6 Climate Change Adaptation in Practice: Navigating Uncertainty in the Real World

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6.1 Introduction

Climate change, though not a new challenge (Houghton et al., 1990), is still considered an emerging and significant issue for practitioners and resource managers. As many chapters in this book discuss, analytic approaches have been developed to assist in making sound decisions in the face of uncertainty about climate change (see Chaps. 3, 4, and 9 in this volume). These contributions either address how to approach uncertainty or offer tools to aid decision-making. How stakeholders are navigating climate change considerations in natural resource-related planning and decision-making efforts is the focus of this chapter.

The challenge of anticipating climate change is that we know the climate is changing and will continue to change in the coming decades, but we cannot forecast precisely when and how this change will come to fruition on the ground. In the past, stakeholders have made decisions considering climate and weather with imbedded assumptions that the future would not be substantially different from past variability in weather and climate. With respect to future climate, we know temperatures and sea levels will continue to rise, but we do not know by how much, by when, and what path—sudden or smooth—the changes in climate will take.

Additionally, we are more certain about the change in direction in some climatological variables than in others. Figure 6.1 displays the relative certainty about the direction of change in key variables. We have the most confidence that temperature and sea levels will rise in the future. Temperature increases will lead to earlier peak snowmelt and more intense precipitation. In contrast, there is less certainty about how precipitation patterns and climate variability will change, although knowledge is improving (Doblas-Reyes et al., 2021; Hayhoe et al., 2018; Seneviratne et al., 2021). This differentiated knowledge does give some direction for adaptation. We know we need to prepare for higher temperatures, sea levels, etc., but the magnitude and manifestation of these changes, especially at localized scales, is less clear (Fig. 6.1).

The uncertainty associated with future climate ripples through the physical, economic, social, and political networks in which stakeholders make decisions (Dewulf & Biesbroek, 2018; Stults & Larsen, 2020). A survey of local adaptation plans across the United States found that most plans acknowledged future climate uncertainty, whereas *few efforts incorporated uncertainty* about local coping capacity, effectiveness of future strategies, or uncertainty related to actions of other entities or governmental policies. Our experience with climate change adaptation also sees the planning approach spectrum described by Stults and Larsen (2020) as ranging from deterministic *Predict and Plan* to more flexible *Adapt and Monitor* approaches.

Based on our experience and that of others working with stakeholders, we offer these observations on uncertainty and the decision-making process through our case studies drawn from the United States:

1. Uncertainty has always been and will continue to be a critical part of the decision-making process. Stakeholders and decision-makers seek to make the best decisions possible in light of uncertainty. A key part of this process is the recognition that actual changes in climate may differ from projections. Decisions should, to the extent practicable, incorporate flexibility and adaptive capacity as information and understanding increases. *Adaptive Capacity* is a "built-in" ability to rapidly adjust, take advantage of new

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L. O. Mearns et al. (eds.), *Uncertainty in Climate Change Research*,
https://doi.org/10.1007/978-3-031-85542-9_6

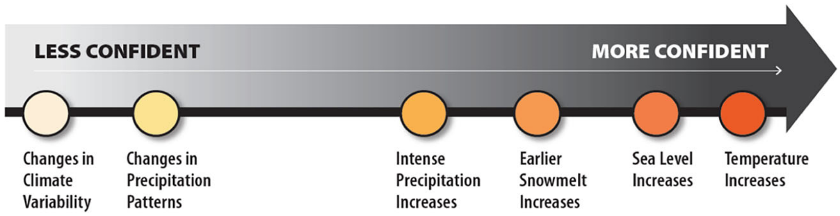

Fig. 6.1 Continuum of certainty on climate change. (Source: U.S. Climate Resilience Toolkit, 2023)

opportunities, or cope with change (California Adaptation Forum, 2016).

2. The desire for certainty and predictive skill when approaching a decision is understandable. User needs for quantitative tools encompass current tools that are predictive, as well as unmet needs for which predictive tools are on the horizon and still yet another area where the needs may not yet be met by existing or in-development tools. Predictive skill comes in the form of accuracy and precision. Precision of climate change projections (i.e., model resolution) does not necessarily result in improvement of accuracy (predictive skill). While estimates of climate sensitivities have narrowed and overall understanding of important dynamics and process-interactions in climate have progressed, uncertainties about future human-generated greenhouse emissions create a fundamental uncertainty (Hausfather et al., 2020; see also Chap. 16 in this volume). Projections should be selected with relevance to the natural resource or environmental question (Snover et al., 2013), treated as plausible futures (Langner et al., 2020; Woodhouse et al., 2021), and not forecasts or predictions.
3. The type and magnitude of response will also depend on the coping capacity of the natural resource being managed. For example, a forest fire in a highly managed, densely forested watershed that would have historically burned regularly will likely be far more disastrous, that is, have a lower coping capacity, than a forest allowed to burn regularly or one subjected to controlled fires. Increasing the coping capacity of the managed natural resource will further help address an inability to decrease the uncertainty in how the future will come to fruition. Decision-makers apply techniques to enhance coping capacity, and increase adaptive capacity while minimizing the need for certainty and prediction.
4. Stakeholder involvement is critical. Stakeholders need to be closely involved in decision-making and buy into outcomes. Decisions on managing climate-sensitive resources have to be made by those who will be affected by and manage such resources. Scientists are needed to advise stakeholders on the state of science and its proper applications to decision-making, but stakeholders need to have confidence in the decisions. Though involving multiple parties is time-consuming, the process of arriving at a shared understanding of goals, constraints, and outcomes results in unpaired success (Yates et al., 2015). Such cooperation between stakeholders and scientists is often referred to as "coproduction" of knowledge (Lemos et al., 2019).
5. Sound decisions that embrace uncertainty about climate change can and are being made (Bierbaum et al., 2013; Halofsky et al., 2015). Examples of climate adaptation in practice are illustrated in the next section.

For each case study, we draw out the particular management or decision focus, the nature of stakeholder engagement, and whether and how uncertainty was addressed. The following examples span private and federal land ownership, as well as a variety of natural resources.

6.2 Collaborative Efforts to Address Grazing Management Decisions under Drought in the Great Plains

Climate change brings the possibility of future sustained droughts in the Great Plains (Frankson et al., 2022). On the short-grass prairie, environmental and socioeconomic systems are tightly connected; drought affects ecological resilience of the shortgrass ecosystem, as well as economic resilience of the private ranch (Joyce & Marshall, 2017). In response to a severe drought, a collaborative effort of federal and private land managers was initiated to explore management decisions on federal land that private ranchers seasonally grazed their livestock. Domestic livestock grazing on Pawnee National Grassland typically starts in May and ends in October. However, very dry weather occurred over a series of years preceding 2009, and these conditions forced seasonal grazing activity to be vacated earlier than planned. Consequently, unplanned decisions about alternate forage sources or the need to move or sell cattle were made quickly. After this experience, federal managers and private rangeland managers began to explore decision-making processes that would incorporate risks associated with weather (Maczko et al., 2019). Federal managers, in this case the United States Department of Agriculture Forest Service, must manage the impact of weather on the availability and use of ecosystem services from federal land, such as Pawnee National Grassland. Private land ranchers must manage the economic risk arising from environmental conditions that affect forage quantity and quality on both federal and private land. The collaborative effort shared available historical and current information on climate and resource conditions. This effort identified the need for an early season look at current conditions, with the potential need mid-season to address declining conditions. This collaborative decision-making process, providing two known points for decision-making by federal managers and ranchers, continues to the present.

In another example of the coproduction of knowledge, the Collaborative Adaptive Rangeland Management project, on the nearby Central Plains Experiment Range, brought together a diverse set of scientists (ecologists, biologists, climate scientists, sociologists, economists) and an equally diverse stakeholder group (ranchers, conservationists, state and federal agencies) to manage 10 herds grazing 3200 acres (1295 hectares) over the last 10 years (Wilmer et al., 2022). Working together and learning to listen to each other, scientists and stakeholders continually evaluated multiple objectives, including grazing management, wildlife habitat provisions, and ranch profitability and economic sustainability (Ganguli & O'Rourke, 2022).

6.3 Coproduction of Climate Change Information to Assess Future Risk to Roads in a National Forest

In this example, several entities organically came together to facilitate coproduction of data to assess future risk to roads in an area where snow/rain patterns were likely to change in the future. In 2013, the United States Department of Agriculture Forest Service Mt. Baker-Snoqualmie National Forests (MBS NF) initiated a travel analysis as required by the 2005 Travel Management Rule using a science-based process called the Sustainable Roads Strategy. A public engagement process asked stakeholders which roads mattered the most (Cerveny et al., 2022). At the same time, the MBS NF was a collaborator in the North Cascadia Adaptation Partnership (NCAP) that brought together resource management agencies from the United States Department of Agriculture and the United States Department of the Interior as well as federal and university research scientists. This partnership, along with numerous stakeholders, explored the current science related to climate change and the effects on natural resources within 6,177,635 acres (2.5 million hectares) of north-central Washington (Raymond et al., 2014).

Using climate change information developed through NCAP and the travel analysis, a University of Washington PhD student explored the impacts to watersheds across MBS NF (Strauch et al., 2015). Staff at Conservation Northwest, building on Strauch et al. (2015), assigned each road segment a composite climate hazard score determined from the combined potential peak 2080 flood-level increase and potential 2080 winter soil moisture increase (Fig. 6.2) (Wooten, 2016). The analysis also considered potential shifts in the timing of shoulder seasons, allowing earlier or later user access and road maintenance (Fig. 6.2).

The final travel analysis product, including the work of Strauch et al. (2015) and Wooten (2016), provided information that the MBS NF can use to minimize future risk of climate hazards in the maintenance of road systems and presents a variety of opportunities for making changes to current road management practices (USDA, 2015). This information will serve as a basis for long-term maintenance cost reductions, prioritizing scarce resources to maintain the desired forest transportation system that meets the access needs for public or administrative purposes. The MBS has completed two access and travel management documents with a climate change roads analysis. This coproduction example shows how bringing scientists and managers together can assist in adding climate change information to a standard planning process on a National Forest.

6.4 Denver Water Embraces Uncertainty through Scenario Planning

Denver Water, the largest drinking water utility in Colorado, has a long legacy of planning for the future. The utility began Integrated Resource Planning (IRP) in the 1990s, and each iteration has built upon the last, factoring in new challenges and taking advantage of new techniques and resources.

In 2002, the utility experienced simultaneous natural disasters. Colorado experienced the single worst drought year in the state's recorded history. Then in June of this same year, the fourth largest wildfire the state has experienced burned across Denver's largest and hardest working watershed. Weeks after the fire was contained, a summer rainstorm brought sediment and debris into streams and reservoirs, significantly impacting water quality and reservoir capacity. Nearly 20 years later, the watershed is still noticeably scarred.

This experience presented Denver Water with an opportunity to reflect on its IRP planning assumptions and approach. Foundational questions such as "Does planning with the observed hydrologic record sufficiently prepare Denver Water for the variability the region has experienced prior to the observed record and may experience in the future?" and "How might local hydroclimatic conditions change over time as anthropogenic warming accelerates?" emerged as critical new inquiries.

Denver Water reconstructed past hydrology using paleohydrology, a technique that uses tree rings to recreate past hydrology, to address the first inquiry. The utility now plans

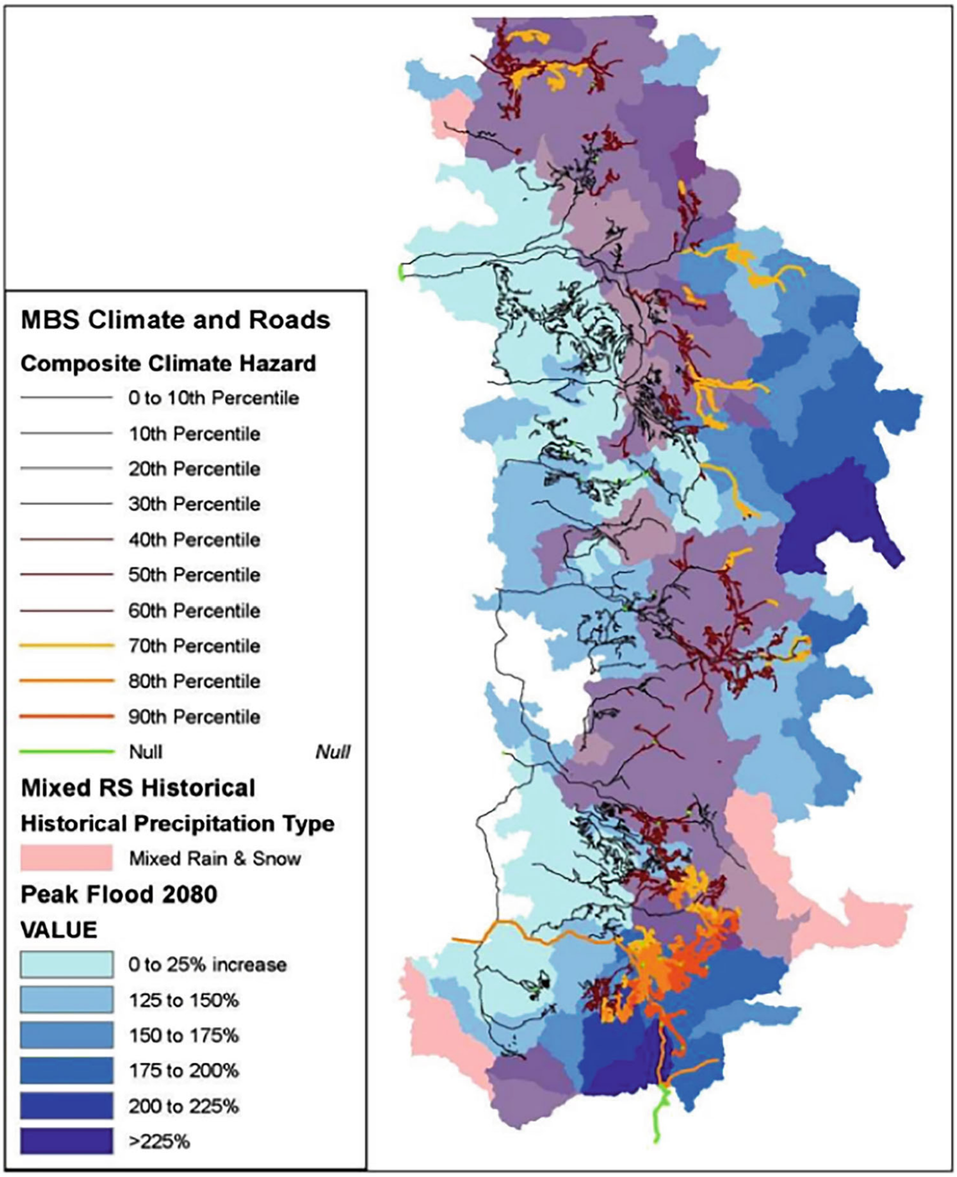

Fig. 6.2 Composite road hazard scores overlaid on the potential 2080 peak flood level percent increase for each sub-watershed, with mixed rain-and-snow sub-watersheds shaded darker. (Source: Wooten, 2016)

with data going back to 1634 and found droughts in the 1600s and 1800s that are much more challenging than seen in the observed record. Next, Denver Water turned to downscaled General Circulation Models coupled with hydrology models to understand potential future hydroclimatic conditions. The utility learned that modeling precipitation is incredibly complicated, its region may not see model agreement for precipitation, it should not expect skillful precipitation projections, and there is significantly more skill and confidence in temperature projections. As a result of these findings, Denver Water shifted its climate analysis focus to higher temperatures and, through simple sensitivity assessments, found its supply and demand is significantly vulnerable to warming. Basic assessments are informative and have proved to be an incredibly valuable mechanism in helping the utility understand and evaluate its vulnerability to climate change. The most important outcomes of these inquiries were the understanding and acceptance that history cannot fully portray the range of possible future conditions and that a *Predict then Plan* approach will not adequately prepare Denver Water for the future.

Following these lessons and seeking to avoid its experience in 2002, Denver Water embraced uncertainty as a critical aspect of planning and adopted Scenario Planning in 2008. Scenarios incorporate combinations of assumptions around external drivers of change (parameters outside of the utility's control including the regional economy, global greenhouse gas emissions, and community values) to evaluate impacts to the water system and prepare for a range of future challenges. A key element of the scenario planning process is to challenge embedded assumptions that staff have about how the water system can operate and what the future will look like, and by envisioning different futures, encourage a broad range of thinking and discussion within the organization. In its current IRP, Denver Water is planning for both a warmer and a hotter future. The utility recognizes climate change is here and now, and that the region will continue to warm for the foreseeable future, though exactly how much it warms and how the warming manifest on the ground is uncertain.

6.5 Adaptation in Practice: Denver Water's "From Forests to Faucets" Program

In this example, a partnership across federal, state, and local agencies depicts the effectiveness of coproduction and value of adaptation investments. The *From Forests to Faucets* program is a multimillion-dollar partnership between Denver Water, the U.S. Forest Service, the Colorado State Forest Service, the Natural Resources Conservation Service, the Colorado Forest Restoration Institute at the Colorado State University, and other agencies. It is creating resilient watersheds by mitigating the impacts of fire by treating overly dense forestland and continuing reforestation efforts in areas ravaged by wildfires.

Between 2010 and 2028, the program will have invested more than $96 million and hundreds of labor hours to conduct fuel reduction and forest management actions. Through the beginning of 2023, over 150,000 acres (60,700 hectares) within Denver Water's priority watersheds have been treated. Program treatments include thinning and hazardous fuels removal, prescribed fire, clear cuts, noxious weed treatments, and tree planting. Treatment plans are individually designed and implemented by program partners based on the characteristics and conditions of each watershed and are intended to decrease the risk of catastrophic wildfires, not mitigate wildfires completely. Wildfires are important occurrences in healthy watersheds and will happen in the future, likely heightened by climate change (Abatzoglou & Williams, 2016; Higuera et al., 2021; Rodrigues et al., 2023) (Fig. 6.3).

Program success, which became evident during the Buffalo Mountain fire above Dillon Reservoir in 2018 (Fig. 6.3), illustrates the effectiveness of coproduced treatment investments. Specific fuel reduction treatments to the 900-acre (364 hectare) Buffalo Mountain watershed were developed and implemented by the partnership and resulted in saved lives, property, ecosystems, and minimized impacts to reservoirs and water quality. Estimates indicate the treatment approach saved nearly $1 billion in damages. As fires increase in frequency, duration, and intensity, and occur outside of the traditional season and across higher elevation bands, coproduced investments in watershed health will save money and decrease impacts on increasingly vulnerable communities and natural resources.

Fig. 6.3 Photograph of burn line near residential homes immediately following the Buffalo Mountain fire in 2018. (Source: Denver Water)

6.6 Incorporating Climate in Culvert Size Selection

Culverts, which are designed to channel streamflow, often below roads, come in standard sizes ranging from 3-inch (0.080 m) diameter increments for small culverts to 1-foot (0.305 m) for large culverts. Each size culvert (Fig. 6.4) (U.S. Department of Transportation, 1972) can handle a range of high stream flows. Therefore, in selecting a culvert size, it is not necessary to know the exact amount of peak flow, but it is important to have an idea about which range of flow is most likely to adequately account for potential increase in future high flows. In the case of culverts, the marginal cost, and downsides of selecting a larger size is relatively small (Fig. 6.4).

Given this situation, it may be possible to readily anticipate future increases in peak flow by installing incrementally larger culverts as they are put in or reach the end of their design life. For example, using Fig. 6.4, assume that a 42-inch (1.067 m) culvert was sufficiently sized for observed peak flows. Perhaps peak flow was 130 cfs (cubic feet per second; 3.7 m^3/s). As a result of climate change, the peak flows could increase. The exact amount by which it would

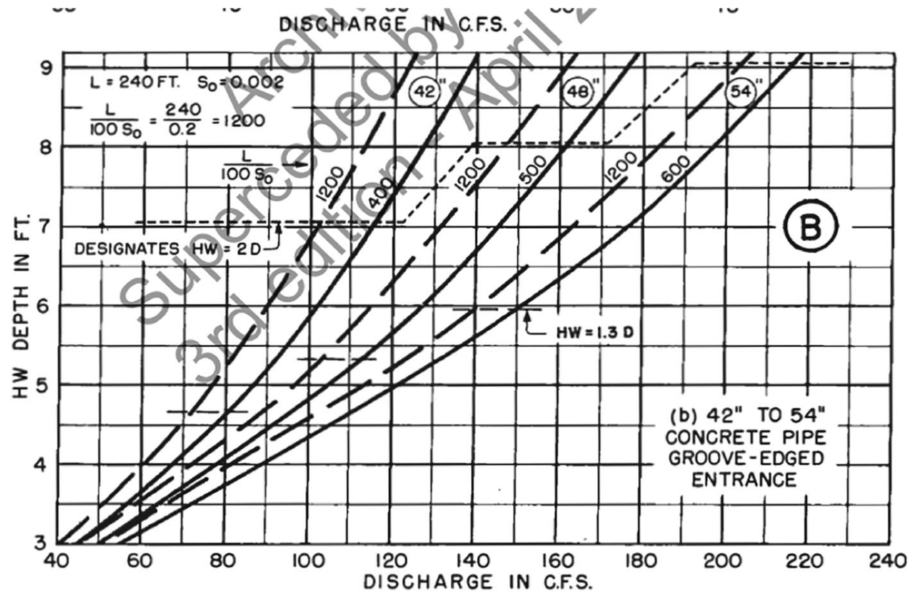

Fig. 6.4 Culvert sizes and capacities. Typical culvert capacity chart. (Source: Fig. 1 in "Capacity Charts for Hydraulic Design of Highway Culverts." Hydraulic Engineer Circular No. 10. 1972. U.S. Department of Transportation. https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hec/hec10.pdf)

increase is uncertain but increases of 10–20% or more over coming decades seem plausible (see Martel et al., 2021). Under this assumption, peak flows of approximately 145–160 cfs (4.1–4.5 m^3/s) could be anticipated. In such a case, the next higher size of culvert, 48-inch (1.2192 m), would be needed. What this suggests is that if a new culvert is being installed or an older one being replaced, where observed peak flows might have supported installation of a 42 inches (1.067 m) culvert, anticipation of climate change could justify installation of an incrementally larger culvert, in this case 48-inch (1.219 m). This simple calculation may only be cost-effective if the marginal cost differences between installing a 42-inch (1.067 m) and a 48-inch (1.219 m) culvert are small and there are no other complicating factors, such as a larger culvert necessitating changing design of the road above.

The sizing of culverts in anticipation of climate change was analyzed by McCurdy and Travis (2017). They analyzed culverts across Colorado examining costs of installing culverts and benefits such as avoiding flooding and traffic diversions. The article found that increasing the "resilience factor," that is, the capacity of a culvert to withstand a flow above design levels, is advantageous. This appears to be consistent with the idea of installing somewhat larger culverts that can withstand larger flows. However, McCurdy and Travis (2017) found that replacing existing culverts with larger ones before their design lifetime was reached would not be cost-effective.[1] So going to a larger-size culvert may only be justified when new ones are being installed for reasons other than anticipation of climate change.

[1] Design lives of culverts can be as long as 50–100 years (CCPPA, 2023).

6.7 Boston Waterfront Planning

Spurred on by increasing climate disasters since the 1990s and a near miss in the Boston area from Superstorm Sandy in 2012, the City of Boston undertook a comprehensive planning effort to prepare for increases in sea levels, temperatures, precipitation, and storm intensity.

Boston used a single scenario of sea level rise, assuming 9 inches (0.229 m) of sea level rise by 2030, 21 inches (0.533 m) by 2050, and 36 inches (0.914 m) by 2070. A uniform scenario was needed to align all the roadways, walkways, and landscapes. The scenario, which is referred to as the "40 inches scenario," includes the 1:100 storm event on top of the sea level rise projections.[2] The plan also allows for the possibility that sea level rise will exceed 40 inches (1.067 m) this century (Bosma et al., 2015).

A key part of the planning included extensive local stakeholder consultations. This was important to develop and sustain community support for the long-term implementation of the plan and enable stakeholders to identify local concerns and develop creative solutions (Walsh, 2016).

The planning focused on eight areas across the city. Here, we describe one area: the "Coastal Resilience Solutions for Downtown Boston and the North End." This is a $200–300-million 50-year project to protect Boston waterfront including Downtown, the North End, and the eastern edge

[2] The 40-inch scenario was based on projections of sea level rise by the US Government in 2012 and analysis of change in storm surge undertaken for the State of Massachusetts (Bosma et al., 2015).

of the city's West End from the 40-inch scenario by late this century (City of Boston, 2020). The integrated plan, which was developed with extensive stakeholder input, relies on a combination of natural (green infrastructure) defenses, breakwaters, sea walls, harbor walks, and raised land to protect the waterfront and inland areas from increases in coastal flooding and sea level rise.

The Downtown Boston and North End plan was developed with extensive input from local stakeholders, including property owners, neighborhood groups, state and federal agencies, and others. Two open houses were held for the public to give input into the plan. The stakeholders strongly preferred a combination of effectiveness, adaptability, feasibility, and consideration of environmental impacts when prioritizing options for protecting the waterfront.

Boston's resilience plan is aimed at reducing flood risks in an area going from Rowes Wharf in Downtown, the Wharf District, North End waterfront, and the eastern part of the West End not including the New Charles River Dam.

There are three timeframes for implementing specific components of the plan:

- Near-term out to 2030. This includes immediate measures to address current flood risks.
- Mid-term actions out to about the 2040s.
- Long-term measures from about 2050–2070 and beyond.

The various time horizons allowed areas with different elevations to take sufficient measures to protect against the uniform scenario. Areas with lower elevation will build defensive measures in the shorter timeframes while areas with higher elevations can put off implementing measures until later time periods. New construction will be built for the 2070 scenario (Paul Kirshen, University of Massachusetts Boston, *pers. comm.*). The resilience plan proposes an integrated coastal defense system, including specific options that provide protection from flooding caused by sea level rise and more intense coastal storms. The defense system includes combinations of

- Green infrastructure (living shorelines).
- Offshore breakwater structures.
- Raising land such as Puopolo Park in the North End.
- Building and raising hard structures such as elevated waterfronts, harbor walks, sea walls, and bulkheads.
- Where necessary to provide additional defense against elevated flood risks, raised roadways, intersections, and bike paths.

The plan incorporates parks and bikeways and maximizes public access to the city's waterfront. Property owners will need to take additional actions to protect their assets. Specific plans are included to defend against the "40-inch scenario," but provisions are made to put in more protections should sea level rise exceed that scenario.

Capital costs are estimated to be between $189 and $315 million, with estimated annual maintenance costs of $3–five million. The plan reports that net benefits over its lifetime (applying discount rates of 3 and 7%) will be $2–6 billion.

6.8 Conclusions

This chapter demonstrates—through selected examples of natural resource management—that added uncertainty about climate change need not paralyze decision-makers or the decision-making process. What the examples show is that sound climate change-informed decisions *can be made* to manage natural resources despite uncertainty about climate change.

- Federal and private land managers collaborate to anticipate and manage grassland production in the Pawnee National Grassland.
- Federal forest managers and stakeholders worked together to anticipate potential impacts of climate change on roads in the Mt. Baker-Snoqualmie National Forests.
- Denver Water uses scenario planning, including scenarios not just of change in climate but also in socioeconomic conditions such as population, economy, and consumer preferences, to improve its decision-making about long-term water management.
- Denver Water works collaboratively with state and federal forest managers to reduce fire risks in watersheds in ways that reduce risks of fire and harm to water supplies.
- Culverts incorporate a safety margin for a range of high flows. Using larger size culverts is a way of incorporating potential increases in high flow in a manner that can be effective over a range of possible future conditions.
- The City of Boston worked with scientists and local stakeholders to plan for sea level by selecting an individual scenario that serves as a minimum for its waterfront but also allows for raising the waterfront above that scenario should sea level rise be higher than currently planned for.

These decisions recognize that while we know (and have known for some decades) that the climate is changing, and for many key variables we know the direction of change (e.g., higher temperatures and sea levels), skillful projections of exactly how climate change will manifest locally are not available now and are not expected to be available in the near future. Despite this, sound decisions that reduce risks and improve resilience to future climate change are being made.

These examples also show that the process of -making is as, if not more, important than the decisions themselves. Stakeholder involvement is critical to arriving at management actions or decisions under climate change. Collaborative and coproduction efforts build trust among the stakeholders, scientists, and decision-makers and facilitate shared understanding of scenarios, effects, and possible tradeoffs. A diversity of perspectives is needed to challenge embedded assumptions about the future. Risk depends on the perspective/interest. Multiple objectives, such as ecological resilience and economic resilience, are needed. These partnerships also provide opportunities to integrate scientific knowledge and experiential knowledge.

What has long been desired to help those making decisions on long-term investments is to provide forecasts or guidance on what exact changes in climate and extreme events can be expected to happen in coming decades. In other words, the perception has been that science was not providing sufficient information, so a major focus has been on improving science. This perception is sometimes expressed as a desire for "actionable science," that is, provide projections with high enough spatial resolution and narrow enough of a range in magnitude to be useful for decision-making.

While improvement in the science of projecting future changes in climate would be helpful, it is not reasonable to expect such a change in the science of projecting climate change will emerge in the near future (Barsugli et al., 2009; Pielke Sr & Wilby, 2012). Yet, given the way we make decisions about long-term climate-sensitive investments, there are ways to productively incorporate what is known about climate change into such decisions. We need to use science in more creative ways than we have in the past to enable us to be better prepared for climate change impacts than the old assumptions of climate stationarity would have yielded.

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