PPIC 30 YEARS

REPORT · MAY 2024

Climate-Smart Tools to Protect California's Freshwater Biodiversity

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Supported with funding from the S. D. Bechtel, Jr. Foundation and the funders of the PPIC-CalTrout Ecosystem Fellowship

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Key Takeaways

California's freshwater ecosystems—and the native plants and animals that rely on them—have been in decline for decades. Roughly half of California's native freshwater species are highly vulnerable to extinction within this century. But efforts to protect and recover native species now face an additional serious threat: climate change, which is accelerating and compounding the impacts of past and current land and water management issues. Simply working harder, using the same insufficient approaches to conservation, is unlikely to be successful. New approaches, including some that are experimental or highly controversial, are urgently needed. Although California has recently made important strides in setting goals for salmon, the state lacks a comprehensive approach to protecting native biodiversity in the face of climate change. We have identified a portfolio of actions that can help California rise to this urgent challenge.

- **California should develop climate-smart conservation plans for freshwater ecosystems.** California needs a comprehensive statewide plan that recognizes and prioritizes bold climate adaptation actions to protect native freshwater biodiversity. This plan will be used to guide the development of collaborative, watershed-scale plans that consider future conditions in all freshwater species conservation actions, identify and screen potential management priorities, assign responsibilities and benchmarks for implementation, and conduct robust monitoring and assessment programs that allow for strategic pivots in approach when conditions change. Where plans and programs already exist, it is time to ask how to retrofit them to take climate change into account.
- **Climate-smart plans will need a portfolio of management strategies and tools.** Traditionally, conservation managers have focused on a handful of management strategies, such as flows and hatcheries, to improve conditions. But in a rapidly changing climate, managers will need to deploy a broader suite of actions to improve habitat and support freshwater species. We have identified 22 tools—including habitat support, rebuilding populations, assisting dispersal and migration, and promoting genetic diversity—that should be evaluated for use in climate-smart conservation plans.
- **Planning for the possible loss of species is an unfortunate, but necessary, part of conservation.** Even with heroic efforts to save native plants and animals, extreme climate effects may transform freshwater habitats so that they can no longer support some species. Contingency actions—while not an excuse to abandon conservation efforts—should be included in all climate-smart conservation plans. They include preserving knowledge of species for future generations to support reintroduction if conditions improve. Contingency actions also need to consider how to manage ecosystems if key species—particularly those protected by the state and federal Endangered Species Acts (ESAs)—are no longer present.
- **Climate-smart planning and many types of conservation projects should begin immediately.** With the acceleration of climate change, the window for action to conserve native biodiversity is closing fast. The California legislature should call for preparation of a statewide plan and provide funding and support personnel for the development of plans in priority watersheds. State agencies should set criteria for the regional plans and provide technical support, review, and approval. Contingency actions and many types of habitat projects are relatively low risk, and they should start as soon as possible, while these more comprehensive plans are in development. Pilot projects and companion research, monitoring, and evaluation are needed to guide decision making, especially given the uncertainties about many of the potential management options. In a subsequent report, we will examine how policies and practices can change to promote climate-smart conservation planning and implementation.

Introduction

California's freshwater ecosystems—including rivers, streams, lakes, ponds, wetlands, vernal pools, and estuaries—are under threat, along with the native plants and animals that rely upon them. Decades of water and land use changes, pollution, and the introduction of numerous non-native species have caused a precipitous decline in native biodiversity. Today, efforts to protect and restore freshwater ecosystems and native species face an additional grave challenge: climate change.

Reversing the decline in freshwater ecosystems is one of California's most vexing water management challenges. (We include a list of our reports on this issue in a text box at the end of this report.) Increasing drought intensity and more volatile precipitation, as well as rising sea levels, are making the task even more difficult. But California needs to meet this challenge. Freshwater ecosystems are vital to California because they provide clean water, support many forms of recreation and economic uses, are reservoirs of biodiversity, and have major cultural and social significance. A failure to protect California's freshwater ecosystems—and the many social, cultural, and economic benefits they bring—would only ensure further disruption.

California has shown great leadership in climate change mitigation and adaptation, including recent efforts to address water supply reliability in the face of increasing drought intensity.[1] The recently updated *California Climate Adaptation Strategy* (State of California 2021) and *California Water Plan Update 2023* (State of California 2024a) offer many important recommendations to help guide statewide climate priorities, including habitat restoration. And the newly released *California Salmon Strategy* (State of California 2024b), which describes efforts underway or planned to conserve salmon, recognizes the urgency of the situation.[2] But the state lacks a comprehensive plan for building resilience so that freshwater ecosystems can support and even recover native biodiversity as the climate changes.[3]

California is running out of time to respond. Healthy, well-managed ecosystems with genetically diverse, abundant native plant and animal populations and relatively intact natural processes are more resilient to climate change, but most California freshwater ecosystems do not fall into this category. Long-term environmental degradation has made many species vulnerable, making them reliant on conservation activities for their long-term survival (Evans et al. 2016). Climate change will have wide-ranging effects on these species, with a strong potential for unexpected outcomes that will reduce native biodiversity and population resilience.

Given the scope of existing environmental issues and the magnitude of change underway, business-as-usual management approaches are unlikely to be successful over the long term. Bold, perhaps even risky innovations in policy and management are needed. In this report, we describe why climate change is such

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1. This report does not address climate mitigation—such as greenhouse gas (GHG) reduction or carbon sequestration—as a strategy. While climate mitigation is the single most important global need right now, changes already underway will have major effects on our freshwater ecosystems for the foreseeable future. Therefore, we focus here on adaptation to support native aquatic biodiversity and their freshwater ecosystems.
2. *The California Salmon Strategy for a Hotter, Drier Future: Restoring Aquatic Ecosystems in the Age of Climate Change* (State of California 2024b) is a summary of priorities and actions to preserve salmon in California.
3. In this report we use "resilience" to describe the ability of ecosystems and native plant and animal populations to recover from a climate-related disturbance, such as drought or flood. We use the term "adaptation" to describe actions that lead to greater ecological resilience in the face of changing environmental conditions.

an urgent concern for California's native freshwater biodiversity. We then outline potential strategies and a range of management tools that can support native species in a changing climate. (Further details are provided in a technical appendix.) Many of these tools are already in use (see case studies below), particularly in terrestrial management, but some are likely to be highly controversial in freshwater ecosystems.

We developed these concepts in consultation with a broad range of experts, and after an extensive review of climate plans. Based on our analysis, we offer a suite of recommendations to policymakers, resource managers, watershed stewards, the scientific community, and other interested parties. We envision that a *portfolio* of tools would be employed to achieve adaptation goals, depending upon the nature of climate risks and the state of habitat and native species in particular locations. We hope that these recommendations will spur efforts to make changes before it is too late.

These ideas need to be implemented within a clear planning process (e.g., reviews, prioritization, monitoring) such as the *Climate-Smart Conservation* framework (Stein et al. 2014). The challenges of integrating climate change adaptation into 20th-century environmental laws are significant, and many legal, institutional, and cultural factors will influence the implementation of our ideas. We will explore these issues in a separate report on implementation, to be released later in 2024.

The Case for Urgent Action

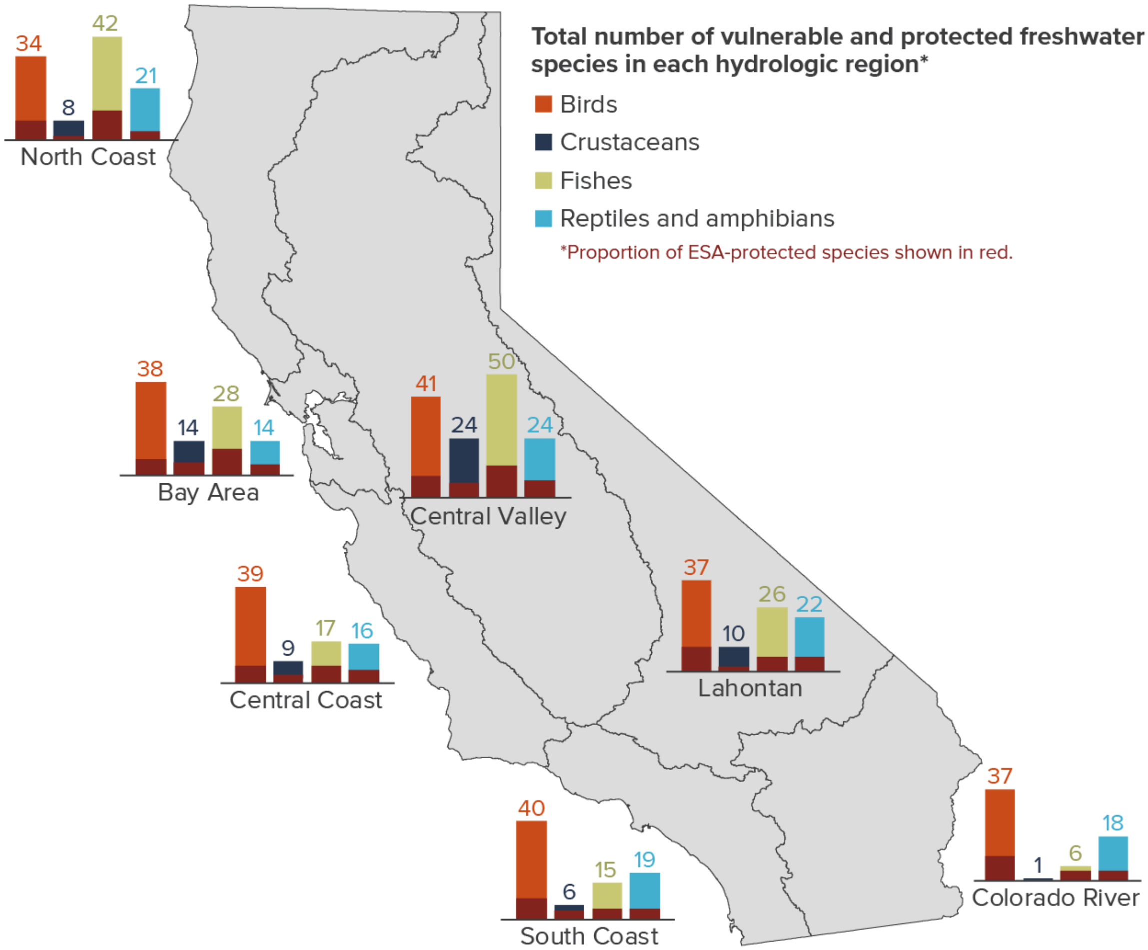
Climate change is often viewed as a future existential threat to ecosystems, which implies that there is time to prepare. But global change is underway, and it is threatening biodiversity throughout the world, not just in California (Weiskopf et al. 2020; Moore and Schindler 2023). While some of the long-term effects may seem subtle and gradual, climate change generates extreme events that can rapidly reduce or even extinguish populations of wild plants and animals. In the 21st century, California has experienced a remarkable series of extreme weather events, including one of its wettest years (2017), its two driest three-year periods (2013–15 and 2020–22), nine of the ten largest wildfires, and the warmest 20-year period in recorded history.[4] California's natural climate variability—now intensified by climate change—is compounding the impacts of over a century of habitat decline.

There are no protections in place for the vast majority of species that we could lose. A comprehensive assessment of the state of California's native freshwater species by Howard et al. (2015) found that nearly half are vulnerable to extinction, yet only 6 percent are protected under state or federal endangered species regulations (Figure 1). And a recent update of the conservation status of native fishes by Moyle et al. (2022) showed that over half are highly likely to be extinct by the end of this century without major interventions. The scale and scope of such losses likely would be unprecedented in our state's history. Both studies found that climate change is accelerating losses among already vulnerable species (see text box).

4. Based on data summaries in National Centers for Environmental Information and CalFire.

Figure 1

Many of California's freshwater species are vulnerable to extinction, but only a small percentage are officially protected



SOURCE: Adapted by the authors from Howard et al. (2015) and Stein et al. (2014).

NOTES: The figure depicts the number of species that are vulnerable to extinction but not listed, or already listed as either threatened or endangered under state and federal ESAs, in each hydrologic region. Many species are present in more than one hydrologic region. The total number of listed species shown is 62, with another 170 vulnerable to extinction. One listed mammal—not shown in this figure—occurs in the Colorado River region. The figure also does not depict plants, insects, or other invertebrates, 47 of which are listed, and more than 600 of which are vulnerable to extinction.

Climate Change and Native Aquatic Species

California's diverse geography hosts an impressive array of freshwater habitats that, in turn, support almost 4,000 native plants and animal species (Howard et al. 2015). The state's topographic diversity—with mountains and deserts separating large regions from each other—leads to a high level of endemism: almost a quarter of native species are found only in California. This rich biodiversity includes:

- fish, including sport (e.g., trout, salmon, sturgeon) and endangered (e.g., smelt, salmon, trout, green sturgeon, pupfish);
- reptiles and amphibians, such as giant garter snakes, western pond turtles, and frogs (many are endangered);
- birds, including wading birds, waterfowl, dippers, and songbirds;
- mammals such as river otters, muskrats, and beavers;
- invertebrates, including mussels, clams, oysters, shrimps, crayfish, and numerous aquatic insects; and
- plants, with diverse wetland, riparian, and vernal pool flora.

Climate change is already affecting habitat abundance, distribution, and quality for all of these groups (Howard et al. 2015; Moyle et al. 2022). And even greater changes are expected in the future, compounding the long-term historical problems that have plagued freshwater ecosystems. This poses a major existential threat, with cascading effects on aquatic species (see the technical appendix for more details).

California's commitment to maintaining and restoring high-quality freshwater habitat and native biodiversity is laudable—and we expect it will guide the state's conservation policy for the indefinite future. It seems unlikely that the state would "give in" and let freshwater species disappear, given both the durability of major environmental laws (e.g., the Endangered Species Act and Clean Water Act) and the many benefits provided by healthy ecosystems and native biodiversity.

Yet while the current management approach has successfully limited the number of species extinctions in California, it has not successfully recovered populations, and it is not well suited to rapidly changing conditions. Simply working harder at what we are currently doing is unlikely to be successful under even more challenging future conditions, for the following reasons:

- **Unrealistic conservation targets.** Efforts to protect species and ecosystems often set conservation objectives based on historical conditions. This fails to acknowledge how conditions already have changed and will change even more in the future, leading to unrealistic conservation targets.[5]
- **Single–species approaches.** Today, regulators often manage freshwater ecosystems by focusing on meeting the needs of species protected by state and federal Endangered Species Acts (ESAs) (Evans et al. 2016; Mount et al. 2019). This means regulators may prioritize critical habitat preservation for small numbers of listed species, often single populations, rather than managing ecosystems to support biodiversity and multiple species more broadly.[6]

5. An example of this is the very durable "salmon doubling goal" in the 1992 Central Valley Project Improvement Act, which seeks to double the population of Chinook salmon in the Central Valley. This arbitrary goal has been adopted in many regulatory forms over the past 30 years, but it has not been reevaluated and updated in light of changing climate conditions.

- **Limited use of available tools.** Most efforts to manage habitat and species emphasize a limited number of tools (e.g., flows and hatcheries). This approach does not take advantage of the broader portfolio of options available to respond and adapt to changing conditions, including many tools described in this report.
- **Slow pace of action.** Despite significant recent advances in permitting, habitat improvement projects take a long time to implement, with major projects—like dam removal or reconnecting rivers to floodplains—taking decades because of funding, staffing, cultural, and environmental issues. The pace of implementation is often too slow to keep up with the pace of change in the climate.
- **Insufficient focus on adaptation.** Current efforts to improve freshwater habitat in California do not adequately incorporate strategies to adapt to changing conditions. While many individual management actions address long-term problems, there is no systematic approach to respond to the cumulative effects of climate change.

In sum, status quo management approaches will not be sufficient to protect native species from the effects of climate change. Broader, ecosystem-level management approaches that improve the quality of freshwater habitat will yield better results than managing species individually. And to protect native species that are on the brink, California also will need to make other major management interventions, requiring innovation from many partners, including agencies, tribes, NGOs, watershed groups, and universities. These efforts need to happen fast to be successful.

Conserving Freshwater Biodiversity Under Climate Change

California is a global leader in climate change mitigation and adaptation, with numerous legislative mandates to plan for and adapt to changing conditions.[7] State and federal agency staff are very aware of the need to promote adaptation strategies. For example, the Newsom administration has advanced several large initiatives, including *30×30 California* (2020), the most recent *California Climate Adaptation Strategy* (2021), the *California Water Supply Strategy* (2022), the *Central Valley Flood Protection Plan Conservation Strategy* (2022), the *California Water Plan Update 2023*, and the *California Salmon Strategy* (2024), all of which stress the urgency of climate change and the need for an adaptive approach.

Although these efforts represent important advances, they are not enough. California still lacks a statewide strategy for climate adaptation with the scale and focus needed to conserve freshwater native species and their habitats.

To gain insights on climate adaptation planning processes for the environment that could support this kind of work in California, we reviewed numerous national and international frameworks. One of the clearest and most relevant frameworks is the National Wildlife Federation's *Climate-Smart Conservation*, a comprehensive guidance document for designing and carrying out conservation in the face of a rapidly

6. The state's 2024 *California Salmon Strategy* (State of California 2024b) appropriately notes that focusing on restoring keystone species—such as salmon—creates benefits to the overall ecosystem. However, the strategy does not explicitly identify how its actions would lead to these broader benefits, and it does not recognize that only some of California's freshwater ecosystems historically supported salmon.
7. A useful summary of state legislation that requires different sectors to address climate change adaptation is maintained by the UC Berkeley Center for Law, Energy, & the Environment.

changing climate (Stein et al. 2014).[8] A broad consortium of scientists and resource managers developed *Climate-Smart Conservation* to create a generalized approach that could be applied to a range of ecosystems and regions.

Figure 2 summarizes the broad contours of this framework, which is designed to help users develop climate adaptation plans. The major steps include: (1) identifying the purpose and scope of the conservation effort, (2) identifying species' vulnerabilities, (3) reviewing conservation goals and objectives, (4) identifying management options, (5) screening and selecting options, (6) implementing priority actions, and (7) monitoring and evaluation. At several points in the process, adjustments can be made. Although not represented in this figure, communication and outreach are an essential part of the process. In this report, we focus on a core element of the *Climate-Smart Conservation* framework and similar efforts: identifying candidate management tools for conservation and evaluating and selecting actions (Steps 4 and 5).[9] And while we are not pushing this specific framework as the best option, it inspires our recommendations to develop the "climate-smart conservation plans" described further below.

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8. Other informative frameworks we reviewed include the National Fish, Wildlife, and Plants Climate Adaptation Partnership (2012), Davis et al. (2013), Feiner et al. (2022), and Rahel and Lynch (2022).
9. Here we go further than the Climate-Smart Conservation framework in the elaboration of tools, which is Step 4 of that process. Stein et al. (2014) include some of the same tools, but we describe many more potential management options for California.

Figure 2

Major steps in the Climate-Smart Conservation framework

SOURCE: Stein et al. (2014).
NOTES: The *Climate-Smart Conservation* framework identifies the multiple planning steps needed to develop conservation programs that adapt to the changing climate. The management tools and strategies explored in this report are an expansion of Steps 4 and 5 of the framework.

Management Strategies and Tools

Native species and their habitats will have diverse responses to climate change. Supporting climate adaptation will therefore require deploying an equally diverse set of management actions, tailored to the unique goals and objectives of each watershed and species assemblage. A list of possible adaptation options forms the foundation of a climate-smart conservation plan. Here we present a comprehensive list of potential management strategies (broad approaches) and tools (specific types of actions), with examples from California. This intentionally broad list does *not* represent our management recommendations. Instead, it is intended as a resource that could be tapped and vetted as part of a statewide assessment of climate change in freshwater ecosystems and the development of watershed-scale climate-smart conservation plans. It could also inform periodic updates of other plans such as the *California Climate Adaptation Strategy*, the *California Salmon Strategy*, the *30×30 Initiative*, and Natural Community Conservation Plans (NCCPs).[10]

10. NCCPs are a California initiative that takes a broad-based ecosystem approach to protect biological diversity. It is broader in its orientation and objectives than the California and federal Endangered Species Acts.

Our Approach

Each of the strategies and tools described below was chosen to address one or more of these vulnerabilities and related issues from ongoing environmental decline. We vetted and refined these management options through multiple workshops with technical experts and other stakeholders representing state, federal, and local agencies; academia; conservation NGOs; tribal communities; and others. We also reviewed multiple climate adaptation plans to expand the list of options. We describe our approach—as well as the specific strategies and tools—in more detail in the technical appendix.

The strategies and tools are based on the following principles:

- **Tailor the strategies and tools to freshwater ecosystems.** This includes rivers, streams, ponds, wetlands, vernal pools, and estuaries—and all aquatic species in these ecosystems, including fish, waterbirds, mammals, invertebrates, amphibians, and plants.
- **Account for current conditions.** Climate vulnerabilities must often be addressed in tandem with pre-existing habitat degradation, so we offer strategies and tools to respond to both. For example, climate change may increase mortality rates in species, so we included both tools to reduce climate vulnerabilities and companion tools that could reduce mortality rates linked to persistent environmental threats (e.g., losses from water diversions and predation).
- **Build resilient populations.** Species are most resilient to climate change when they are abundant and genetically diverse, with access to high-quality habitat connected across large geographic areas (Moore and Schindler 2023). Resilient populations would ideally require little or no human intervention. However, when multiple historical stressors are amplified by climate change, management interventions such as the tools listed here are needed to build population resilience. This is the case for most freshwater species in California.
- **Plan for mid-century.** We chose mid-century as a timeline because some of the more extreme climate effects on flow and temperature are predicted to occur by then (e.g., Dettinger 2016), and because many of the actions we describe will take many years to implement, even if the work starts now. However, we acknowledge that major climate events will occur before then.
- **Consider controversial actions.** We recognize that some of the strategies and tools in this report are highly controversial and may raise substantial legal, policy, financial, technical, ethical, and cultural issues. Controversial issues represent an important part of the discussion, however, as traditional “easy” fixes are unlikely to be sufficient for species conservation under climate change (*US Climate Resilience Toolkit* 2023).[11]

Adaptation Strategies and Tools

We identify two general management strategies: habitat support, including actions to improve the abundance and quality of habitat for native species, and species support, including direct actions that seek

11. Our approach is not unique—for example, the *US Climate Resilience Toolkit* (2023) has an options database that contains an impressively broad list of policies, programs, and technology options that can be prioritized for the needs of different communities. And as described above, the *Climate-Smart Conservation* framework (Stein et al. 2014) advocates the development of a comprehensive set of conservation options (Figure 2, Step 4) that are subsequently screened (Figure 2, Step 5).

to increase the abundance, genetic diversity, and resilience of vulnerable species.[12] We also recognize that climate change, coupled with past changes, may not allow species to persist in their historical ranges and that natural selection or human intervention cannot prevent all local species extirpation or even extinction.[13] We therefore include contingency actions as a parallel strategy to habitat and species support. Identification of these strategies corresponds to Step 4 in the *Climate-Smart Conservation* framework (Figure 2). All of these tools could be considered as candidate approaches in the process.

The potential habitat- and species-focused tools range from those commonly used today—such as actions to restore or improve flows and habitat diversity—to more experimental and controversial approaches, such as species support through assisted migration or genetic engineering. Below we briefly describe each tool and provide some case studies of current implementation. The technical appendix provides many additional case study examples.

As detailed in the technical appendix, the tools are not equivalent in terms of their uncertainties, risks, tradeoffs, and benefits. Ecosystem-based actions are most likely to benefit an array of species and habitats across broader geographical areas. These types of actions mostly fall within the habitat support strategy. Ecological risks and uncertainties tend to be higher for some of the most intrusive species support management concepts, such as gene editing and population supplementation. The discussion identifies the most intrusive tools within each strategy.

12. Some tools could be included under more than one strategy. We picked a single strategy to avoid repetition. Also, there are potential overlaps in outcomes across strategies. For example, habitat support also benefits species, and species support may have some habitat benefits.
13. Extirpation is the loss of species in a portion of their historical range. Extinction is the loss of genetically distinct species throughout their historic range.

Table 1

Management tools for climate-smart conservation

Strategy	Tools	Approaches	Current examples
Habitat support	Improved freshwater flow	Flow augmentation; shift hydrograph towards more natural patterns	Flow requirements for many rivers
	Substrate restoration	Mechanical removal of excess fines, gravel supplementation, dam modification	Gravel supplementation below valley floor dams
	Increased food	Increase diversity of habitat to enhance resources; provide external supplements of food or nutrients	Salmon carcass additions to nutrient-poor streams
	Restoration of habitat diversity and processes	Increase range and amount of habitat types available for species; improve connectivity and processes	Many examples of complex restoration projects
	Temperature and water quality	Natural and artificial shade, cold water inputs, water treatment, watershed management	Cold dam releases, riparian restoration, water treatment plants
	Invasive species control	Mechanical removal, chemical treatment, gene drives, biocontrol, robotic removal, barriers	Chemical and mechanical approaches in many waterways
	Focused management zones	Maximize restoration activities in specific areas	Many examples of localized intensive projects
Species support: distribution	Planning for range shifts	Support shifting range of species and habitats through legal, policy, and restoration activities	Unknown
	Helping species access historical habitat	Within historical range, transport individuals past barriers or unsuitable habitats; reconnect habitats by removing barriers (e.g., dams, levees, water control structures)	Winter-run salmon reintroduction project; Klamath River dam removal
	Assisting migration to new geographic ranges	Transport populations outside of historical range to new suitable habitats	High Sierra trout planting; Sacramento perch
	Refuges	Build refuges such as conservation hatcheries or naturalized constructed habitats	Livingston Stone National Hatchery

Strategy	Tools	Approaches	Current examples
Species support: population	Reduce sources of mortality	Increased enforcement of illegal harvest, stricter regulations for fisheries, reducing losses at water diversions & excessive predation	Pumping restrictions at Delta water diversions
	Remediate diseases	Nutrient supplementation to counteract deficiencies, veterinary treatment of individuals	Chytrid fungus treatment of frogs, wildlife rescue centers
	Population supplementation	Supplement imperiled populations with captive-raised individuals in hatcheries	Salmon, trout, Delta smelt
Species support: genetics	Diversity protection	Hatchery genetic conservation (HGC) plans; reduced reliance on hatchery supplementation; move hatcheries away from wild populations	Many examples of HGC plans
	Assisted evolution	Select for resiliency with traditional breeding, epigenetics, gene editing	Oyster breeding programs
	Hybridization	Develop more resiliency using hybridization of species	Many terrestrial examples
Contingency actions	Historical conservation	Collect as much information as possible about species (e.g., diets, behaviors, physiology) and habitats (e.g., structure, videography, substrate)	Long history of basic science on species
	Tissue archives	Archive tissues for later use in science and conservation	Salmon tissue archives
	Genetic libraries	Genetic analyses to have a record of diversity of populations and species	Genetic records for salmonids
	Seed banks	Embryo, gamete, and seed cryopreservation or other storage approach	Salmon cryopreservation; many agricultural examples
	Planning for species loss and novel ecosystems	Contingency plan for alternative ecosystem management—focus on ecological processes (e.g., water quality, circulation) and novel ecosystems (e.g., invader dominated)	Many examples of water quality criteria in waterways, but none designed necessarily as an ecosystem "backstop"

SOURCE: Developed by the authors.
NOTE: See the technical appendix to this report for details.

Habitat support

Habitat support seeks to expand the area of high-quality habitat for native species as well as habitat investments that anticipate future conditions and species distributions. It includes actions within current aquatic ecosystems as well as in their watersheds. For example, actions may focus on improvements to stream systems, but also the surrounding forests that influence their hydrology, temperatures, and water quality. This represents the broadest and perhaps most powerful category of tools, which are most likely to yield ecosystem benefits for numerous species. Most of these are in use today at some level, although several are more experimental, and all require further investigation to determine the most suitable approaches in different watersheds in a changing climate.

- **Flow improvements.** Flow is a defining need for freshwater ecosystems, making this a foundational component of our toolbox. Improvements could include flow augmentation, the creation of a more natural flow regime, and the restoration of channels, floodplains, and basins that were historically channelized, dredged, or riprapped. This action may require access to water rights, groundwater and watershed management, new engineering facilities, policies to restrict diversions, and channel improvements.
- **Substrate improvements.** Many fish, invertebrates, and plants need suitable substrates (gravel and other sediments). Substrates can be degraded by major climate-related events (fire debris, floods, megadrought), by dams that block the transport of sediment, and by river channelization. Substrate quality can be improved through supplementation, rehabilitation, watershed management, and dam modification or removal.
- **Increased food.** Freshwater species need food, and some aquatic ecosystems now have low supplies. Augmenting food supply (e.g., plankton, invertebrates) in freshwater ecosystems could help fish and wildlife deal with the need for more food as temperatures rise, and with historical impacts on the food web. Options include restoring habitats such as productive floodplains that have been largely erased, improving connectivity to increase productivity, and producing food or nutrients in off-channel or upstream locations to supplement food supplies in aquatic ecosystems.
- **Restoration of habitat diversity and processes.** Increased climate volatility, with more intense droughts and more severe winter storms, could reduce habitat quality and diversity. Restoration projects can create or enhance access to more diverse habitat and support the physical processes (e.g., connectivity, circulation, erosion, and sediment deposition) that create and maintain habitats. Restoring habitat diversity and connectivity is essential for maintaining genetic diversity.
- **Temperature and water quality improvements.** In addition to historic issues such as contaminants and eutrophication (low oxygen levels, arising from excessive nutrient levels), warming will increase water temperatures, exacerbating these problems and triggering other adverse water quality changes (e.g., harmful algal blooms). Some temperature effects can be mitigated by natural or artificial shade and flow inputs from reservoirs or groundwater management. There are many tools to improve water quality, including local and watershed management of nutrients and increased circulation or aeration.
- **Invasive species control.** Climate change makes freshwater ecosystems more hospitable for many invasive species. Traditional approaches to managing invasive species include mechanical removal or chemical treatment. More futuristic approaches are being developed such as biocontrol (using natural enemies to reduce invader populations), gene drives (breeding programs to weaken invader populations), and robotic tools to selectively remove invaders.
- **Focused management zones.** It may not be feasible to protect all parts of every freshwater ecosystem.

Focused management zones may be used to try to protect priority regions that support as many species and habitat types as possible. These include current habitats, as well as future habitats that will be created under climate change.

Case Study 1: Salton Sea Species Conservation Habitat Project

The modern-day Salton Sea was created at the beginning of the 20th century when a flooding Colorado River spilled into the Salton Sink for two years. The saline lake came to support millions of migratory birds on the Pacific Flyway. However, Salton Sea inflow has declined since its original creation, shrinking the sea's area and increasing salinity. Habitat area and quality are both decreasing, resulting in major impacts on fish and wildlife, as well as air pollution from dust on the drying lakebed.

The Salton Sea Restoration Project illustrates how multiple habitat support tools can be used to improve habitats. First, the project team is creating a focused management zone to provide high-quality habitat in a key portion of the Salton Sea. This includes a network of managed ponds and wetlands at the southern end of the Salton Sea to support fish and birds. These ponds rely on local flow improvements (through a new water-diversion facility) to maintain suitable salinities. In addition, the design for the ponds and wetlands includes restoration of habitat diversity and processes to maximize their value to fish and wildlife.

Case Study 2: Foothill Yellow-Legged Frog

The most common habitat issue in freshwater ecosystems is flow, which has been widely altered to meet California's residential and business demands for water and hydropower. Although dams and water diversions are the dominant cause of these changes, these facilities often have some operational flexibility, so there are opportunities to modify flows to support species. A case in point is the modification of dam operations for the foothill yellow-legged frog (Rana boylii), a good illustration of how flow improvements can provide habitat support.

This rare species occurs along the Pacific coast and western slopes of the Cascade and Sierra Nevada mountains, where it lives in foothill and mountain rivers and streams. Managed flow regimes in these streams are often out of sync with different life stages of the Foothill yellow-legged frog, particularly in spring, when sharp drops in flow are harmful. Yarnell (2012) describes how this finding led to revised dam operations in several watersheds, including the Feather, American, and Yuba Rivers. These flow changes were accomplished through negotiations among dam managers, scientists, environmentalists, and recreation advocates. In addition, resource managers are working to reestablish populations in suitable habitats within this frog's historical range (Reinsel 2023).

Species support

Habitat support is essential for improving the resilience of freshwater species. Yet for many species, multiple factors—including low population size, long-term habitat degradation, and the rapid pace of climate change—make it difficult to rebuild and protect populations through habitat improvements alone. Some species may need special support actions beyond habitat improvement. Here we organize these actions under three approaches: distribution support, population support, and genetic support.

Distribution support

Species need to move. Mobility allows species to seek out food sources, find the best spawning grounds, and find mates. However, many barriers now prevent species from dispersing and migrating within their customary ranges, and climate change will further exacerbate mobility issues. Distribution support represents actions that help species overcome existing barriers to dispersal and migration. This kind of support anticipates where migration or dispersal help maintain populations and genetic diversity under future climate conditions. These efforts will often be combined with habitat restoration (see above) to ensure that the current and anticipated future range has suitable conditions. Some distribution support tools are already in use, while several need future study and experimentation. These tools are listed roughly in order of the intensity of management intervention, from lowest to highest.

- **Planning for range shifts.** In the best-case scenario, mobile species that are not impeded by barriers (dams, roads, cities) should be able to migrate on their own in response to geographic shifts in habitat as the climate changes (e.g., higher temperatures, sea level rise). To support species' movement into these new areas, managers can anticipate these range shifts and make any needed habitat improvements in the expanded range.
- **Helping species access historical habitat.** Some aquatic species will also need assistance in reaching currently inaccessible historical habitat that is resilient to climate change. Actions include transporting individuals (e.g., migrating spawners) past dams to upstream cold-water habitat; transporting downstream migrants (e.g., young salmon) past unsuitable areas (reservoirs, high-temperature zones); and improving habitat connectivity through dam removal, the construction of passage structures, and removing barriers between habitats (e.g., reconnecting rivers to wetlands and floodplains). Additional habitat measures may be needed in these historical areas.
- **Assisting migration to new geographic ranges.** Where climate change makes habitat conditions unsuitable throughout the current and historical range of a species, conservation planners could transplant individuals to other locations where temperatures (and other conditions) are suitable.[14] Additional habitat measures may still be needed in the new range of the species.
- **Refuges.** Climate change is expected to severely reduce or eliminate habitat in some areas. To safeguard against extinction, special refuges may be needed. These range from relatively natural constructed outdoor habitats within the historic range of the species to indoor conservation hatcheries, nurseries, and rearing facilities.

14. Assisted migration was recently incorporated into federal policy to support conservation of federally listed endangered species (Thompson 2023).

Case Study 3: Winter-Run Chinook Salmon Reintroduction

Winter-run Chinook salmon (Oncorhynchus tshawytscha) are an endangered race of salmon that are unique to California. They only occur in the Sacramento River drainage, where access to their historical cold-water habitat is blocked by valley dams. To safeguard against recent and impending temperature increases from climate change, a suite of agencies and tribal groups are working to reintroduce winter-run into two cold-water tributaries, Battle Creek and the McCloud River. Both rely on distribution support as one management approach, with helping species access historical habitat as the primary tool.

The Battle Creek project (CDFW 2016) is seeking to reintroduce winter-run Chinook salmon to reliable cold-water habitat within the Battle Creek watershed. A first step in the project was to conduct extensive habitat restoration in the watershed. The reintroduction project is already showing signs of success as hundreds of adult winter-run have returned to Battle Creek to spawn in recent years. The McCloud River reintroduction project was initiated in 2022 as a partnership between the California Department of Fish and Wildlife, NOAA Fisheries, and the Winnemem Wintu Tribe (Bland 2022). The first step in this process involved transporting fertilized salmon eggs to the cold McCloud River above Shasta Dam. In a novel development, the Tribe and university collaborators developed streamside egg incubators to help young salmon "rewild" to local conditions (Dadigan 2023). Juveniles are being collected and transported downstream of Shasta Dam so that they can migrate naturally to the ocean. Although both the Battle Creek and McCloud River projects represent fairly high levels of management intervention, they are part of a portfolio of actions to help this culturally and ecologically important species survive climate change.

Case Study 4: Devils Hole Pupfish Refuge

The Devils Hole pupfish (Cyprinodon diabolis) is an endangered fish found only in Devils Hole, a water-filled cavern close to the California-Nevada border (Kolbert 2021). Since it naturally occurs at only this location, it is an especially vulnerable species. This tiny fish was first listed in 1967 under the Endangered Species Preservation Act,[15] a predecessor of the Endangered Species Act of 1973, making it famous in conservation circles. The species became the subject of a high-profile Supreme Court case when local agricultural water diversions caused water levels in its habitat to drop to dangerously low levels. The court's ruling curtailed groundwater pumping to save the fish's habitat.

Efforts to conserve the species exemplify the reliance on refuges as part of a distribution support approach. Multiple refuges were built (1972, 1973, and 1990), but all were closed by 2007 because of maintenance failures and biological issues. In the early 2010s, a replica of part of the Devils Hole habitat—including a rock shelf favored by pupfish—was constructed at Ash Meadows Fish Conservation Facility and stocked with eggs collected from Devils Hole.

Population support

This group of tools includes additional actions that seek to bolster the population size of native species to increase overall resilience. Many of these are already in use in response to ongoing problems. They are listed by increasing levels of management intervention, with higher biological risks for the latter options.

15. See USFWS (n.d.).

- **Reduce sources of mortality.** In addition to habitat and distribution support, populations harmed by climate change can also be boosted by reducing other sources of mortality. These include stopping illegal harvest (i.e., poaching), imposing stricter regulations in sport and commercial fisheries, reducing losses at water diversions (which can trap or kill fish and other species), and adopting measures to prevent excessive predation.
- **Remediate diseases.** Climate change—particularly higher temperatures—will increase the prevalence of diseases in populations through overcrowding and reduced habitat quality. Potential higher-level management interventions include veterinary treatment of individuals and habitat improvements such as strategic flow pulses.
- **Population supplementation.** When population sizes are small, extreme events (which are becoming more common) can trigger populations to rapidly slide towards extirpation or extinction. One of the most intensive management interventions involves supplementing imperiled populations with hatchery or nursery-grown individuals. This action requires establishing methods to culture species, as well as strategies for reintroduction. Although this tool is widely used for salmon and trout, wild populations have suffered from reduced resilience due to hatchery practices (see the discussion of diversity protection below and in the technical appendix).

Case Study 5: Closure of the Chinook Salmon Fishery in 2023 and 2024

All of California's Chinook salmon runs have been devastated by water diversions, migration barriers, invasive species, disease, habitat loss, and other stressors. In recent years, salmon populations also have suffered at an unprecedented level because of climate-driven changes: a multi-year megadrought and adverse changes in ocean circulation. Population support approaches are being widely used to protect these fish.

In 2023, the Pacific Fishery Management Council took the extreme step of totally closing both the commercial and recreational fisheries in California (Bland 2023). The fishery was closed for a second consecutive year in 2024. The current fishery is dominated by fall-run Chinook salmon, but the declining status of all races is a major concern. Similar fishery closures also occurred in 2008 and 2009 during extreme drought years. Reducing harvest to reduce sources of mortality is an established approach to enhance salmon survival; however, the fishery closure put hundreds of commercial fishermen and women out of work in Northern California and had cascading economic effects on fish sales, restaurants, tackle shops, private fishing guides, campgrounds, and other services. The loss of the subsistence fishery has also severely impacted Native American tribes including the Yurok, Hoopa, and Karuk tribes in Northern California. Companion measures to support the fishery include veterinary treatment of returning salmon to remediate disease incidence and many habitat projects.

Case Study 6: Delta Smelt Population Supplementation

Delta smelt (Hypomesus transpacificus) is a small fish that only lives in the open water of the San Francisco Estuary. Smelt are impacted by many factors, including water diversions, invasive species, disease, habitat loss, and contaminants. They are protected under the state and federal Endangered Species Acts (Moyle et al. 2018). Climate is recognized as one of the most important threats, as the species is very sensitive to high water temperatures and reduced streamflow. The decline of this fish has resulted in one of California's major natural resource conflicts, as the habitat of Delta smelt is impacted by export operations of the State Water Project and the Central Valley Project.

To safeguard against extinction, university researchers developed methods to grow Delta smelt in hatcheries (Lindberg et al. 2013). In 2021, a consortium of university and agency scientists conducted the first experimental release of cultured Delta smelt (Bacher 2021). Supplementation efforts are expected to be scaled up in the coming years. Wild Delta smelt have now declined to the point where they are rarely captured by the extensive fish monitoring programs in the estuary; the population is now primarily supported by hatchery-reared fish. In other words, the species would likely be extinct without population supplementation.

Genetic support

This group of tools includes actions that seek either to take advantage of existing genetic diversity or to introduce genetic diversity into existing populations. Genetic diversity is essential for adapting to changing conditions. When populations are small or fragmented, they run the risk of losing key genes due to random chance or inbreeding, making them more homogeneous. This reduces their resilience to major events like heatwaves, wildfires, and flow changes. Maintaining genetic diversity and gene flow between populations creates the genetic capacity to adapt to different habitat conditions. Conservation efforts that seek to improve genetic diversity are often referred to as *genetic rescue* (Fitzpatrick et al. 2023). Many of the previously described actions in habitat support and distribution support can help maintain genetic diversity and resilience, but additional tools focused on genetic diversity may be needed. These tools are highly experimental and need further assessment, particularly considering legal, cultural, and ethical issues. The tools below are roughly listed from the lowest to highest levels of management intervention.

- **Diversity protection.** For species currently produced in hatcheries (e.g., salmon and steelhead), state-of-the-art breeding programs can maximize genetic diversity in hatchery stocks. Where there is evidence that hatchery practices have adverse effects (e.g., loss of diversity, inbreeding), the best way to protect the diversity of wild river populations might be to limit breeding between wild and hatchery stock. This could be accomplished by suspending hatchery fish stocking or by relocating hatcheries to seaward locations away from spawning grounds. In addition, many of the previously described management tools (e.g., various habitat support approaches) can be used to help enhance the diversity of wild populations.
- **Assisted evolution.** Even with large, diverse populations, the pace of natural selection may be insufficient to cope with future extreme conditions. Assisted evolution represents a very intensive intervention to help select for individuals that can better survive warmer and drier conditions under climate change. Selective breeding in hatcheries is a traditional tool, but future applications might include highly experimental approaches to influence how genes are expressed (epigenetics) or the introduction of new genes.[16]
- **Hybridization.** Another relatively extreme action is to crossbreed races or closely related species. Plant hybridization is commonly used to generate specific desirable traits such as fast growth, appearance, and disease resistance. More recently, hybridization also has been used in commercial aquaculture for fish and invertebrates. A similar strategy might be used in situations where individual species are unable to adapt quickly to climate change.

16. Epigenetics occurs when environmental factors such as diet, stress, and toxins affect gene expression in animals without altering the DNA sequence. For example, high temperature exposure during the larval stage may cause certain genes to be expressed as the individuals get older.

Case Study 7: Climate Adaptation Through Shellfish Breeding

Bivalves—including clams, oysters, and mussels—are a critical ecological component of healthy estuaries. In addition, shellfish farms in coastal areas provide high-quality and sustainable sources of seafood. These resources are all threatened by climate change, particularly by rising temperatures and ocean acidity, as well as harmful algal blooms. Negative impacts are already underway, with episodes of mass mortality of bivalves occurring in farms, hatcheries, and natural populations (Johnson 2015).

Assisted evolution programs involving selective breeding are underway to develop bivalves that are more resistant to climate-induced changes (Tan et al. 2020). These programs are intended to support both aquaculture farms and shellfish restoration projects (Tan and Zheng 2020).

Case Study 8: California Tiger Salamander

The habitat of the endemic California tiger salamander (Ambystoma californiense) is limited to the vicinity of large, fishless vernal pools and similar water bodies like agricultural ponds (Hammerson 2004). The salamander's current range is confined to coastal and inland areas of Northern and Central California. The decline of California tiger salamander populations is likely due to the loss of breeding habitats and the presence of invasive predators such as American bullfrogs, but increasing drought intensity poses a significant risk. The Sonoma and Santa Barbara populations have been federally listed as endangered since 2000 and 2003, respectively.

The California tiger salamander is increasingly influenced by interbreeding with the introduced Barred tiger salamander (Ambystoma tigrinum mavortium), which has been occurring for as long as 50–60 years (Fitzpatrick et al. 2007). Researchers have found strong evidence of hybrid vigor between the two types of salamander, including higher survival rates for the hybrids than for the native California tiger salamander. Since these hybrids are capable of breeding, it is possible that these more robust hybrids may eventually replace the historically pure California tiger salamander. Although loss of the original, genetically pure individuals is a major concern, hybridization may give the species an evolutionary advantage—an important consideration in the face of a rapidly changing climate.

Contingency actions

As discussed above (Figure 1), there is a shrinking opportunity to preserve many at-risk fish, amphibians, invertebrates, and birds, which are already veering towards extinction. Controversial as it may be, contingency actions are needed to deal with a highly uncertain future. This strategy includes tools to preserve knowledge about habitat, as well as genomic and life history traits of native species. Such tools are widely used in terrestrial conservation and adaptation work, but they are less common in freshwater aquatic systems. Contingency actions also include anticipating what to do when extirpations and extinctions occur. Contingency actions are not an excuse to de-emphasize other strategies that seek species persistence and resilience. Rather, they are a complement to habitat support and species support—a form of bet-hedging in case best efforts in these other areas are not successful (USGS 2023).

Contingency actions include:

- **Historical conservation.** California has a strong legacy of scientific inquiry, but there are still large gaps in the understanding of freshwater biota, particularly for plants and animals that do not have special status. Historical conservation entails collecting baseline information about current species (e.g., diets, behaviors, physiology) and habitats (e.g., structure, substrate, soundscapes) before these species risk being lost to climate change and habitat decline.
- **Tissue archives.** In recent decades, there has been a proliferation of chemical and genetic techniques that allow scientists to learn much about species using small samples of their tissues. Tissue archives (libraries) are common for terrestrial species, but they are rare for aquatic species other than high-profile types such as salmon and amphibians.
- **Genetic libraries.** Related to the previous tool, genetic libraries are increasingly common to record the diversity of populations. They represent the analytical results of genetic assessments conducted on species' tissues and can be used to record the genetic legacy of biodiversity.
- **Seed banks.** Seed banks are common in terrestrial conservation but relatively rare for California aquatic species. The tool involves developing live or cryopreserved archives of embryos, gametes, and seeds, and it raises the possibility of "de-extinction" at a later time when habitat conditions are suitable.
- **Planning for species loss and novel ecosystems.** Even with aggressive action, climate change is very likely to result in the loss of some original species, communities, and habitat features. Yet there will likely still be options to maintain healthy ecosystems, and these novel ecosystems will support new communities that are most likely a mix of native and non-native species.[17] Under this action, resource managers would develop contingency plans that include alternative ecosystem management goals and objectives like water quality, recreation, aesthetics, and new communities of animals and plants, depending upon projected changes in these ecosystems.

17. Novel ecosystems are ecosystems that did not occur historically in a region and have no analogues in natural systems. Climate change alone will alter ecosystems in ways that change their condition and function along with their species assemblages. However, in much of California, non-native plant and animal species have colonized freshwater ecosystems, often taking advantage of changes in habitat conditions due to water and land use practices. Where these have been introduced, non-native species significantly change ecosystems, and they are often referred to as "invasive." The trajectory of climate change—increased warming and more extreme variation—will change habitat conditions in many ecosystems in ways that will favor some non-native species and lead to the extirpation of some native species. Most novel ecosystems will be a mix of native and non-native species.

Case Study 9: Svalbard Global Seed Vault

Globally, more than 1,700 seed banks have been established for food crops as an insurance policy against catastrophes including climate change. Likely the most ambitious of these is the Svalbard Global Seed Vault, designed as an insurance policy for the world's food supply. The remote facility in cold northern Norway stores millions of seeds that represent every important crop variety available in the world today. The Seed Vault is owned and administered by the Norway Ministry of Agriculture and Food and is intended as a service to the world.

Case Study 10: Salmon Cryopreservation

As described in Case Study 3, winter-run Chinook salmon have been a focus of conservation efforts since the late 1980s, when they were listed under the state and federal Endangered Species Acts in response to plummeting populations. Measures to support their populations have included habitat support actions and all three types of species support (distribution, population, and genetic support). However, in recognition of the dire status of the population, the Livingston Stone National Hatchery has also employed contingency tools (seed banks, genetic libraries) (USFWS 2016).

For decades, scientists have used cryopreservation of salmon milt (sperm) to conserve the genetic diversity of winter-run Chinook salmon and to support the Livingston Stone hatchery program (USFWS 2016). Samples are stored, along with their companion digital genetic information. Cryopreserved milt samples are frequently cycled into the hatchery's captive broodstock spawning program and they have been used occasionally for the insemination of wild eggs. The viability of cryopreserved milt is highly variable and generally lower than that of fresh samples from males, but still offers an important tool to maximize genetic diversity in the population.

Building Climate-Smart Plans and Management Portfolios

Climate change is expected to have broad and multifaceted effects, with a strong potential for unexpected outcomes that will impact species diversity and resilience. Especially for those species protected by regulations, current management approaches often focus heavily on restoring historically optimal conditions (e.g., peak reproduction months or specific habitat features like water depth), or on addressing single limiting factors (e.g., freshwater flow). To support adaptation in an uncertain future, a new approach is warranted.

The Role of Climate-Smart Conservation Planning

Implementing climate adaptation tools on a broader scale will be complicated, requiring multiple considerations to pick the right suite of actions. Any one tool, used inappropriately, could result in negative outcomes. Even with careful choices, there is some inherent risk of unintended consequences, so resource managers need to be willing to adjust conservation actions if outcomes are poor. Additionally, resource managers need to evaluate the tradeoffs of potential actions before implementation, using quantitative planning tools such as population models, which help to predict a population's response to management actions. Scientifically rigorous monitoring and evaluations of experimental actions will be key. It will help managers adjust if outcomes have unintended consequences or fail to provide expected benefits. Planning frameworks such as *Climate-Smart Conservation* (Figure 2, above) offer flexible and robust processes to develop climate adaptation plans. Such frameworks offer a systematic approach to working with stakeholders, identifying the major issues, identifying management options, prioritizing tools, and developing robust monitoring and evaluation programs so that adjustments can be made.

The challenge is how to encourage the investment of the considerable time and resources necessary to develop climate-smart conservation plans. After all, there are numerous regulatory and water management planning efforts underway throughout California, and many of these acknowledge the threat of climate change. Why add the burden of another planning process and possibly an additional bureaucracy to oversee it?

In our view, the various planning efforts underway—ranging from water quality control plans, species recovery plans, regional water management plans, multiple statewide strategies, and more—are helpful, but often do little to address climate effects. These disparate efforts tend to focus on one component of the problem (for example, water quality or a few protected species), and few articulate how their actions would create biodiversity resilience in the face of the changing climate. In short, simply doing a better job with the many efforts underway is unlikely to change the trajectory of biodiversity decline. That said, many of these processes provide a useful foundation for climate adaptation plans.

Here we offer some preliminary thoughts on how climate-smart conservation planning might proceed in California. A follow-up report to be released later this year will examine the legal and policy issues associated with implementing these plans.

We recommend that the state encourage the development of climate-smart conservation plans that are fully integrated into water management, planning, and regulation at the watershed scale. To accomplish this, the state should undertake a comprehensive statewide assessment of the conservation status of native freshwater species and the likely impacts of climate change on ecosystems and biodiversity.[18] This assessment would be used to identify priority watersheds that are in the greatest need of climate-smart conservation plans. In addition, this effort would set guidelines and technical requirements for these plans, including timelines for their development. This assessment also could be used to guide research to support planning.

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18. Climate change vulnerability reports are already available for many California species, but a broader effort will be needed.

To be effective, climate-smart conservation plans need to be developed in a collaborative manner, involving landowners, conservation groups, watershed stewards, various agencies (local, state, and federal), local communities, and tribes. This approach will integrate conservation actions with the many other activities in the watershed and encourage the incorporation of climate-smart conservation principles in watershed planning. Often, the various state, local, and federal agencies will have technical expertise and access to resources to help implement plans.

The state should offer financial and technical support for these collaborative groups to produce these plans. The state would also play a role in reviewing and approving the plans.[19] In some respects, this approach could borrow governance concepts from the 2014 Sustainable Groundwater Management Act (SGMA), which has both state and local involvement.[20]

As described in an earlier PPIC report (Mount et al. 2019), the state could adopt watershed plans as water quality control plans, or integrate them into existing water quality plans.[21] Where ESA-listed species are involved, plans should seek to eventually meet the requirements of federal Habitat Conservation Plans and state Natural Community Conservation Plans for habitat management and incidental take of listed species, or use other instruments—such as Safe Harbor Agreements—as appropriate.

In addition to the need for a robust planning process to support climate-smart conservation, we recognize the urgent need to start implementing projects now. This includes pilot projects, larger-scale projects for relatively well-understood tools like habitat restoration, and contingency actions (see below). Each of the tools that we have described presents tradeoffs, and many have large uncertainties. The development of effective climate-smart conservation therefore depends on the availability of good information. Since climate planning for watersheds may be a lengthy process, these pilot and larger-scale projects, along with associated research, monitoring, and evaluation, need to begin as soon as possible to garner good information to support decision makers, and to potentially provide immediate benefits to at-risk species.

Finally, climate-smart plans should steer away from over-reliance on a few traditional approaches to conservation. Given the magnitude of the challenge and the numerous uncertainties, it is best to adopt a portfolio approach. Here we briefly describe the portfolio concept in climate-smart planning, and we illustrate how portfolios might differ across watersheds.

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19. We are agnostic about which agencies would take on the role of approving and administering climate-smart conservation plans. Although the California Department of Fish and Wildlife usually takes on the role of conservation management, the California Department of Water Resources plays the primary role in climate planning for water and has extensive technical capacity for this kind of effort. Additionally, the State Water Resources Control Board plays a central regulatory role and has the capacity to mandate climate-smart conservation planning as part of its water quality control plans and other authorities.

20. The Sustainable Groundwater Management Act (SGMA) requires that high- and medium-priority groundwater basins form groundwater sustainability agencies (GSAs) to develop and implement Groundwater Sustainability Plans (GSPs) that mitigate the impacts of groundwater overdraft over a 20-year period. The state provides oversight, funding, and technical assistance for the development of these plans, which must be approved. If the GSA is unable to produce an acceptable GSP, the state can take over administration of the groundwater basin and impose pumping restrictions. In the case of climate-smart conservation plans, the role of state approval of watershed plans would likely be quite different than under SGMA—perhaps involving regulatory incentives for approved watershed-level plans.

21. The climate-smart conservation plans proposed here are essentially the same as the sustainable watershed management plans recommended in Mount et al. (2019), but with the explicit addition of a portfolio approach to climate-smart planning, including habitat and species support tools and contingency actions.

The Importance of Management Portfolios

Our list of 22 tools represents a starting point for developing a portfolio of management strategies and actions. The development of portfolios corresponds to Step 5 of the *Climate-Smart Conservation* framework (Figure 2, above). Populations decline in number and lose genetic diversity and climate resilience because of habitat loss and degradation. Habitat support is therefore foundational to any portfolio because it can generate ecosystem effects that improve conditions for many species simultaneously. In addition, habitat restoration typically benefits other ecosystem services—recreation, improved water quality, flood mitigation, and cultural benefits—which can build broad support and buy-in.

We also identify many species support actions, which target specific types of plants and animals. These tools could provide a valuable supplement to habitat support as part of a portfolio. While habitat-focused actions can address long-standing stressors like habitat degradation, focused interventions to support species (e.g., assisted migration) can help deal with the most severe population effects of climate change. Similarly, the portfolio might be designed to address limiting factors during different seasons and different life stages, or in wild-versus-hatchery stocks. To help illustrate this point, Case Study 11 highlights a recent example of an innovative project in Southern California that used a suite of actions to save a unique fish species.

Case Study 11: Unarmored Threespine Stickleback

The endangered unarmored threespine stickleback (Gasterosteus aculeatus) lives in just a few streams in Santa Barbara, Los Angeles, San Bernardino, and San Diego Counties. It is generally found in shallow, slow-moving water, where it is vulnerable to many threats including water diversions, disease, and invasive species. Increasing drought intensity poses a high risk of extinction.

A recent project by the California Department of Fish and Wildlife, US Fish and Wildlife Service, US Forest Service, and the Wildlands Conservancy is designed to help the species survive in the face of current and future threats, particularly climate change. The project provides a good example of applying multiple tools for conservation—specifically, combining habitat support (invasive species control, focused management zones), and species support (assisted migration). The project first drained the introduction site, Bluff Lake Reserve, to eliminate all invasive fish. After Bluff Lake was refilled, more than 200 unarmored threespine stickleback were captured with nets and traps at a nearby donor lake and then released into Bluff Lake. Additional translocations are planned for this site. Expanding the range of the species is considered an important population buffer against extreme regional events such as wildfires and debris flows.

How Approaches Might Differ Across Watersheds

A comparison of two California watersheds illustrates how local conditions might inform the selection of strategies and tools (Figure 3). Management objectives in coastal watersheds of the North Coast hydrologic region—such as the Smith River, Redwood Creek, and the Eel River—tend to focus on conserving anadromous fish, including Coho salmon, Chinook salmon, and steelhead.[22] Similarly, on the Sacramento River and its tributaries, major efforts are underway to protect and restore the multiple races of Chinook salmon, along with other anadromous species. Despite similar objectives, the strategies and tools are likely

22. Anadromous fish spawn in freshwater but spend part of their lives in the ocean.

to be very different. The North Coast rivers are far less impacted by past and current water use practices, although mining, forestry, and water diversions can be major issues. In addition, their proximity to the ocean is likely to mute some of the impacts of climate change (Dalsin et al. 2023; Wilson 2023). In contrast, the Sacramento River watershed is heavily impacted by dams, water diversions, high temperatures, levee construction, contaminants, invasive species, poaching, hatcheries, and other effects of water and land development. The Sacramento River will also experience substantial warming because of its inland location, as well as major climate-induced changes in flow (Andrew and Sauquet 2017).

Many North Coast waterways may therefore only require a moderate amount of intervention to provide resilience against climate change, principally through habitat support. In the Sacramento River, where current habitat conditions are already poor, there is less baseline resilience. Planners may need to consider a long list of major interventions for climate-smart conservation.

This comparison is not intended to identify the exact climate adaptations that would be required in these two regions. Rather, we aim to show that the number and magnitude of adaptation measures needs to be location specific. In general, freshwater ecosystems that are already heavily degraded will require much greater levels of intervention. The specific choice of tools will require careful consideration of multiple factors as part of climate-smart conservation planning. The list of strategies and tools developed in this report allows for a systematic evaluation of potential actions, including actions that may be controversial or carry some risk.

Figure 3

Climate-smart portfolios in the North Coast and Sacramento rivers might vary with the level of habitat degradation and projected climate change impacts

North Coast Rivers

Moderate Intervention

Habitat support
- Substrate improvements
- Habitat diversity
- Invasive species control

Distribution support
- Planned migration

Population support
- Reduce sources of mortality

Genetics support
- Diversity protection

Contingency actions
- All approaches

Sacramento River

Major Intervention

Habitat support
- Flow improvements
- Substrate improvements
- Increased food
- Habitat diversity
- Temperature and water quality
- Invasive species control
- Focused management zones

Distribution support
- Planned migration
- Dispersal support
- Assisted migration
- Refuges

Population support
- Reduce sources of mortality
- Remediate disease
- Supplementation

Genetics support
- Diversity protection
- Assisted evolution
- Hybridization

Contingency actions
- All approaches

SOURCE: Authors' assessment.

NOTE: This is a potential list of climate-smart strategies that may be needed to manage rivers in the North Coast, which are in better condition and less impacted by climate change, and in the Sacramento River and its tributaries, which are highly degraded and strongly impacted by climate change.

The Importance of Contingency Actions

Finally, we also believe that contingency actions will be desirable in most, if not all settings, including watershed plans and climate portfolios. Most adaptation plans—particularly those that focus on ecosystems—fail to include contingency actions. Yet actions are needed in case it is no longer possible to maintain suitable conditions for native species (USGS 2023). As described earlier, including these actions in watershed plans and climate portfolios is not an excuse to de-emphasize other approaches. But contingency actions are important for three reasons. First, they create an option for restoring species that may go extinct in the future. Second, many of these actions provide important information needed to guide conservation. And third, they allow for difficult but necessary discussions about how to manage ecosystems if some species are extirpated—particularly vulnerable native species that are protected by the state and federal Endangered Species Acts. The presence of a listed species in a waterway guarantees some environmental protections for that ecosystem. And the actions currently used to sustain many of these listed species play a much broader role in maintaining ecosystem health and water quality benefits for people. The loss of listed species could entail the loss of the environmental regulations that protect them—with profound consequences for the ecosystem as a whole.[23] It is better to envisage how to manage this eventuality than to assume it could never happen and be unprepared if it does.

Recommendations

We live on a profoundly altered planet. The year 2023 was the warmest in recorded human history by a wide margin (NOAA National Centers for Environmental Information 2024), highlighting how dramatically the earth's climate is changing. At the time of this writing, 2024 is on track to be even warmer. The pace of change—coupled with the poor habitat conditions in many watersheds in California—is placing great pressure on native freshwater biodiversity. Roughly half of California's native freshwater species are highly vulnerable to extinction within this century. The window of opportunity to arrest and reverse the declines is closing. Status quo management approaches have largely failed to recover at-risk species, and they will be insufficient to protect many in the future. Even with important advancements in permitting for ecosystem restoration (e.g., Sustainable Conservation 2023) and efforts to implement the new *California Salmon Strategy*, California's current approach to habitat and species management is simply too slow and too limited in scale to meet this challenge.

It will take courage to meet this moment—but we have the tools. In this report, we have examined an array of strategies and tools for tackling the impacts of climate change on native freshwater biodiversity. How different groups might use this information will vary, depending on their focus (Table 2). We offer three general recommendations for policymakers, ecosystem managers, the scientific community, and various other stakeholders to consider. We will examine the policy and legal implications of implementing these recommendations in a subsequent report.

23. Delta smelt are a good example of how species-focused management can help protect the broader ecosystem. To meet federal and state protections for Delta smelt habitat, significant volumes of water must be allowed to flow out of the Delta and into San Francisco Bay (Moyle et al. 2018). This additional outflow creates ecosystem benefits for numerous species that are not protected currently and improves water quality for a range of human uses (Gartrell et al. 2022). Extinction of this species—called "delisting" by regulatory agencies—could lead to changes in flow and water quality standards that might harm other species and uses of the Delta.

Figure 4

Potential ways that different groups might use the management strategies and tools in this report

Action group	Example activities
Scientists and engineers	Identify relevant topics for research, development, and monitoring
	Research and develop potential tools
	Research, monitor, evaluate, and communicate outcomes for pilot and full-scale projects
Resource managers, conservation NGOs, tribes, watershed groups	Establish management objectives and priorities, identify climate vulnerabilities, screen and prioritize management options, develop and evaluate alternatives, identify monitoring criteria
	Develop watershed plans
	Design, implement, manage, and evaluate projects: pilot and trial efforts, full-scale efforts
Legislatures and agencies	Set policy priorities
	Make legal and regulatory changes
	Provide funding and staff to implement priority actions

SOURCE: Developed by the authors.

1. Develop Climate-Smart Conservation Plans

Although California has made significant advances in preparing for the water supply impacts of climate change, it has yet to develop a statewide adaptation plan for freshwater ecosystems. Many laudable plans and programs already exist, and they should not be thrown out. However, it is time to evaluate how climate change will impact them, and retrofit them if needed. We recommend using the *Climate-Smart Conservation* framework of Stein et al. (2014) or a similar approach to guide adaption planning and implementation. What's needed is a statewide plan that identifies broad priorities, selects important watersheds for immediate action, and supports the development of climate-smart conservation plans for these watersheds.[24] The state legislature should encourage the development of these plans and provide funding for technical assistance.

The watershed plans should:

- Assess current habitat conditions, likely climate change impacts, and species' vulnerabilities;
- Set goals and objectives for native biodiversity management, including priorities for action and metrics of success;

24. The need for watershed-scale planning from freshwater ecosystems is further described in the list of companion PPIC reports at the end of this document.

- Select management strategies and tools to employ (as described in this report), and identify roles, responsibilities, tradeoffs, and funding sources; and
- Implement priority actions, monitor impacts, and establish mechanisms for refining goals and objectives and updating actions as new information becomes available.

Statewide and watershed-level climate-smart conservation plans would guide future adaptation efforts and be regularly updated and revised. These plans would be foundational for future revisions of statewide climate plans such as the *California Climate Adaptation Plan* and the *California Salmon Strategy*. To be most effective, these plans should be integrated with regulatory frameworks like federal Habitat Conservation Plans (HCPs), state Natural Communities Conservation Plans (NCCPs), and water quality control plans.

2. Build Portfolio Approaches for Conservation Actions

Too often, conservation efforts focus narrowly on a handful of strategies and tools to improve the resilience of aquatic animal and plant populations. A broader portfolio of approaches will be needed to meet the evolving challenges of our warming climate.

We identified two general strategies—habitat support and species support—that resource managers and others will need to use in responding to climate change impacts. Habitat support includes a broad array of water and land management actions, including some that are used widely today. But species support will also be necessary, particularly in highly degraded ecosystems where investments in habitat support alone cannot restore resilience. Species support includes efforts aimed at improving species distribution; rebuilding populations through supplementation or reducing mortality and disease; and supporting genetic diversity through hatchery reform, selective breeding, and even hybridization. It is important that all tools be systematically considered in climate-smart conservation plans, no matter how controversial. Bold measures will be needed.

All the tools described here come with some uncertainties and tradeoffs, and a range of technical, social, political, and ethical issues will need to be addressed as part of the statewide commitment to climate-smart conservation (for more on the tools, see the technical appendix). Improved science support for conservation is a major need, since strong research and monitoring will be essential to accompany implementation, develop new approaches, and evaluate and improve the effectiveness of the chosen strategies.

Beyond investing in suitable habitat and species support strategies, it is essential that California recognize that the pace of climate change, along with species' capacity to adapt, will likely result in permanent changes in ecosystems and native biodiversity. Contingency actions should therefore be part of all climate-smart conservation plans. This includes identifying responsibilities and resources for collecting information about the life histories and habitats of existing species, along with archiving genetic material—all with the goal of the potential reintroduction of species in the future. In addition, this statewide effort should examine the consequences of extinction and how best to manage ecosystems if certain species—particularly those protected by state and federal Endangered Species Acts—are no longer present.

3. Start Climate-Smart Conservation Actions Now

Although it is important to develop comprehensive watershed plans and climate portfolios, these processes are often time consuming. It would be a mistake to delay the testing and implementation of climate-smart conservation tools until each of these processes are completed. This is particularly true for tools that are relatively well established, such as many of those providing habitat support. Many high-risk species need help immediately and could benefit from early implementation of conservation projects. Case studies in this report and the technical appendix demonstrate how pilot and larger-scale projects can provide relatively rapid benefits for species. Results from pilot projects are also needed to help decision makers develop, refine, and adjust watershed plans and portfolios. Multiple groups—including tribes, agencies, NGOs, watershed groups, and universities—could lend valuable support by generating and implementing pilot projects and conducting rigorous testing and evaluation. Some contingency actions should also begin immediately, while the broader plans are under development, to prepare for the potential loss of some species in their historic ranges.

Conclusion

California is a global leader in policies to mitigate climate change, and the state is pursuing efforts to plan for and adapt to change, particularly in the energy, agriculture, transportation, flood mitigation, forests, and water supply sectors. But the state still lacks a comprehensive adaptation plan for the impacts of climate change on freshwater ecosystems and the native biodiversity they support. This report recommends the development of climate-smart conservation plans for important watersheds and offers guidance on the array of strategies and tools that should be incorporated in these plans. The portfolio of tools goes well beyond the most common approaches to conservation because business as usual, even done better, will not be adequate. California needs better planning, and it needs to act very soon to protect vital freshwater ecosystems and their unique arrays of native species. The time for courageous action is now.

PPIC Reports on Freshwater Ecosystem Management

For the past nine years, researchers at the PPIC Water Policy Center have been exploring new approaches to freshwater ecosystem management, with the goal of finding ways to be more efficient and effective with resources allocated to environmental protection while adapting to rapidly changing conditions. This report is part of a series that provides recommendations for ways to arrest and reverse ecosystem decline while minimizing impacts on other benefits like water supply and flood control. The reports that inform this effort include:

- Managing Water for the Environment during Drought: Lessons from Victoria, Australia (2016). A summary of innovative practices used in Australia to manage water in reservoirs for environmental needs
- Managing California's Freshwater Ecosystems: Lessons from the 2012–16 Drought (2017). A suite of proposals for managing drought, including ecosystem water budgets and planning
- A New Approach to Accounting for Environmental Water: Insights from the Sacramento–San Joaquin Delta (2017). Identifies trends in the amount of water used for various purposes in the Delta
- Managing Drought in a Changing Climate: Four Essential Reforms (2018). Recommends new policies for drought management in all sectors, including the environment
- A Path Forward for California's Freshwater Ecosystems (2018). Describes the concept of ecosystem-based management and highlights the importance of setting aside budgets for the environment
- Making the Most of Water for the Environment: A Functional Flows Approach for California's Rivers (2020). Describes how to use water allocated to the environment more efficiently
- Advancing Ecosystem Restoration with Smarter Permitting: Case Studies from California (2021). Recommends reforms in permitting to speed up habitat improvement efforts
- Tracking Where Water Goes in the Sacramento–San Joaquin Delta (2022). An update of the New Approach to Accounting for Environmental Water report, including accounting for changes in runoff and use upstream of the Delta
- Storing Water for the Environment (2022). Demonstrates ways to store and release water in reservoirs and aquifers to improve freshwater ecosystems

These reports, and their accompanying technical appendices, provide background to many of the proposals contained within this report.

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Acknowledgments

This research would not have been possible without the contributions of state and federal representatives, academics, water managers, tribal representatives, and nonprofit organizations who participated in our workshops and met with us to discuss and share their perspectives on climate adaptation and conservation. We also acknowledge the generous contributions of a team of California water experts who participated in an advisory group for this project, meeting with us during the past year as a group and providing additional input through smaller meetings: Karrigan Bork, Jim Cloern, Greg Gartrell, Ted Grantham, Rachel Johnson, Sam Luoma, Peter Moyle, and Anna Sturrock. Peer reviews by Lewis Bair, Louise Conrad, Jim Cloern, Heather Dyer, Ted Grantham, Steve Lindley, Nat Seavy, and Eric Stein also greatly improved the report. We would also like to thank Andrew Ayres for early guidance on the project, Brad Franklin for his constructive comments, and Caitlin Peterson and Jerica Miles for administrative support. The authors alone are responsible for any remaining errors or omissions.

Finally, special thanks to Carson Jeffres, who gave permission to use the cover photo; Sarah Bardeen, who provided expert editorial support; and Ellen Hanak, who served as lead reviewer and provided overall guidance to the team.

This publication was developed with support from: the S. D. Bechtel, Jr. Foundation and the donors of the PPIC CalTrout Ecosystem Fellowship: Gary Arabian, John Osterweis, Berniece and Pat Patterson, and the Rosenberg Ach Foundation. Research publications reflect the views of the authors and do not necessarily reflect the views of our funders or of the staff, officers, advisory councils, or board of directors of the Public Policy Institute of California.

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