relied upon for most of the critical land use and planning decisions (Hurlimann & March, 2012; McEvoy, Matczak, Banaszak, & Chorynski, 2010; Measham et al., 2011). Unfortunately, the work of adapting to sea level rise is challenging and requires significant local capacity (Gupta et al., 2010). For example, Ventura Beach's recent plan to retreat from the shorezone over time took 10 years and significant stakeholder outreach to develop ("U.S. Climate Resilience Toolkit," 2015). Recent research indicates that many places still lack this capacity (Baker et al., 2012). There is, however, a growing body of literature to help identify the key elements of institutional capacity in the face of climate change (Gupta et al., 2010).

It is clear from the literature that having sufficient internal resources (e.g., funding and staff capacity) allows local and regional institutions to move plans forward (Aylett, 2015; Carmin et al., 2012; Gupta et al., 2010). Additionally, researchers have found that local governments and associate regional institutions need to conduct in-depth analysis of possible funding, work to develop new funding sources, and develops cost estimates for different specific strategies to address sea level rise (Baker et al., 2012; Nordgren et al., 2016). Research shows that local champions, especially those that stimulate action, are necessary to address sea level rise (F. Westley et al., 2011).

Research quality

There is extensive scientific evidence supporting the existence of anthropogenic climate change and many associated impacts including rising sea levels (IPCC, 2014). There are also increasing amounts of downscaled data that provide more localized information. For example, Hayhoe et al. (Hayhoe et al., 2004) developed detailed projections based on two emissions scenarios for California. Similarly, researchers have developed different models to predict future impacts of sea level rise for California (Barnard et al., 2014; Biging et al., 2012). Despite this increase in available climate data, climate issues do not seem to have a strong impact on urban planning in actual practice (Eliasson, 2000). Barriers to the use of climate science can be placed into clusters (e.g., technical, conceptual and knowledge based, policy, organizational, and the market) (Eliasson, 2000). For example, in some communities, the pressure to develop the land and increase the present tax base outweighs future threats and thus those in power can undermine the use of hard to understand scientific information (Tribbia & Moser, 2008).

Researchers studying climate change adaptation contend that the development of local vulnerability assessments is a strong indicator that a place has overcome some barriers (e.g., data availability, data acceptance, or data understanding) associated with developing a local appreciation of climate impacts (Füssel & Klein, 2006; Smit & Wandel, 2006). To further evaluate these assessments, one can look at the degree to which the mapping and modeling of sea level rise has been locally calibrated (Baker et al., 2012). The degree to which secondary impacts from sea level rise are considered and made regionally specific in vulnerability assessments or planning is another measure of the research quality (Nicholls & Kebede, 2012).

Climate adaptation planning theorists recently proposed a shift toward the use of adaptation pathways and thresholds to handle decision making in the context of uncertainty (Walker et al., 2013; Wise et al., 2014). This shift requires the collection of baseline data to measure in the future when a threshold has been reached (Kwadijk et al., 2010). Some plans, such as the one for the Thames Barrier, put this theory into practice (Reeder & Ranger, 2011). Though a relatively new approach, there is mounting evidence that such baseline data will be useful as adaptation planning moves forward. Thus I included evaluation criterion RQ4: Development of baseline data, which is used to test if baseline data is being collected at the regional scale.

Planning processes

There is a long history of evaluating planning based on the actual final plans documents themselves (P. Berke & Godschalk, 2009; Lyles & Stevens, 2014). However this approach overlooks critical insights that evaluating the planning process can provide (Corburn, 2003). For example, planners in the past have alienated community members by using confusing scientific language or ignoring their concerns (ibid). Researchers find that including the public through greater participation leads to better long-term outcomes (P. Burton & Mustelin, 2013). To evaluate the process of public engagement broadly I use two measures (see Table 5.1). In the first, I determine the number of strategic efforts used to involve the public in sea level rise planning. In the second I look at the use of polling data to inform sea level rise planning.

Climate change and sea level rise will disproportionately impact certain communities and exacerbate existing pressures and problems (Martinich, Neumann, Ludwig, & Jantarasami, 2013; Nicholls & Klein, 2005). Researchers using interviews and fieldwork demonstrate that local knowledge can improve planning for these vulnerable populations. Improvements come from (1) adding to the knowledge base; (2) increasing the effectiveness of policy solutions; and (3) achieving distributive justice (Corburn, 2003). Therefore, I included three evaluation criteria (PP3, PP4, and PP5) to look specifically at how regions are addressing vulnerable communities in the sea level rise context (see Table 5.1).

Regional collaboration

As noted above, there are some definite benefits to engaging in regional collaboration when strategically planning to adapt to climate change. Specifically, researchers found benefits in terms of participant satisfaction, ability to utilize scientific knowledge, and ability to implement policies when multi-actor networks were developed and supported in their work on climate change adaptation (Mills et al., 2014; Schmid et al., 2016). Practitioners who work on managing cross-jurisdictional resources identified as part of the development of this rating system formal partnership agreements (RC2) and facilitation of the permitting processes (RC3) as key to their success.

The Regional Planning Fingerprint

To structure the information and communicate it clearly, I developed the Regional Planning Fingerprint in 2018 (see Figure 5.1). The center coxcomb graph shows a region's score in all five evaluation categories (note that this demonstration version shows perfect scores; however figure 5.2 shows actual scores). These scores represent the aggregation of the scores in each category. Along each axis I show the percentage score—meaning the raw score divided by the highest possible score—a region achieved. By showing percent scores, this coxcomb graph may be used to both assess and inform social actors about how their region is performing and identify specific opportunities for discussion and reform.

Figure 5.1. This is a model version of the Regional Planning Fingerprint. Each wedge of the coxcomb graph represents a single evaluation category. Within each category are between 3 and 5 evaluation criteria as shown in the category's specific table.

Assessing work in California: Data and methods

In this chapter, I report on work I led as part of the CRI research team. This work is one part of a larger yearlong assessment of sea level rise efforts in California. In 2017 I conducted a comparison of six different coastal regions of California based on those used for California's Fourth Climate Change Assessment: Central Coast, Sacramento-San Joaquin Delta (Delta), Los Angeles Region, North Coast, San Diego Region, San Francisco Bay Area (Bay Area) (see Figure 5.2). I evaluated these regions using the Regional Planning Fingerprint described in the previous section. I based these regional comparisons on practitioner interviews, publicly available locally adopted plans, and more detailed analysis as explained below. I provide details on the scoring system and information on access to the actual data in the subsequent sections.

Region	Cities	Counties
North Coast	8	3
Bay Area	62	9
Delta	8	5
Central Coast	20	5
Los Angeles Region	25	2
San Diego Region	10	1

Figure 5.2. The State of California, the six coastal regions I evaluated, and the number of jurisdictions (both city and county) within each region.

Details on data collection

From April 2017 to May 2018 I used several methods to gather information and create regional summary reports called "Regional Sea Level Rise Snapshots" for the Climate Readiness Institute (CRI). First, I, in consultation with Dr. Kristina Hill, Bruce Riordon, and other stakeholders, developed a standardized set of questions to gather key information. These questions are provided as part of the published data available through UC Berkeley's online data archive (DASH), and access details are described below. Then, using web searches, I generated initial answers to these questions. In October and November of 2017, as part of the CRI team, I held in-person group meetings with key sea level rise stakeholders in each region to further complete the set of questions. The stakeholders worked for city or county governments, relevant state or federal agencies, and for connected non-profits. A full list of involved stakeholders is available through DASH. I used some in-person follow-ups with individuals to finalize answers for each region. The final reports, called "Regional Sea Level Rise Snapshots," were reviewed and approved by Dr. Kristina Hill and Bruce Riordon.

I used specific locally adopted plans and vulnerability assessments to supplement the survey information, when the responses lacked sufficient detail for evaluation. This allowed me to verify information provided by local stakeholders and translate their responses into final scores. The locally adopted plans and vulnerability assessments I assessed include all Local Coastal Programs Updated for Sea Level Rise according to the California Coastal Commission, General Plans with Safety Elements Updated for Sea Level Rise, all local Hazard Mitigation Plans Updated to Include Sea Level Rise according to the California Governor's Office of Emergency Services, and Comprehensive City or County Vulnerability Assessments. Input from all of these plans and assessments was vital to inform the adopted actions category (1) and the planning processes category (4).

Details on scoring

I used three scoring systems and tailored them as needed to each evaluation criteria (see Table 5.2). The first and simplest scoring system is a *"Yes or No"* system where a region received a score of one for having a specific resource and a score of zero for not having such a resource. For example, regions such as the Bay Area with local champions for sea level rise action received a score of one, while regions such as the North Coast with no local champions received a score of zero.

Table 5.2. Score categories, evaluation criteria and scoring type.

Categories	Evaluation Criteria	Score Type
1. Adopted Actions	AA1: General Plan	Jurisdiction percent
	AA2: Hazard Mitigation Plan	Jurisdiction percent
	AA3: Local Coastal Program	Jurisdiction percent
	AA4: Regional Plan	Scale 0–4
2. Institutional Capacity	IC1: Grant funding	Scale 0–4
	IC2: Internal staffing	Scale 0–4
	IC3: Development of new funding	Scale 0–4
	IC4: Localized cost analysis	Scale 0–4
	IC5: Leaders (Champions)	Y or N
3. Research Quality	RQ1: Vulnerability assessments	Jurisdiction percent
	RQ2: Model and mapping tools used	Scale 0–4
	RQ3: Secondary impacts	Scale 0–4
	RQ4: Development of baseline data	Y or N
4. Planning Processes	PP1: Public engagement strategies	Scale 0–4
	PP2: Use of polling	Y or N
	PP3: Vulnerable communities identified	Jurisdiction percent
	PP4: Voice for vulnerable communities	Y or N
	PP5: Inclusive citizen science	Y or N
5. Regional Collaboration	RC1: Collaborative structures	Scale 0–4
	RC2: Formal agreements	Scale 0–4
	RC3: Permit procedures	Scale 0–4

The second scoring system is the *"jurisdiction percent."* In this system I used only the jurisdictions in the region that are within the coastal zone (see Figure 5.2). I tallied all these jurisdictions that had a specific plan or used a specific assessment and divided them by total number of coastal zone jurisdictions. This percentage was then translated into a score of zero to four based on Table 5.3.

Table 5.3. Jurisdiction percent system.

Percent of coastal jurisdictions	Score
No Action	0
0.1 %–20.9 %	1
21 %–49.9 %	2
50 %–74.9 %	3
> 75 %	4

The third scoring system is an evaluative system shown in Table 5.4. For example, the San Diego Region, where local leaders operate the San Diego Regional Climate Collaborative with regular meetings and facilitated collaboration efforts, received a score of four for the "Collaborative structures" evaluation criterion (RC1). The Bay Area, on the other hand, received a score of one for RC1 since the region has had a few meetings, but has not yet established a full region-scale effort. I provide further details on how each evaluation criterion is scored as part of the published data, which can be accessed as described below.

Table 5.4. Evaluative scale 0–4.

Description	Score
No action	0
Meetings or discussions held, but no specifics established	1
Steps in the direction of functioning systems, but nothing formal established	2
Some fully functioning systems in place, but not yet operationalized regionally	3
Fully functioning system in place at the entire regional scale	4

Data and methods access

Data and detailed methods are available at UC Berkeley's online data archive (DASH). The data contain the original source reports, the scores assigned, the standardized questions used, and links to all plans analyzed. Data can be accessed here: https://doi.org/10.6078/D1W98G. This analysis builds on an ongoing effort in California to enhance resilience to climate change; two state legislative bills supported the development of a statewide database of climate change adaptation resources. The "Regional Sea Level Rise Snapshots," which I used to supplement this analysis, can be found through the state's database housed on the website: ResilientCA.org

Results

Here I present findings for the six regions. In the first Section, called "Regional comparison," I cover the aggregate percent scores for each category. Then in the second Section, called "Scores for each category," I provide the percent scores for each evaluation criterion in all five categories.

Regional comparison

Here I present the comparison of all six coastal California regions (see Figure 5.2) in terms of their level of preparedness to address sea level rise. The results here reflect the summation by category of the raw scores for each evaluation criterion divided by the highest possible category score. Figure 5.3 shows the percentage each region achieved in the five different categories. We see that every region has a unique fingerprint. Some regions, such as the San Diego Region, score moderately (50%–75%) in all categories. The Bay Area scores well (>75%) in two categories, moderately (50%–75%) in one category and low (25%–50%) in two categories. The Delta excels relative to the other regions in one category (institutional capacity) and then scores low (25%–50%) or poorly (<25%) in all other categories. The Los Angeles Region does not score well in any category. This region instead scores moderately (50%–75%) in three categories, low (25%–50%) in one category, and poorly (<25%) in in the regional collaboration category.

The data also indicates that there is variety in performance across the different categories. No region performs well (>75%) in Category 1—Adopted Actions, Category 2—Institutional Capacity, or Category 5—Regional Collaboration. Category 4—Planning Processes on the other hand has scores ranging from 45% to 100%.

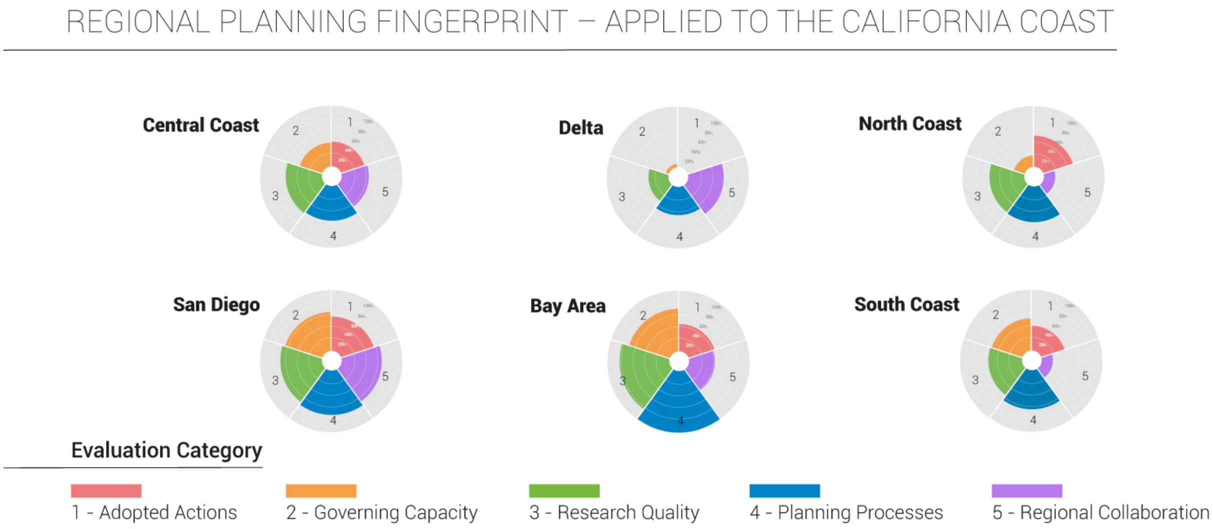

Figure. 5.3. Coxcomb graphic showing the aggregate percentage score for the six regions in each of the five categories used to determine capacity for sea level rise adaptation planning.

Scores for each category

In this section I present the scores of all six coastal California regions (see Figure 5.2) for every evaluation criterion (see Table 5.1) as a percentage of the maximum possible score. As in the previous section, called “Regional comparison,” we see that every region has a unique fingerprint.

Figure 5.4 shows the scores by each region for all the evaluation criteria in Category 1—Adopted Actions. The figure shows that the San Diego Region is the only region to score well (>75%) on any of the evaluation criteria in this category. The Delta Region stands out in this category since it receives a zero in all evaluation criteria. It should be noted that the Local Coastal Program evaluation criterion (AA3) is actually not applicable to the Delta. The Bay Area is the only region to perform below 50% on all evaluation criteria. In this figure we also see that the regions are more consistently performing in the middle range of scores for the Local Coastal Program evaluation criterion (AA3). There is a wider range of scores on the other evaluation criteria. Specifically changes to local hazard mitigation plans and general plans are less common.

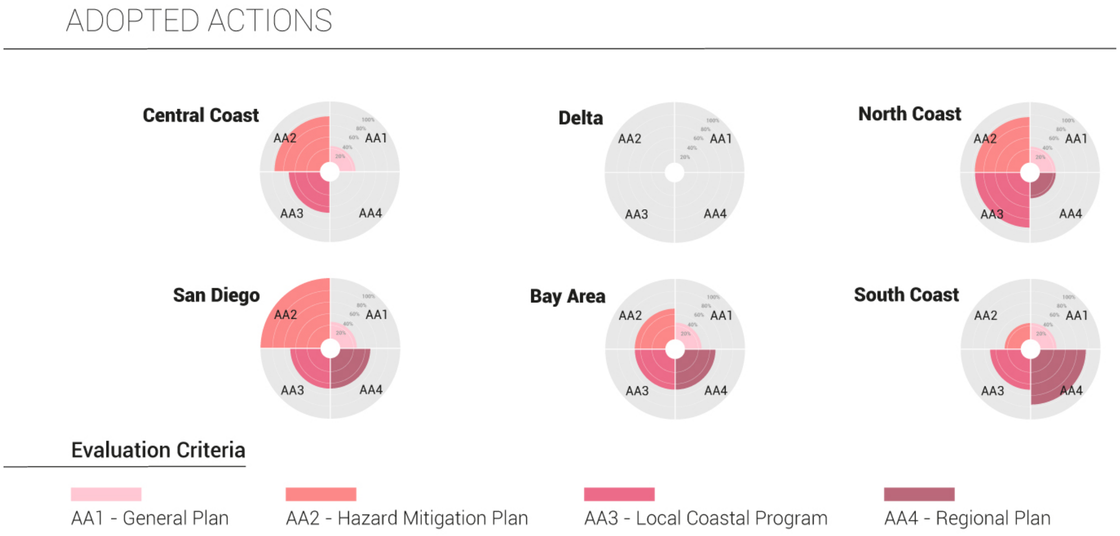

Figure 5.4. Coxcomb graphic showing the percentage score for each of the six regions in the four evaluation criteria for Category 1—Adopted Actions

Figure 5.5 shows the scores by each region for all the evaluation criteria in Category 2—Institutional Capacity. The Delta and the North Coast score below 50% on all evaluation criteria. The Central Coast and the San Diego Region score above 50% on two evaluation criteria (GC1 and GC5), however they score 50% or below on the remaining three criteria. The Bay Area and the Los Angeles Region both score above 50% on at least three evaluation criteria. Grant funding (GC1) and Leadership (GC5) are evaluation criteria where many regions score well.

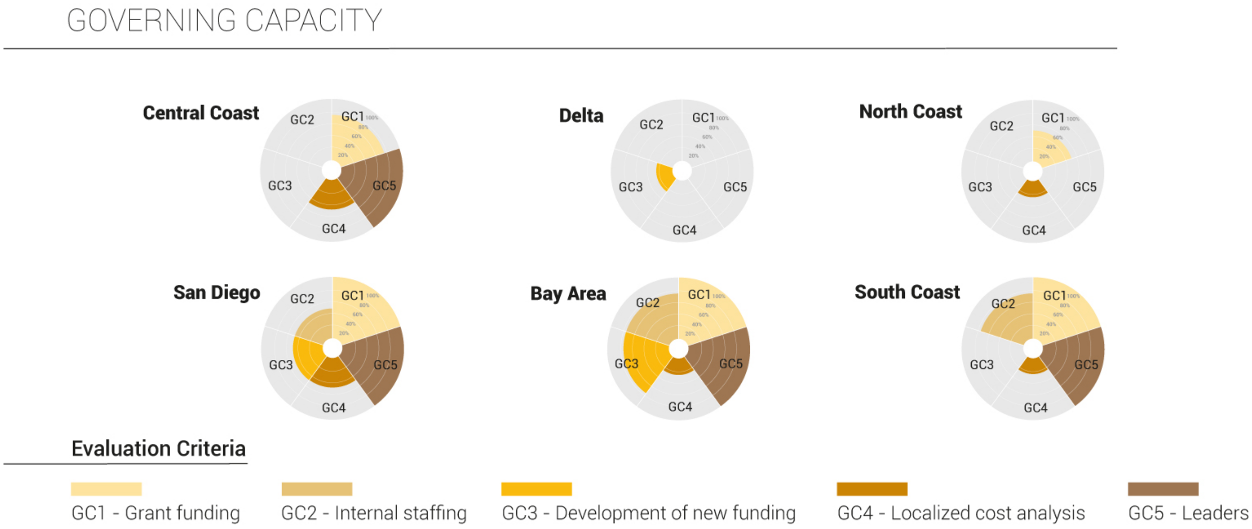

Figure 5.5. Coxcomb graphic showing the percentage score for each of the six regions in the five evaluation criteria for Category 2—Institutional Capacity

Figure 5.6 shows the scores by each region for all the evaluation criteria in Category 3—Research Quality. Currently, no region is collecting or tracking data to help identify threshold points (RQ4). The Bay Area scores well (>75%) in the other three evaluation criteria. The San Diego Region and the Central Coast score moderately or higher in the other three evaluation criteria. The Delta received one moderate score (50%) on the vulnerability assessment criterion (RQ1). However, it continues to score low or poorly on most criteria.

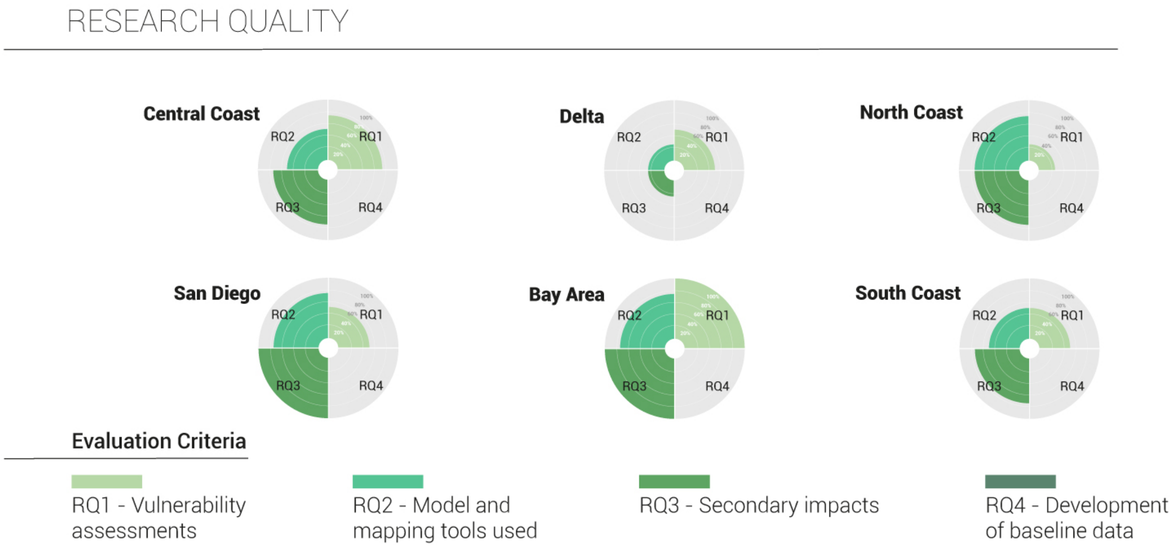

Figure 5.6. Coxcomb graphic showing the percentage score for each of the six regions in the four evaluation criteria for Category 3—Research Quality

Figure 5.7 shows the scores by each region for all the evaluation criteria in Category 4—Planning Processes. This is a category where most of the criteria are scored based on a *"Yes or No"* system (See Table 5.2); therefore, regions score very well. For example, the Bay Area received a perfect score in this category. The Los Angeles and San Diego regions also received 100% in three criteria (PP1, PP2, PP5 and PP1, PP2, PP4, respectively). A few communities have identified socially vulnerable communities for sea level rise impacts; however the work with vulnerable populations lags behind the more general public engagement efforts.

Figure 5.8 shows the scores by each region for all the evaluation criteria in Category 5—Regional Collaboration. No region scores well (>75%) on all three evaluation criteria. However, we see that both the Delta and the San Diego Region score well (>75%) on collaborative structures (RC 1). Some regions, such as the North Coast and the Los Angeles Region, have not yet begun work on developing formal agreements (RC2) or improving permitting procedures (RC3) to enable sea level rise adaptation across jurisdiction lines. The only region to perform above 50% on permitting procedures (RC3) is the Bay Area.

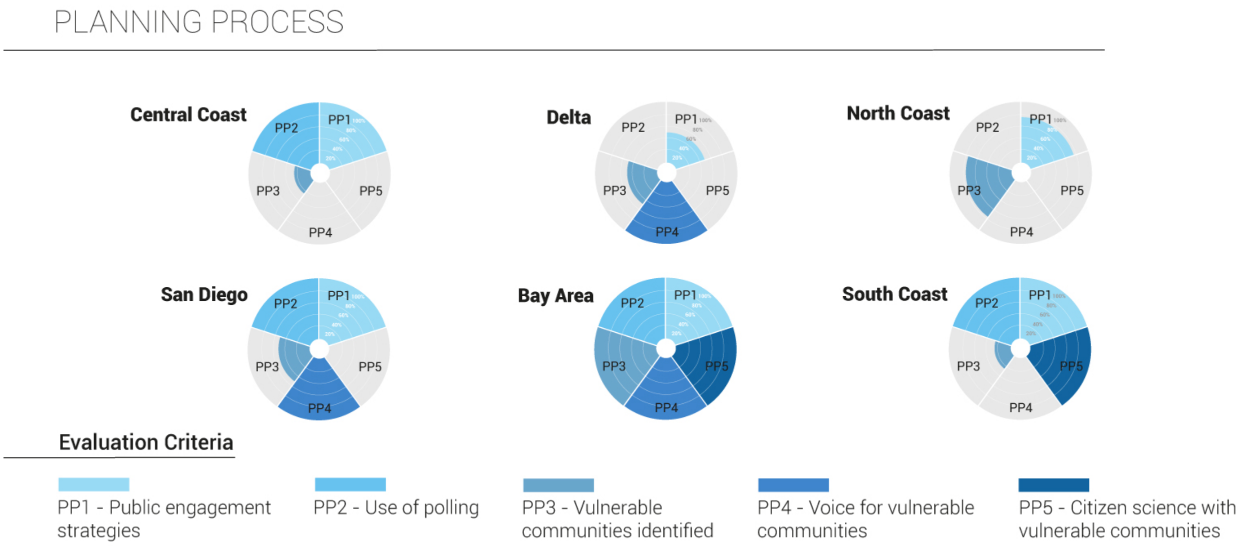

Figure 5.7. Coxcomb graphic showing the percentage score for each of the six regions in the five evaluation criteria for Category 4—Planning Processes

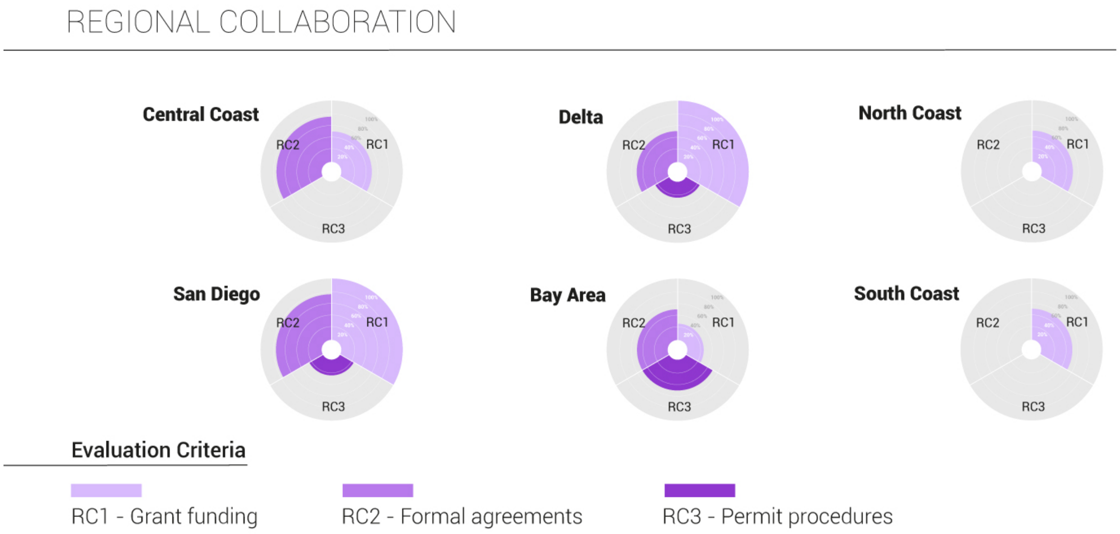

Figure. 5.8. Coxcomb graphic showing the percentage score for each of the six regions in the three evaluation criteria for Category 5—Regional Collaboration

Discussion: Strategic implications of results

In this chapter of my dissertation, I describe a new method to assess a region's capacity to create transformative change through transformational adaptation actions and adapt to long-term sea level rise impacts. Based on a literature review, expert solicitation, and field application, I developed five evaluation categories with 21 associated evaluation criteria to assess regional adaptive capacity. This information is presented in the model Regional Planning Fingerprint (Figure 5.1) and in an application to Coastal California. This work was funded by a grant from Ocean Protection Council to Climate Readiness Institute and was designed by Dr. Kristina Hill and Bruce Riordon through a series of meetings with many stakeholders. This discussion focuses on two themes that emerged: the key insights derived from applying the Regional Planning Fingerprint (in the first two subsections) and the areas for future work (in the third and fourth subsections)

Insights from the Regional Planning Fingerprint

There are clear advantages to using the Regional Planning Fingerprint. First the fingerprint is a simple summary of a complex set of evaluation criteria. By nesting measures into each of the five wedges (Figure 5.1) I was able to capture a wealth of information in one graph. The nested graphs (Figures 5.4–5.8) for each evaluation category thus provide supporting information allowing one to dig deeper and better understand a specific final score.

Second the evaluation criteria provide a comprehensive picture of the dimensions relevant for assessing a region's adaptive capacity. In all of my meetings and interactions with experts and stakeholders I asked participants if I had overlooked a key dimension that was missing in the literature. Participants supported all of these evaluation criteria and helped by adding RC2: Formal agreements and RC3: Permit procedures. Generally, I followed Gupta et al. (2010) and erred on the side of being too comprehensive rather than miss a critical piece of information. However, this rating system allows for future expansion or contraction as new knowledge on managing regional resilience emerges.

Third, the Regional Planning Fingerprint can be used to generate meaningful quantitative results from a qualitative analysis. These quantitative results can be used to rank and thereby compare regions. For example, one could use the Regional Planning Fingerprint to determine which regions score better and which score worse on the specific evaluation category of Research Quality. The aggregated picture (Figure 5.3) draws our attention to the fact that the Bay Area and San Diego are leading the way in this category while the Delta is lagging behind all the regions. This shows which regions are leading the way and which regions need the most support to move forward. Some might argue that a quantitative analysis of this nature reduces complex information into too simple a format and thus reduces the information to something relatively meaningless and too aggregated. However, I would argue that by shedding light on a regional deficiency, this rating system allows practitioners, policy makers and local stakeholders to dig deeper and discuss in detail the possible areas for improvement.

In addition to comparing regions on a specific evaluation category, the Regional Planning Fingerprint allows researchers to compare regions more holistically. Specifically, looking at Figure 5.3 one can see that the Bay Area and San Diego are outperforming the other regions. The Central Coast and the South Coast are middle tier performers, and the North Coast and the Delta get the lowest scores. Researchers have often pointed to resources as a key driver of planning and climate change adaptation success (Carmin et al., 2012; Nordgren et al., 2016). In the case of the Bay Area, these resources could simply be defined as monetary resources; however the same would not hold true in San Diego. Based on interviews I found that practitioners repeatedly pointed to the network of actors present in the regions as a key to success. This network included connections between urban planners, resource managers, designers (engineers, landscapers, etc.), as well as critical decision makers such as champions in the state legislature. Thus this research indicates that a mix of resources and leadership is required for regions to make progress on these complex planning efforts.

Digging deeper: Insights from specific evaluation criteria

By applying the Regional Planning Fingerprint to Coastal California, I gained new insights into current regional successes and failings. These insights can be translated into areas for policy interventions. When one looks at Category 1: Adopted Actions, one sees that only moderate progress has been made on adopting sea level rise language into existing planning frameworks. Based on our meetings with local officials, there are two reasons for this lack of progress. One issue is that there are too many different and sometimes conflicting sea level rise/flooding directives from state and federal agencies. The second issue is a lack of understanding at the local level that integrating sea level rise planning into other planning frameworks is currently required in California. Each of these reasons is supported by the literature that focuses on collecting data directly from stakeholders (e.g., Nordgren et al., 2016; Tribbia & Moser, 2008). Some possible options for overcoming this failing include providing substantial state resources to go with state mandates on changes to planning, aligning and coordinate participation by utilities and other large actors that are currently not engaged in local planning, and building a "cross-walk" to enable coordination of separate legal processes for hazard mitigation plans, general plans, local coastal programs, and climate action plans.

Looking at Category 3: Research Quality: one very noticeable issue is that all six regions received a score of zero on evaluation criterion RQ4: Development of baseline data. This data is particularly important in creating robust physical plans for adapting to sea level rise. This finding is surprising in California where significant investment in climate adaptation work and science is already underway (Moser & Tribbia, 2007). However the finding is also in keeping with previous research that suggests that translating the science into local planning is falling behind the science itself (Woodruff & Stults, 2016)). There are many ways to address this gap, including: 1) bringing together scientists, policy makers, legal experts, and local government staff to create a strong, state-region-local agreement on sea level rise science and action, 2) developing and implementing a statewide educational program to increase scientific literacy on sea level rise among key public, private and non-profit leaders, and 3) creating clear monitoring programs to collect consistent data, develop key indicators, and track triggers and thresholds for changing coastal and bayside conditions.

Limitations of the 'Regional Planning Fingerprint'

There is one critical design flaw in the Regional Planning Fingerprint. This rating system does not account for regional differences. Every region poses different vulnerabilities associated with its specific geomorphology, rates of change, and population dynamics (Cutter et al., 2003; Nicholls & Mimura, 1998). These differences could require different adaptation actions and thus require different capacities (Füssel & Klein, 2006; Smit & Wandel, 2006). Similarly, this rating system assumes that all regions are equally connected within the region and therefore require significant collaboration (i.e., Evaluation Criteria AA4, RC1, RC2, & RC3). However, some regions share infrastructure systems and ecological systems that truly require collaboration, while other regions possess fewer crossborder concerns. For example, the Bay Area shares a complex interconnected transportation network (Biging et al., 2012) and ecologically sensitive baylands (Schile et al., 2014) that will be impacted by climate change and requires crossborder collaboration to address these threats. However the Central Coast shares fewer roads and ecosystems across jurisdictional borders and thus may require less collaboration.

To address this issue, future iterations could allow for a relative scoring process that weights specific criteria differently dependent on details relevant to the region. For example when evaluating the Bay Area, researchers could add weight to evaluation criteria that emphasize collaboration, which is critical in such a highly connected place. Making this change would allow the rating system to be a better signpost to the region providing. Specifically it would provide local practitioners with signal on areas that need improvement. However, a change of this nature would make comparisons between regions more difficult, as the weights could result in an apples and oranges scenario. Significant changes to the rating system making it very specific to any one place would reduce one's ability to meaningfully compare regions. Therefore, I propose building some nuance into the rating system, but caution against too much local tailoring.

There are three flaws specific to the way I applied these categories and criteria in my evaluation of the California coast. First the survey and subsequent interview process was very time consuming. Thus this approach would be expensive and difficult to iterate frequently. Second, the data used to score certain evaluation criteria could overlook more relevant information. For example, when scoring PP1: Public engagement strategies, I relied on practitioner reporting on the number of different ways they tried to engage the public; however this criterion could be better evaluated by determining how many people meaningfully engaged in these activities. Finally, there's the potential that the scores included some level of subjectivity. Specifically there could be a bias toward evaluating criteria harshly due to an expert's overconfidence (Morgan, 2014). For example, when scoring RQ3: Secondary impacts, I decided that a region would need to have evaluated at least six secondary impacts to get the highest score; however that may be an unrealistically high standard. Despite this criticism, there is a precedent in using expert opinion to generate scores for multi-criteria assessments of this nature. Moreover, some argue that biases have been exaggerated (Kynn, 2008). In this study, the same person scored all of these projects to increase the reliability of the scores. Other experts checked the scores to validate the final numbers.

Potential future research

The development of the Regional Planning Fingerprint establishes an important foundation and can be used as part of answering the three significant questions for future research that arose during the development and implementation this rating system. As part of answering all of these questions the rating system could be applied to other locations, other climate impact areas, and could itself be further refined.

The first question is what geomorphological, ecological, economic (i.e., gross regional product), or infrastructure characteristics of a region could be correlated with regions' scores. For example in Figure 5.3 we see that the San Diego Region and the Bay Area score moderately or better in all categories while the Delta and the North Coast perform poorly getting low scores in most categories. This could perhaps be explained by the economic wealth of each region (Brooks, Adger, & Kelly, 2005). Similarly, do places with open coast and associated erosion risks have lower scores on regional collaboration than places with baylands and associated flooding risks? Research of this nature could be mirrored on the regression analysis conducted by Woodruff & Stults (2016) to better understand urban characteristics that correlated with plan quality.

The second question is how could this data be tracked over time to provide continous updates into a region's ever changing capacity. The theoretically ideal planning approaches use thresholds and triggers to enable places to shift paths (Walker et al., 2013). Continuously updating a region's adaptive capacity would be one way to track progress and see when it needs to act in order to enact certain transformational adaptation actions.

Finally, this research raises the question of what additional climate adaptation work could be evaluated through this lens. In this project I focus on capacity to adapt to sea level rise. However, there are many climate change impacts—including, but not limited to, increases in heat waves, changes to precipitation patterns, and shifts in agricultural productivity (Hayhoe et al., 2004; IPCC, 2014). Measures in adaptive capacity lend themselves well to being applied broadly (Gupta et al., 2010) and thus this rating system could be used to investigate other impacts of climate change faced by California or other regions around the globe.

Conclusions

Here I answer two key questions through the development of a new evaluation assessment technique called the Regional Planning Fingerprint. First I show one way regional efforts to prepare for the long-range impacts of climate change and the need for transformational adaptation actions can be evaluated. Second, through this assessment, I highlight critical areas for strategic intervention by state and local planners in California. I find through this evaluation that each region is truly unique. I also find that all regions in California struggle with regional collaboration, the collection of baseline data and the inclusion of vulnerable populations in their planning processes.

This work establishes an important foundation for future critical analyses. As climate adaptation efforts continue, researchers or practitioners could dynamically update aspects of this assessment. This current assessment would then be used as the baseline against which future climate adaptation work can be evaluated. The Regional Planning Fingerprint can also be applied to other locations to set local baselines and to further refine the assessment technique. Finally scores can be compared with regional specific variables, such as gross regional product, to determine if they can be proxies for a place's capacity to adapt to climate change.

Finally, through the Regional Planning Fingerprint I connect work from previous chapters of this dissertation weaving together my understanding of physical planning and the actors associated with transformational adaptation. By interviewing and gathering data directly from the actors such as urban planners and resource managers identified by my literature review (Chapter 2), I am able to ground my findings in current planning practices. I was also able to gain meaningful insights into each region's readiness for physical planning by having robust metrics for the use of science in current planning practice. Specifically, measures RQ2: Model and mapping tools used and RQ3: Secondary impacts help to call attention to knowledge that I found in Chapter 3 leads to quality physical planning. This knowledge includes a deep understanding of climate change science, its associated uncertainties and the interconnected impacts (e.g. changes to the water table from sea level rise).

CHAPTER 6: CONCLUSION

This dissertation and the associated research was motivated by theoretically and practically relevant questions: how can we transform complex social-ecological systems to build future resilience? And how can we evaluate current progress and compare possible strategies? The four preceding chapters provide important insights related to these questions. They also provide ideas for new avenues for future research. In this concluding chapter I begin by providing a summary of the key findings and contributions from this work while also highlighting some limitations. I then provide an outline of a future research agenda at the critical intersection of climate change adaptation, urban ecology, and environmental planning.

Summary of major findings and contribution

A growing number of scholars, organizations, government agencies, and regions are planning for resilience in the face of climate change and associated threats. Transformations of social and ecological systems are one key way to address these risks. My research helps to advance existing knowledge of changing landscapes, regional adaptive capacity, and climate adaptation planning, particularly as they relate to the urban ecology and environmental planning fields. I submit that the most important contributions of this dissertation are the unique assessment approaches I developed for three different scales—region, city, and site—and the critical insights gained through applying these approaches.

In Chapter 2 I use a systematic literature review to investigate over 30 peer-reviewed publications specifically on the topic of planned and anticipatory actions to achieve transformational adaptation. In the review I explore the scope, the leading actors, and the knowledge needs for transformational adaptation. Through this work I find that recent literature does not meaningfully capture the complex interactions between many actors at different scale others have found to be critical for creating needed transformations (Berkes et al., 2003; Ostrom, 2009; Steinitz, 2012). This research also reveals the crucial need for more knowledge in the social realm, which according to Markolf et al. includes many topics such as economic and financial systems, equity and affordability, codes and regulations, and behavior and decision making (2018). I use this investigation to develop a conceptual schematic of transformational adaptation in a landscape context (Figure 2.5). This schematic then forms a visual way of understanding subsequent chapters.

In Chapter 3 I investigate two different approaches for evaluating first-generation physical plans to adapt to sea level rise in an urban estuary. In the first approach, I look at the how these plans would change the landscape from the perspective of Hill's typology derived from research on evolutionary landscapes (2015). In the second approach, I tailored the methods used by Baker et al. (2012) to evaluate climate adaptation plans to match with the needs of physical plan evaluation.

Based on these two approaches I find clear evidence of positive shifts that could be initial signals of a more significant transformation. First, I find that current physical sea level rise adaptation projects in the San Francisco Bay Area are starting to shift toward using dynamic landforms as a strategy. Dynamic landforms confer more ecologic and social benefits and thus are a preferable strategic option (Zedler & Leach, 1998). Second, I find that the quality of physical plans is improving over time (Figure 3.5). This trend implies that future physical projects for adapting to sea level rise will continue to better deal with uncertainties and be more resilient in the context of these long-term impacts.

My research in Chapter 3 also reveals two critical shortcomings of current physical plans to adapt to sea level rise. First, many plans failed to take a shorezone approach which would include partnering shoreline strategies with appropriate urban development (Hill, 2015). Second, most plans focus to the shoreline and fail to see what is directly underfoot. Specifically, the plans generally overlooked the connectivity between sea level rise and a rising water table (see Figure 3.6).

Chapter 4 was published in the Journal of Marine Science and Technology's Special Issue of Coastal Sea Levels, Impacts and Adaptation in 2017. In this chapter we looked at climate adaptation from a cost perspective. This lens is a unique way of looking at climate change adaptation strategies, since most of the literature focuses on the costs of impacts. This chapter demonstrates the clear benefits of using a simplified typology and exploring adaptation from a costs-of-action perspective. Specifically, we gained new knowledge related to critical strategic planning questions, including shoreline positions, design heights, and infrastructure types. Our work questions the commonly held notion that defending the shortest shoreline is the best approach. Instead we find that realignment to a longer shoreline that allows for marshes to thrive is the most effective approach. Through this cost estimate we find that shoreline adaptation would be more successful if the shoreline structures continued to allow flooding in extreme events and were part of a shorezone strategy that included the urban development in partnership with the shoreline structures (Hill, 2015). This work is supported by others looking at human behavior in flooded environments (Di Baldassarre et al., 2013; Restemeyer et al., 2015). Finally, our work shows that single purpose walls are significantly more expensive than levees and should only be used as a last resort approach to protection

In Chapter 5 I introduce a new evaluation technique called the "Regional Planning Fingerprint". This tool creates a simple summary of a complex set of evaluation criteria. It allows one to deeply investigate the following five key areas related to region's adaptive capacity: (1) adopted actions, (2) institutional capacity, (3) research quality, (4) planning processes, and (5) regional collaboration. By applying this research tool to coastal California, I find that each region is truly unique. I also find that all regions in California struggle with regional collaboration, the collection of baseline data and the inclusion of vulnerable populations in their planning processes. The work presented in Chapter 5 establishes an important foundation for future critical analyses.

Future research agenda: Theories of transformational adaptation and planning pathways

In the face of the increased pressure that climate change is placing on social-ecological systems, there is an emerging consensus among researchers that local transformations are necessary to avoid the most catastrophic of losses (Heynen et al., 2006; Kates et al., 2012; Pelling & Manuel-Navarrete, 2011). However, there is no consensus on many specifics of transformational adaptation (as defined in Chapter 2) and there are many questions which can be clustered around the themes of who, what, when, where, and why.

In the area of who there are those working to investigate the capacity of people and associated networks to proactively transform to build resilience (Berkes et al., 2003; Gupta et al., 2010; Ostrom, 2009). In terms of what, questions remain as to the scope and scale of adaptation action needed to constitute a transformation (Moser and Ekstrom 2010; Kates, Travis, & Wilbanks 2012). Significant work is required to grapple with questions of where transformations to the landscape should occur and spatial challenges that climate change adaptation ultimately poses (Hurlimann & March, 2012; Roggema, 2009). In thinking about why, researchers raise important questions about the social implications of transformations and bring our attention to who actually benefits from specific system changes (Heynen et al., 2006; Romero-Lankao & Gnatz, 2013).

Building on the insights above from my dissertation and these ongoing theoretical questions, I propose the need for a research agenda focused on understanding transformational adaptation. This research would be best designed though a hub to connect science, policy and the processes of designing physical plans. This research should continue to bridge theory and practice to tackle with my previously stated overarching research question. This research will need to create models and use a mixed methods approach that combines key techniques from the natural and social sciences. This research will need to grapple with issues relevant to the defense of environmentally and economically challenged communities in the context of a rapidly changing climate system.

In my dissertation I use sea level rise as one avenue for exploring complex questions related to transformational adaptation; however the insights gained and this future research agenda can be applied to other climate impacts, such as fire or drought, in key interlinked ways: 1) advancing theories of transformation and adaptation pathways; 2) conducting empirical assessments of climate adaptation plans and designs; and 3) engaging with local leaders and design professionals. In this final section I present these themes and future research questions.

Who: Actor networks for transformational adaptation

My work in Chapter 2 and Chapter 5 points to the key roles played by different actors in creating intentional and anticipatory climate change adaptation actions. Specifically, my research in Chapter 5 further grounds theories stating that change is made through the complex interactions between many actors at different scales (Berkes et al., 2003; Ostrom, 2009; Steinitz, 1990). Additionally, in Chapter 5 I find that decision makers, acting as champions, (as in state legislators who have the power to give regions specific funds) play a critical role in advancing adaptation strategies. While the empirical evidence suggests this key role of decision makers, the literature that I reviewed suggest that there is a gap in our understanding of this role.

To better understand actor networks and the role of decision makers I propose that future research in this field build on the study presented in Chapter 5. Researchers could apply the Regional Planning Fingerprint to other locations and other climate change impacts—including, but not limited to, increases in heat waves, changes to precipitation patterns, and shifts in agricultural productivity (Hayhoe et al., 2004; IPCC, 2014). Others could also use a regression analysis, similar to the research conducted by Woodruff & Stults (2016), to better understand regional characteristics that correlate with adaptive capacity. Finally, efforts should be made to track this data over time to provide continuous updates into a region's ever-changing capacity. Each of these investigations would inform our current understanding of local capacity and the ability to intentionally transform a place to address long-term climate impacts.

What: Designs for the future

One theme that emerged from this work was the benefits of creating a simplified landscape typology. This approach allowed for the comparison of diverse and place specific landscape designs. The flexibility of this approach also meant that it could be used to develop cost models and conduct a complex regional comparison. In future research this typology could be applied to other places to further understand its benefits. Moreover, as of now, no such typology exists for other landscapes impacted by climate change. I could see a clear benefit for both research and practice in building out a similar typology for landscapes threatened other climate change impacts such as fires, heat waves, changes to precipitation patterns, and shifts in agricultural productivity

When: Developing critical triggers to enhance resilience of multifunctional landscapes

While the development of triggers (also called signposts) to enhance resilient landscapes was not the main focus of my dissertation, the theme emerged as critical through the process of my research. Specifically in each chapter I found the understanding of key triggers for action to be lacking. Therefore, I suggest that this ought to be a major emphasis in the future. In particular researchers and practitioners need to determine what the best triggers for actions look like and how these triggers can be included in local and regional plans.

Where: Spatial assessments of climate adaptation planning

In recent years there has been a rise in climate adaptation planning (Bierbaum et al., 2013; Wheeler, 2008). Researchers looking carefully at the status of these efforts find that the work has helped to raise awareness and establish goals; however the plans lacked strong actions (Wheeler, 2008) and did not developed a collective set of strategies sufficient to address future threats (Bierbaum et al., 2013). Additionally, these analyses do not focus on spatial questions despite the fact that climate change adaptation at its core is a spatial challenge (Hurlimann & March, 2012; Roggema, 2009). In light of these facts, I see numerous opportunities to expand on my dissertation work and further build an agenda for research in to spatially understanding climate change adaptation.

One theme that emerged primarily from Chapters 3 and 4 is how deeply interconnected places are when looking from a landscape perspective. Specifically in Chapter 3 I find that if one limits their focus to the shoreline one misses the broader issue of partnering shorelines with appropriate urban development (Hill, 2015). Similarly, this chapter reveals that many fail to see the connectivity between sea level rise and the water table. Future research must take an operational landscape unit perspective to make sure that spatial assessments connect singular sights with their larger context (Beagle et al., 2018; Verhoeven et al., 2008).

Another theme that emerged by utilize Hill's typology derived from research on evolutionary landscapes (2015) to investigate spatial questions in the context of sea level rise was the potential for ecologically sensitive sites to part of future sea level rise adaptation solutions. This finding lays the groundwork for similar work in other places globally. Specifically, others can take a critical look at the potential for shoreline realignment in light of a deeper understanding of long-term costs. This research would include a deepening of our how coastal protective infrastructure can be paired with adjacent land uses and ecosystems to provide the greatest combined level of resilience. Another avenue for research is into connections between ecologically sensitive solutions and climate change adaptation strategies for other climate impacts.

Why: For whom do we design?

There are tremendous social implications of transformations and some researcher today bring our attention to who actually benefits from specific system changes (Heynen et al., 2006; Romero-Lankao & Gnatz, 2013). Moreover, Climate change and sea level rise will disproportionately impact certain communities and exacerbate existing pressures and problems (Martinich et al., 2013; Nicholls & Klein, 2005). My research found that despite the need to better address this disparity, the inclusion of vulnerable populations was a major challenge for practitioners today. I suggest that future research must more rigorously address two questions: 1) for whom are these changes designed? and 2) how can underrepresented voices be heard? Answering these questions will help us to grapple with the social implications of climate change adaptation.

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