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Climate-Smart Tools to Protect California's Freshwater Biodiversity

Technical Appendix

CONTENTS

Appendix A. Conceptual Model for Climate Effects on Aquatic Ecosystems and Native Biodiversity
Appendix B. Approach to Develop Climate Adaptation Options for Freshwater Ecosystems
Appendix C. Climate Adaptation Strategies and Tools

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Appendix A. Conceptual Model for Climate Effects on Aquatic Ecosystems and Native Biodiversity

An essential first step in the development of a climate adaptation plan for freshwater biota in California is to identify vulnerabilities to climate change. In this section we describe a simple conceptual model that captures climate impacts on native species and ecosystems. We recognize that climate effects do not operate independently of all the other environmental stressors in California. Climate change acts as a compounding threat that further stresses aquatic ecosystems.

Baseline: Brief summary of long-term environmental issues

Our planet's waterways have all been touched in some way by humans. California therefore has a long history of water- and land-use development that has produced a multitude of chronic, long-term environmental issues that affect freshwater ecosystems (Mount et al. 2023a). The problems are so broad that one or more of these issues occur in every single freshwater ecosystem in the state. Here we briefly summarize some of the major causes of habitat decline.

Dams. California's landscape has been extensively altered throughout the state by its water infrastructure, particularly dams and diversions (Mount 1995; Mount et al. 2023b). Numerous reservoirs have been constructed for water supply, hydropower generation, recreation, flood control, and debris management. The ecosystem effects of these facilities can be extreme, blocking access to upstream habitat and radically altering flow regimes, sediment transport processes, and water quality.

Water diversions. California's water diversions are extensive, including smaller local projects to large-scale export facilities to transport water across the state (e.g., State Water Project; Central Valley Project; Grimaldo et al. 2009). For example, the Sacramento–San Joaquin Delta alone has over 2,000 water diversions (Herren and Kawasaki 2001). On average, about 50 percent of runoff that would flow through the Delta is diverted upstream or within the Delta for farms and cities (Mount et al. 2023b). Groundwater pumping also depletes aquifers that supply lakes, rivers, ponds, and streams (Hanak et al. 2017). The net effects of water diversions are reduced streamflow across the state, substantially altered hydrographs, salinity intrusion, and losses of aquatic organisms due to entrainment at diversions.

Habitat loss and degradation. California's landscape has been extensively altered by human development including urbanization, agriculture, and flood management (Mount et al. 2023a). Rivers and streams have been channelized, and bankside vegetation removal is common, limiting shading and habitat complexity along and within rivers. Wetland loss has been extreme throughout the state. For example, approximately 95 percent of the historical wetlands in the San Francisco Estuary (Bay–Delta) have been lost (Nichols et al. 1986). Even when these habitats still exist, their quality is often adversely affected by local land use changes.

Habitat loss as well as water diversions have seriously affected connectivity across freshwater ecosystems (Mount 1995). Migratory species are commonly cut off from headwater areas by dams, and many types of organisms can no longer access off-channel habitats such as floodplains and wetlands because of levees and irrigation structures. Dams also limit sediment flow, causing degradation in downstream habitat.

Contaminants. California has extensive agriculture and urban areas, all of which generate contaminants that enter freshwater ecosystems (e.g., Brooks et al. 2012). The list of potential contaminants is long, so we only cover some of the major groups. Nutrient inputs from agriculture, urban runoff, and water treatment plants result in higher nitrogen and phosphorus levels. When combined with rising temperatures, these nutrient changes are driving algal blooms. Runoff from urban areas and roadways contributes a variety of contaminants (including tire and brake dust, and hydrocarbons). Numerous herbicides and insecticides are used in all watersheds of the state, with the potential for acute and chronic effects on aquatic life. Anthropogenic activities are also responsible for many other water quality problems such as contamination by mercury, cadmium, selenium, and other salts.

Invasive species. Given the high degree of landscape modification, it is no surprise that California's freshwater ecosystems face major challenges from invasive species (Angulo 2021). The invaders include aquatic plants, bivalves, amphibians, fish, and mammals, resulting in very different species assemblages than historical conditions. For example, the Bay–Delta region has been characterized as the most invaded estuary on the planet (Cohen and Carlton 1998).

The ecological effects of these non-native species can be extreme since some of these invaders are ecosystem engineers (e.g., bivalves, aquatic weeds, emergent vegetation), resulting in major changes in the structure and function of freshwater ecosystems (Angulo 2021). Other ecological effects include increased competition, higher predation rates, worse water quality, and more disease.

Additional issues. The previously described environmental issues may be compounded by several other factors. Hatcheries have been constructed to supplement salmon and trout populations impacted by loss of habitat due to dams. However, hatcheries can have adverse impacts on wild populations including loss of genetic diversity and a higher incidence of diseases (McMillan et al. 2023). In some cases, populations can be adversely affected by excessive harvest by sport or commercial fishing, particularly poaching activities.

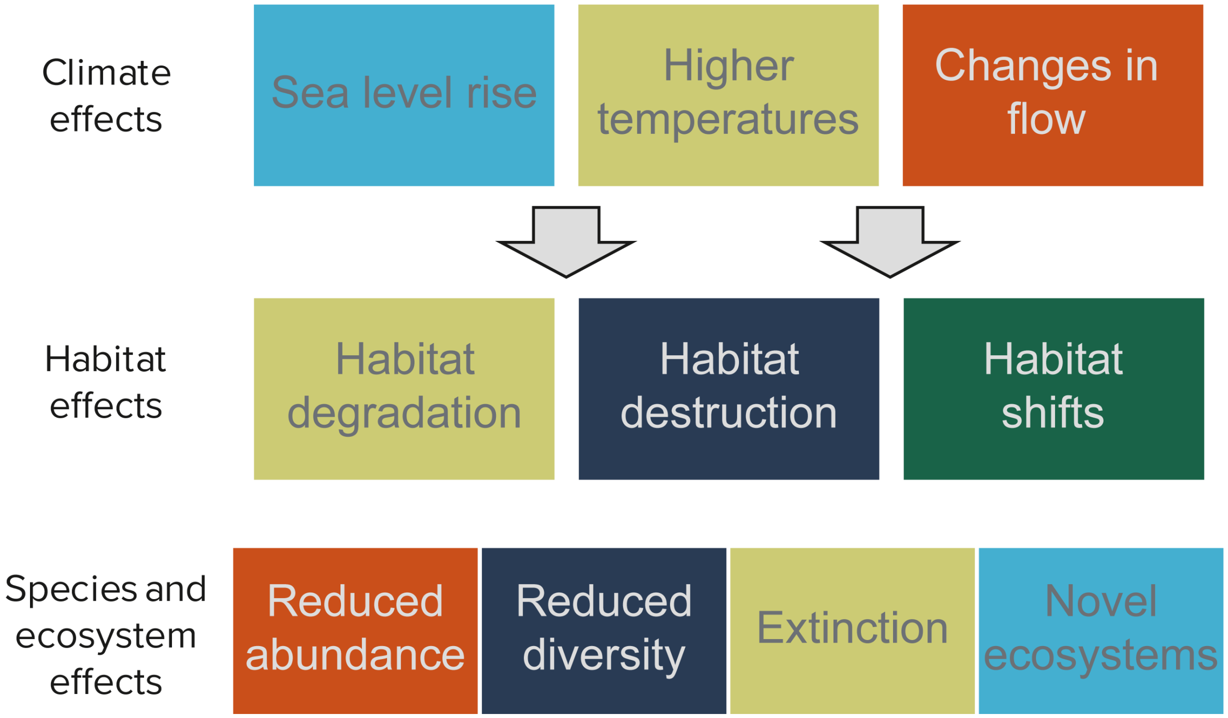
Climate Change Conceptual Model

As summarized above, California has numerous long-term environmental issues such as habitat loss, water development, contaminants, and invasive species—climate change will create additive effects on top of these serious problems. Ongoing and future changes in climate will further alter freshwater ecosystems, with cascading effects on aquatic species populations (Hanak et al. 2018).

Climate change is often viewed as a future existential threat to ecosystems, implying there is time to prepare. But global change is underway, threatening biodiversity throughout the world, not just in California (Weiskopf et al., 2020; Moore and Schindler 2023). In the 21st century, California has experienced its wettest year (2017), two driest three-year periods (2013–15; 2020–22), nine of the ten largest wildfires, and the warmest 20-year period in recorded history. While many changes are gradual, extreme conditions beyond historical ranges are already affecting every part of the state. Even greater changes are expected in the future, compounding long-term historical problems that plague freshwater ecosystems (Moore and Schindler et al. 2022).

To help guide the development of tools and strategies for adaptation to climate change, we present a simple conceptual model that highlights the major climate vulnerabilities in California's freshwater ecosystems (Figure A1). Note that there are many conceptual models for climate change that describe the expected effects. For example, Staudinger et al. (2021) provide a generalized conceptual model on climate effects in aquatic ecosystems. For California, Herbold et al. (2022) and IEP (2022a and 2022b) provide conceptual models for climate change effects on multiple freshwater ecosystems including tidal wetlands, floodplains, and brackish marsh, focusing on issues for target species groups. There are also good narrative conceptual models for species groups such as salmonids (Herbold et al. 2018) and summaries of how climate may affect water infrastructure, management, and ecological services (Chang and Bonnette 2016; Weiskopf et al. 2020). We used several of these efforts to develop a generalized model that would be relevant to multiple regions of California.

FIGURE A1
Cascading effects of climate change on California's ecosystems



NOTES: The upper tier shows the three major categories of climate effects, and the lower tiers represent the corresponding ecosystem effects on habitats and species. See text for details.

Climate change drivers: As summarized in Figure A1, climate change results in three major changes that have cascading effects on California's freshwater ecosystems: 1) higher temperatures; 2) sea level rise; and 3) changes in flow (Hanak et al. 2018).

The most prominent effect of global climate change is a rise in temperature. During the 21st century, statewide air temperatures have already increased significantly (Herbold et al. 2022)—this trend is expected to continue with an additional increase of 1.5 to 4 degrees Celsius by 2100 (Cayan et al. 2008; Cloern et al. 2011). Consistent with these expectations, 2023 was the warmest year since global records began in 1850 (NOAA 2023).

Since air temperatures are a primary driver of water temperatures, there have been corresponding temperature increases in many aquatic ecosystems (e.g., Bashevkin et al. 2022). In general, the effects are expected to be greatest in shallow-water ecosystems, where thermal contact between air and water is maximized. The effects of climate change on water temperature have been modeled for several aquatic ecosystems in California, showing significant increases (e.g., Cloern et al. 2011). Increased water temperature alone, even without considering other habitat changes, can lead to reductions in the windows of opportunity for species to complete critical life stage transitions, such as maturation and spawning, and may increase the periods of time that species are working to persist in physiologically stressful, if not lethal, conditions (e.g., Brown et al. 2016). These temperature increases are compounded by reductions in flow (below).

Sea level rise is a direct consequence of increasing temperature, leading to an increase in ocean volume through thermal expansion and the melting of land ice. Regional model projections suggest major increases in California sea levels in coastal areas—for example, Cloern et al. (2011) modeled increases of one meter or more at the Golden Gate Bridge by 2100. Estuarine and coastal freshwater ecosystems may be especially vulnerable.

Flow changes from climate change are an additional major concern for freshwater ecosystems (Hanak et al. 2018; Mount et al. 2023b). Variation in precipitation is common, which results in corresponding high variability in streamflow across years (Dettinger 2011). While climate change may not necessarily change average annual total precipitation in California, a prominent effect is an increase in the frequency and magnitude of "weather whiplash," involving alternation between extreme wet and extreme dry years (Hanak et al. 2018; Swain et al. 2018). This translates into more flow extremes, including destructive floods and extended low-flow conditions. As an example, in 2023 California experienced nine back-to-back atmospheric rivers, resulting in widespread damaging floods and near-record snowpack in the Sierra Nevada (NOAA 2023). This was preceded by the drought of 2020–22: the warmest and driest three-year period in recorded history (Mount et al. 2023a).

In addition, warmer storms lead to more rainfall in the mountains rather than snowfall (Mount et al. 2023b). The net result is increased rain-generated streamflow in winter, with higher peak flows and decreased snowmelt runoff in the spring. The effects of these changes are broad, with impacts on both ecosystems and infrastructure (Chang and Bonnette 2016), including the capacity to store cold water in reservoirs to regulate downstream water temperatures.

Habitat effects: Climate change will alter habitat conditions in freshwater ecosystems throughout the state (Hanak et al. 2018). First, some of the changes described above may destroy key habitats. Sea level rise may inundate coastal areas, changing or causing destruction of historical freshwater and brackish habitats. The combination of warmer temperatures and flow changes may also dry out shallow-water ecosystems, resulting in a complete loss of those resources. Finally, some freshwater ecosystems could be destroyed by extreme flow events (Swain et al. 2018) that erode the component habitats or inundate them with debris (e.g., mud from fire damage).

Likely the most prominent effect on freshwater ecosystems will be deteriorating habitat quality. Since flow is a defining characteristic of freshwater ecosystems, the previously described climate-induced flow changes will alter freshwater ecosystems across California. Habitat degradation may therefore occur from loss of flows that connect habitats for sustained periods of time, changes in substrate, increased salinity intrusion in estuaries, and more stagnant conditions that exacerbate poor water quality. Combined with increasing temperatures, the suitability of these ecosystems may also be degraded by aquatic heat waves, increases in aquatic weeds, harmful algal blooms, and introduced predators and competitors that are better adapted than native biota to these changed conditions.

The net effect of many of these changes will be a geographic shift in habitat zones. The regions with suitable habitat conditions such as temperature and salinity will shift in elevation or latitude. The ability of plants and animals to adapt to these shifts will be moderated by barriers, primarily human structures such as dams, levees, and roads, but also impassable natural geographic features (e.g., cliffs).

Species effects: Changes in habitat may affect many native aquatic species in multiple ways by causing higher metabolic stress, slower growth, reduced reproductive success, and higher mortality due to increased predation, competition, and disease (Karvonen et al. 2010: Staudinger et al. 2021). The pace of change will exceed the capacity of many native species to move or adapt through natural selection, resulting in lower population sizes, reduced species diversity due to local extirpation, or overwhelming competition from invasive species. In some instances, this will result in extinction, particularly for species adapted to a narrow range of conditions. Some native and introduced species will benefit from changing environmental conditions, affecting their distribution and abundance. The net effect of these changes will be the creation of "novel" ecosystems which have a substantially different structure and function than historical conditions and support new species assemblages, often involving a mix of native and non-native species (Moyle 2014).

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Appendix B. Approach Used to Develop Climate Adaptation Options for Freshwater Ecosystems

In the previous section, we summarized how climate change causes new vulnerabilities for California's freshwater ecosystems. Understanding these vulnerabilities and historical issues allowed us to develop lists of adaptation options tailored to address specific ecosystem stressors. Below we describe how we developed these options, including some of the major parameters. We sought to achieve the following in the strategies and tools:

- **Tailor to freshwater ecosystems.** The strategies and tools are tailored to all inland ecosystems of California—including rivers, streams, ponds, wetlands, vernal pools, and brackish 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 (Evans et al. 2016), 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., water diversion 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 (Evans et al. 2016; 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 and maintain 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).[1]

One of our first steps was to outline the expected impacts of climate change on California's freshwater ecosystems. We developed a generalized conceptual model that describes the vulnerabilities of species and habitats (See Section A). Each of the strategies and tools described below were chosen to address one or more of these vulnerabilities and related issues from long-term environmental stressors. For example, we developed management options that addressed habitat issues (*destruction, degradation, distribution shifts*) and species effects (*reduced abundance, reduced diversity, extinction, novel ecosystems*). We vetted and refined these management options through multiple workshops and interviews with scientific and technical experts and other stakeholders and reviewed multiple climate adaptation plans to expand the list of options (Appendix C below).

Expert workshops, presentations, and interviews:

- **State agencies:** California Department of Fish and Wildlife, California Department of Water Resources, State Water Resources Control Board, Sacramento–San Joaquin Delta Stewardship Council

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[1] Our approach is not unique—for example, the *US Climate Resilience Toolkit* 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. Similarly, the *Climate-Smart Conservation* process (Stein et al. 2014) advocates the development of a comprehensive set of conservation options (Figure 2, Step 4 in main report) that are subsequently screened (Figure 2, Step 5 in main report).

- **Federal agencies:** US Fish and Wildlife Service, National Marine Fisheries Service, Bureau of Reclamation
- **Academia:** UC Davis, UC Berkeley, San Francisco State University, Woods Hole Institute of Oceanography.
- **Environmental groups:** CalTrout, River Partners, The Nature Conservancy, National Audubon Society, American Rivers, Trout Unlimited
- **Local and regional water agencies:** Metropolitan Water District of Southern California, Valley Water, Sacramento Regional Sanitation
- **Additional groups:** Tribal representatives, farmers, Cramer Fish Sciences, Water Foundation

Examples of climate adaptation plans reviewed:

- **State plans:** California (California Climate Adaptation Strategy; Maven's Notebook 2024), Iowa (Poff et al. 2015) Wisconsin (Feiner et al. 2022), Florida (Florida Fish and Wildlife Commission 2016)
- **Federal agency plans:** US Fish and Wildlife Service (Lynch et al. 2021), US Geological Survey (Rahel and Lynch 2022)
- **International plans:** Food and Agriculture Organization (Brugere and De Young 2020), Scotland, International Union for Conservation of Nature, Australia (Davis et al. 2013), Canada (Kittel et al. 2011)
- **NGOs:** National Wildlife Federation (Stein et al. 2014); National Fish, Wildlife and Plants Climate Adaptation Partnership (2012)
- **Other sources:** Palmer et al. (2009), Poff et al. (2015), Evans et al. (2016), Moore and Schindler (2022)

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Appendix C. Climate Adaptation Strategies and Tools

The list of potential strategies and tools are summarized in Table C1 (Table 1 of the main report) and are discussed in detail below. The strategies and tools range from those commonly used today—such as suites of action to restore or improve existing habitat—to more experimental and controversial actions, such as assisted migration or genetic engineering. A total of 22 tools are included in our summary.

We identify two general strategies that correspond to the habitat and species tiers of the conceptual model (see Figure A1 above): **habitat support**, including actions to improve the abundance and quality of habitat for native species, and **species support**, including actions outside of habitat improvement that seek to improve resilience of vulnerable species. For **species support**, we describe three sub-strategies: **distribution support**, **population support**, and **genetic support.**

Some climate changes may be so extreme that they pass ecological or physical thresholds beyond which adaptation cannot feasibly prevent a loss of historic ecosystem functions (USGS 2023). Because of this issue, we include **contingency actions** as a third general strategy. Given the pace of climate and ecosystem change, there should be management options in the event of a complete loss of species.

Some tools that we describe below could be included under more than one strategy. We placed each tool under a single strategy to avoid redundancy. For each tool we provide a basic description, and list some of the implementation issues.

A key point is that ecosystem-based actions are most likely to benefit a broad suite of species and habitats across larger geographical areas. These types of actions are mostly contained within the **habitat support** strategy, while most of the other actions are focused on individual species. As will be discussed further, ecological risks and uncertainties tend to be higher for some of the most intrusive management approaches such as gene editing and population supplementation. The most intrusive tools are therefore identified within each strategy.

A generalized uncertainty that applies to all tools is that it is difficult to accurately predict the precise impacts of climate change on species and habitats (Staudinger et al. 2021). Existing climate models give a reasonable sense of the general trajectory of change, but climate effects are likely to be non-linear in aquatic ecosystems. They will fundamentally alter many of the species interactions, resulting in novel ecosystems and unexpected outcomes. In addition, human responses to climate change effects can and will alter those effects (for example, the choice between protecting areas from flooding due to sea level rise compared to allowing areas to flood).

In our view, implementation uncertainties should not be interpreted as an excuse to "do nothing," or ignore tools with higher risk and uncertainty. As described in the main document, a *portfolio* of tools is the most appropriate strategy. Innovation and experimentation is critical and will certainly involve accepting a higher level of risk. Research and development will therefore be urgently needed to help reduce risk and uncertainty for many tools.

Finally, we provide real-world examples of each tool, mostly from California. These are intended to allow readers to more easily understand how tools might be applied, the range of possible applications, and their feasibility. They are not intended as comprehensive examples of each tool.

TABLE C1
Management Toolbox

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 alley 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”

SOURCES: Developed by the authors.

Strategy 1: Habitat Support

This strategy includes actions that seek to improve the amount and condition of habitat for native species as well as habitat investments that anticipate future conditions. These represent the broadest and perhaps most powerful category of tools since they are most likely to benefit a wide range of native species. Most of these are in use today at some level, although several are more experimental and require further investigation to be used for climate adaptation.

Flow improvements

Flow is a defining need for freshwater ecosystems, making this foundational to our toolbox. As described in our Conceptual Model (Appendix A), flow regimes have been altered throughout the state, leading to a suite of environmental problems (Mount 1995; Grantham et al. 2020). Climate change will exacerbate the impacts of flow changes.

Potential improvements include flow augmentation, the creation of a more natural flow regime (Grantham et al. 2020), and correcting habitat issues. These actions may therefore require access to water rights, and sometimes engineering new water management infrastructure (e.g., Maven's Notebook 2024). Where there is existing water infrastructure, the quantity and timing of flows could be managed through dam releases, pumping, groundwater programs, wastewater recycling, and changes in the amount and timing of water diversions. However, under some circumstances new facilities such as pipelines, wells, and pumps may be needed to augment control flows within desired ranges.

As will be described below in the **habitat diversity and processes** and **dispersal support** sections, many rivers have been radically altered by channelization or other modifications. To realize the benefits of increased flows, addressing physical habitat conditions will be required. These could include physical restoration of the stream channel, the addition of gravels, boulders, or large wood, and the removal of levees to reconnect rivers with their floodplains. Channel improvements including fixing connectivity issues may also be needed to provide a suitable flow regime. In many locations, the waterways have been radically altered by channelization or historic mining activities—remediation of these issues can help to improve the efficacy of flows intended to improve ecosystem conditions (Mount et al 2019).

Implementation issues

There are numerous competing demands for water in California, making it extremely challenging to secure water rights for the environment (Mount et al. 2023). Existing laws to ensure adequate water for the environment are inconsistently applied. Climate change will potentially make conflicts over environmental water even worse, especially considering increasing weather whiplash (Swain et al. 2018; Hanak et al. 2018). In addition, existing infrastructure may not be suitable or even available to support some of the flow needs. For example, isolated wetlands, streams, ponds, and vernal pools generally do not have the infrastructure available to augment freshwater inputs.

Securing water for the environment will likely require the reallocation of water from consumptive uses, which will require new policies and the potential modification of water rights. Channels that require restoration to ensure a more natural flow regime will also require a suite of permits. Finally, long-term monitoring and adaptive management will be required to ensure that water allocated to the environment is achieving its desired benefits.

If there are other major limiting habitat issues (e.g., contaminants, habitat loss, invasive species)—a common situation in California—restoring flows to historical levels may still be insufficient to restore or maintain some freshwater ecosystems.

Case examples

Foothill yellow-legged frog flows. More natural flow regimes have been implemented in several California locations to better match the life-cycle needs of Foothill yellow-legged frogs (Yarnell 2012).

San Joaquin River environmental flows. Environmental flows have been established in the lower San Joaquin River to support fish and other species. The program includes the appointment of a manager to oversee flow actions (Meadows 2023a).

Mono Lake levels. In a groundbreaking case, the State Water Resources Control Board ruled in Decision 1631 (1994) (Salton Sea Restoration Project) that water levels must be maintained in Mono Lake, an iconic habitat for invertebrates and shorebirds. Lake levels depend on inputs from the local watershed, which had been reduced by water exports.

Salton Sea Species Conservation Habitat Project. A network of managed ponds and wetlands is being created at the base of the Salton Sea—local flow improvements (through a new water diversion facility) are being constructed to maintain suitable salinities.

Substrate improvements

Healthy rivers and streams rely on the transport of sediment to create and sustain spawning, rearing, and foraging habitats for aquatic species (Wampler 2012), and to support the recruitment of riparian vegetation. Substrates for fish, invertebrates, and plants can be degraded by climate-related events (runoff of debris from fire scars, debris flow floods, extended drought); dams that block sediment transport; channelization that leads to scouring; or changes in flow regime that reduce or eliminate sediment transport. Substrate quality in rivers and streams can be improved through supplementation and dam modification or removal, and watershed management of sediments (Kondolf and Matthews 1991). Dam removal can reinitiate the historic sediment transport processes needed to sustain riverine ecosystems but is a particularly challenging type of project (see below).

Where dam removal is not feasible or timely, it is sometimes possible to develop facilities to transport sediment past the dams into the downstream channel, although these are rarely economically feasible. More commonly, mined material is trucked and placed into sediment-starved rivers and streams (Kondolf and Matthews 1991; Bunte 2004). An additional practice is to mechanically disturb (“rip”) channels that receive insufficient sediments. Channels below dams often become “armored” when their fine sediments are washed away leaving only large cobbles in the channels, which are not suitable substrates for the spawning of species like salmon and trout. Vigorous ripping of armored riffles is sometimes used to break up the hard surface, freeing finer sediments below.

Below dams, removal of riprap from channel banks and reconnection of riverine habitats with floodplain and side channels can remobilize off-channel sediments that were previously trapped. Less common approaches include dredging river pools where sediments have accumulated and constructing sediment traps.

Implementation issues

While it is widely recognized that dams block sediment supply to rivers and streams (Mount 1995), they are exceptionally difficult to remove because of many legal, economic, social, and ecological issues (Kondolf and Matthews 1991). As an instructive recent example, the removal of four dams on the Klamath River (see example below) took over 20 years to implement. Many impoundments occur in watersheds with a history of mining, so the sediments contained behind the dams have become contaminated with metals and nutrients, making them less suitable for habitat restoration and creating downstream water quality issues.

Direct sediment placement and gravel ripping only represent short-term solutions (Kondolf and Matthews 1991). Moreover, sediment placement is labor intensive, and requires an economical supply of clean sediments at a location not too far away from the restoration site. These approaches also can create permitting challenges, especially since there are typically environmental impacts.

Case examples

Upper Sacramento River. The Upper Sacramento River Anadromous Fish Habitat Restoration Program has conducted numerous substrate projects in the Sacramento River and its tributaries. The projects include gravel placement in locations below Keswick Dam, and side channel construction in the Feather River and mainstem Sacramento River.

Klamath River dam removal. This high-profile project is designed to restore connectivity between the upper and lower Klamath River watershed by removing four dams (Iron Gate, Copco 1, Copco 2, and JC Boyle) and opening up fish passage to over 400 miles of potential spawning and rearing habitat.

Nationwide dam removal. There have been numerous dam removal projects across the country. American Rivers has catalogued and mapped these efforts in an extensive database.

Increased food

Food supply in aquatic systems includes plankton, invertebrates, plants, and microbes (Thompson et al. 2012; NOAA 2019). Many of the previously described habitat alterations (dams, levees, urbanization) have directly impacted how much food is available to support aquatic ecosystems, often creating substantial food limitations (Cordoleani et al. 2022). Climate change is expected to make this situation worse by destroying habitats and increasing bioenergetic costs from warmer temperatures (See Appendix B; Staudinger et al. 2021). Boosting food supply can therefore help species survive in a warming climate (Herbold et al. 2018).

Since more diverse and connected habitats often have higher productivity, habitat restoration is the most desirable approach to augment food supply in freshwater ecosystems. Example actions include improved flow regime (see above; Cross et al. 2011; Grantham et al. 2022), removal of levees and dams (see **substrate improvements** above), and restoration of productive, shallow-water habitats such as floodplains and wetlands (Bellmore et al. 2017; Also see **habitat diversity and processes** section below). Invasive species management (see below) may also be critical when trophic resources are shunted away from native biodiversity by introduced species.

Other approaches to enhance the food supply may be considered where habitat restoration is not immediately feasible, or when habitat restoration won't produce enough food for species to survive warmer temperatures. In food-limited systems, these include limited addition of nutrients via fertilizer or fish carcasses (Kiernan et al. 2010; Bellmore et al. 2017) and off-channel production (aquaculture) of invertebrates (see examples below). Upstream reservoirs can also be a potential source of food subsidies for novel river and stream ecosystems (Corline et al. 2023).

Implementation issues

Flow and habitat projects face numerous economic, cultural, legal, and engineering obstacles, making it challenging to achieve the necessary level of change to adequately support food webs in aquatic ecosystems. Invasive species are also an increasing challenge for habitat restoration projects—even well-designed aquatic restoration projects can be overrun with aquatic weeds and invasive animals, limiting their productivity for native species (e.g., Baxter et al. 2004; Bellmore et al. 2017). Moreover, temperatures may increase beyond the point where species can find enough food, even with high-quality habitats.

Additions of nutrients, carcasses, and off-channel subsidies are still highly experimental (but see rice field waterfowl example below), so the outcomes of these types of manipulations are inherently uncertain. Poorly designed or executed food supplementation projects could result in worse water quality in target waterways (harmful algal blooms, low oxygen). Food subsidies may also require a long-term commitment to expensive and labor-intensive actions.

Case examples

Habitat restoration. Many of the other case examples under the habitat support strategy could support improved food supply. In the flow improvements section (see above), these include the Mono Lake Levels, Salton Sea Species Conservation Habitat Project, and San Joaquin River Environmental Flows. Many of the nationwide dam removal projects described above (**Substrate Improvements**) should improve food conditions in downstream areas.

Carcass addition. Salmon carcasses act as a natural "fertilizer" in streams by increases in the biomass of periphyton and macroinvertebrates, resulting in more food for young fish (Bellmore et al. 2017). Adding salmon carcasses and pellets (i.e. pasteurized fishmeal) has been tested in numerous western streams as a tool to stimulate aquatic productivity and fishes, particularly salmonids (Kiernan et al. 2010). Management of sport and recreational harvest could also potentially help enhance the number of natural carcasses in rivers and streams.

Sacramento Deep Water Ship Channel fertilization. In heavily modified areas, nutrient deficiencies may limit the productivity of aquatic ecosystems. Experimental additions of nitrogen into Sacramento Deep Water Ship Channel have been tested to boost food web productivity in these freshwater tidal channels (Lenoch et al. 2021).

Rice field production of invertebrates. Fallow rice fields have been seasonally flooded for many years to support waterfowl on the Pacific Flyway—these managed areas provide resting habitat and generate large amounts of invertebrates for waterfowl (e.g., Dybala et al. 2017). Managed flooding is now a widespread and successful strategy for waterfowl habitat. In recent years, seasonally flooded rice fields have been tested as a supplemental source of invertebrates for the adjacent Sacramento River. Under pilot studies, riverside rice fields are flooded (after harvest) to grow invertebrates, mainly plankton and insects. The food-rich water is then discharged in the Sacramento River to support juvenile salmon rearing (Romero 2018).

Habitat diversity and processes

As described repeatedly in this report, many of California's freshwater ecosystems have been severely altered by human activities, resulting in a loss of habitat quality, diversity, and connectivity, as well as natural processes such as food web production and water circulation—key features that support resilience for California's freshwater ecosystems and native biota (See Section A). Increased climate volatility, with drought intensification and more severe winter storms, has the potential to further degrade habitat conditions. Habitat restoration projects are therefore essential tools to create and maintain high-quality habitat (Malhi et al. 2020; McElwee 2021). Habitat restoration has become relatively common across multiple habitats and regions of the state, with examples for estuaries, lakes, rivers, streams, wetlands, floodplains, and springs (e.g., EcoAtlas). However, much more extensive restoration will be needed to support aquatic ecosystems because of the compounding effects of climate change (Moore and Schindler 2022).

One of the most important components of habitat diversity is the restoration of connectivity to landscapes. Levees, dams, roads, and other structures severely limit movements of organisms and processes such as sediment transport, food web subsidies, and circulation (See Distribution section below). Reconnecting these landscape components is therefore an extremely high-value approach to restoring habitats and is essential for supporting the genetic diversity of populations.

Implementation issues

Most, if not all, the issues described for other tools within the **Habitat support strategy** apply here as well. Specifically, there are numerous legal, policy, economic, cultural, ethical, and ecological issues that can be an obstacle for these projects.

Case examples

Nationwide dam removal. See description above.

Klamath River dam removals. See description above.

Habitat restoration. See description above.

San Francisco Estuary tidal wetlands restoration. The San Francisco Estuary, including its various bays and upstream tidal delta, has been greatly simplified by dredging, channelization, riprap, and diking and draining wetlands (Brown 2003). This is particularly true for tidal wetlands, which have largely been lost in most areas. To correct this issue, there have been numerous projects to restore wetlands and mitigate anthropogenic effects in the system (EcoAtlas). Note that the EcoAtlas resource also provides examples of wetlands restoration from regions throughout the state.

Yolo Bypass restoration. See description below.

Temperature and water quality improvements

In addition to some of the habitat effects described in previous sections, human activities have caused temperature and water quality conditions to deteriorate (see Appendix A). Long-term habitat loss has resulted in less shade cover (e.g., riparian trees, emergent native vegetation), resulting in warmer conditions. Water quality in freshwater ecosystems is also exacerbated by nutrient inputs in the form of fertilizers, sediments, and contaminants (Brooks et al. 2012; Hanak and Chappelle 2015). Regional warming from climate change and associated flow and habitat effects will further increase water temperatures (Staudinger et al. 2021), and trigger more frequent adverse water quality conditions (e.g., anoxic conditions, harmful algal blooms).

Restoration of habitats in riparian areas as described in the previous section therefore represents an important tool to support freshwater ecosystems. However, other measures may be needed when habitat restoration is neither feasible nor sufficient to address extreme climate effects. Potential additional options to mitigate temperatures include installation of natural or artificial shade, and colder flow inputs from reservoirs or groundwater.

Riparian restoration is a well-recognized approach to moderate water temperatures by enhancing shade in channel margin habitat (Justice et al. 2017). An added benefit is that they can create a buffer zone to reduce contaminant inputs to waterways (see below). In areas that do not historically have major riparian zones (e.g., isolated springs), there may be situations where tree-planting is a desirable approach to maintain cooler water temperatures.

Engineered shade structure might be possible in smaller ecosystems (e.g., springs) or in a section of an ecosystem designed as a natural temperature refuge. Such canopies are commonly used in agriculture, particularly nurseries. In California, shade structures are also frequently used in fish hatcheries. Floating shade balls have also been used in California water supply reservoirs to reduce evaporative water loss and to maintain water quality (Cassella 2019; Krosofsky 2021).

Cold-water releases from dams are also used to maintain cooler conditions in downstream waterways, typically to protect trout and salmon. Deep reservoirs commonly stratify during the summer, with less dense warm water at the surface and dense, cold water deeper in the reservoir (the latter is often referred to as the “cold-water pool”). In some reservoirs, temperature-control devices are able to tap into water from different depths to manage downstream temperatures (e.g., Meadows 2023b; Maven's Notebook 2024) to meet regulatory requirements to protect downstream fishes (e.g., USBR 2023).

In some ecosystems, seeps and springs from groundwater already provide a source of cold water. Even in the desert, springs can be a vital source of high-quality water to sustain ecosystems (NPS 2024). Where springs are not already present, groundwater pumping facilities could be considered as a potential tool to provide cool water. These inputs require abundant and sustainable groundwater resources, which is often not the case in California (Hanak et al. 2017).

Nutrient management can mitigate water quality issues that cannot be fully addressed through habitat restoration. Municipal, industrial, and agricultural wastewater treatment facilities are a common approach to reduce nitrogen and phosphorus loading in aquatic ecosystems (Water Education Foundation 2023). Also, regional land use and air management are common approaches to controlling inputs of nutrient-rich runoff and aerial inputs into aquatic ecosystems. The State Water Boards use *Total Maximum Daily Load* criteria for the management of land use and air inputs across the state (Water Boards 2024).

For waterways that already have a high level of nutrients, sediment removal may be used to remove long-term accumulations. Capping or sediment treatment may also be feasible in some locations. Also, mechanical aeration (air compressors or paddles) or flow inputs may be used to try and keep waterways from becoming too stagnant, avoiding low oxygen levels and algal blooms. Sediment removal via suction or mechanical dredging has historically been used in many locations in the US as a restoration technique (EPA 1981). Finally, invasive species control (see section immediately below) can also help reduce eutrophication issues. For example, invasive carp disturb sediments, thereby moving nutrients into the water column.

Most of the state has issues with contamination (Hanak and Chappelle 2015). Specifically, an estimated 95 percent of California's rivers, lakes, bays, and wetlands are plagued by pesticides, metals, pathogens, acids, and trash, as a result of the harmful effects of human activities. Salt inputs are an additional major issue that affects aquatic ecosystems, as well as human populations (Hanak and Chappelle 2015). Remediating these issues often requires extensive land, air, and water management regulation (see TMDL above). California has over 900 wastewater treatment plants that reduce inputs of municipal and industrial contaminants into the state's waterways (Water Education Foundation 2013).

Implementation issues

Managing cold-water inputs from reservoirs and groundwater may not be technically or economically feasible in many regions of the state, particularly in remote areas. Ongoing and future changes in inflow from climate change may further erode cold-water resources. Even when available, cold-water inputs may not persist downstream as waters warm due to ambient air temperatures. Groundwater is also heavily impacted by pumping, creating unsustainable conditions in many regions (Hanak et al. 2017). The drawdown of groundwater in many parts of the state has eliminated the connection between rivers and groundwater, including the temperature benefits. The recently released *California Salmon Strategy* (Maven's Notebook 2024) recognizes the need to sustainably manage groundwater to support river temperatures as well as flow.

Habitat restoration such as tree planting may not provide sufficient shade to reduce water temperatures (e.g., lakes, estuaries, and wide rivers). Moreover, planting trees in areas that did not historically have riparian zones could substantially alter the structure and function of those ecosystems, resulting in an extra water burden because of riparian vegetative growth. Shade structures would not have a similar water burden, but would frequently be undesirable due to aesthetic, economic, and ecological consequences. Shade balls may have similar concerns—for example, their use was abandoned in a California reservoir for economic reasons (Krosofsky 2021).

Finally, managing water quality is also frequently very expensive. For example, every year roughly $10 billion is spent on water pollution control in California, with the vast majority for site-specific sources of pollution (known as "point sources") such as wastewater treatment (Hanak and Chappelle 2015).

Case examples

Riparian habitat projects. There are many examples of riparian habitat projects in California that have temperature and water quality benefits. For example, River Partners describe a suite of impressive projects across the state including the Sacramento River, San Joaquin River, San Diego Bay National Wildlife Refuge River, and San Dieguito Creek.

Shasta Reservoir temperature control device. Winter-run Chinook salmon require cold water in the Sacramento River, particularly during the summer when their eggs are incubating. In 1997, the US Bureau of Reclamation installed a structure on the face of Shasta Dam to regulate the temperature of releases (Meadows 2023b). The series of gates can be opened and closed, allowing managers to optimize temperature releases and management of the cold-water pool. However, this system is less successful in drought years, when the cold-water pool in Shasta Dam is depleted.

Lake Elsinore phosphorus control. Lake Elsinore suffers from periodic harmful algal blooms, a product of stagnant conditions and phosphorus inputs from its sediments. Nanobubbles are being tested to oxygenate the water and decrease the amount of phosphorus released from bottom of the lake to reduce harmful algae blooms (Stormwater Solutions 2023).

Santa Ana River salinity management. The Santa Ana Regional Interceptor pipeline diverts high-saline waste (brine from desalting facilities) to special treatment plants to reduce water quality impacts in the watershed.

Regional wastewater treatment plant upgrades. In the Delta, one of the biggest regional changes in water treatment is the EchoWater project upgrade by RegionalSan in Sacramento to help reduce nitrogen inputs. This project follows a similar engineering upgrade to Stockton Wastewater Treatment Plant, which led to improved water quality (Beck et al. 2018).

Floating shade balls. Floating shade balls were tested in a large southern California reservoir for water conservation and water quality. A total of approximately 96 million floating balls were placed in the Los Angeles Reservoir. Although the project appears to have helped reduce losses due to evaporation, the effort was eventually stopped because of high costs (Krosofsky 2021).

Lake Tahoe Total Maximum Daily Load (TMDL). Lake Tahoe's famous water clarity is threatened by inputs of nutrients (nitrogen and phosphorus) and sediment. The lake is currently protected by a Total Maximum Daily Load (TMDL) plan, which was adopted by the states of California and Nevada and approved by EPA in 2011 (EPA 2023). The plan guides restoration efforts that seek to reduce several sources of pollutants. The effort has resulted in many land and water management efforts by state and local governments.

Pinto Lake watershed management. Pinto Lake in central California has suffered from periodic harmful algal blooms, resulting in fish kills, bird deaths, and other ecosystem effects. A suite of actions including in-lake treatment, carp control, erosion control, and irrigation management have been used to improve water quality conditions (SWRCB 2013; 2018).

Invasive species control

California's freshwater ecosystems already face major challenges from invasive species including aquatic weeds, invertebrates, fish, and mammals (Cohen and Carlton 1998). Climate change will make many ecosystems even more suitable for invasive species through altered flow regimes and increased temperatures (Moyle et al. 2013; Finch et al. 2021; Staudinger et al. 2021).

The most cost-effective approach to invasive species control is avoiding invasions in the first place (Kurth 2017). Common approaches include border inspections; regulation of ballast water, pet and aquarium trades; as well as public education about the risks of new introductions.

For established invasive species, traditional approaches to control include mechanical removal (e.g., harvesting) or chemical treatment with herbicides, pesticides, or piscicides (Simberloff 2022). Biocontrol is increasingly being used in aquatic ecosystems via the introduction of grazers that will target invaders (Conrad et al. 2023).

More futuristic technologies have been developed for terrestrial invaders, and some of these approaches could be an option for selected aquatic invaders (Simberloff 2022). Autonomous or assisted robotics could potentially make mechanical removal more cost and labor efficient—there have been recent tests of these technologies in California for aquatic plants (e.g., "Pixiedrone").

Pheromones have long been used in managing invasive insects, especially moths (Simberloff 2022). These techniques are used to disrupt mating, or to attract invaders to a location where they can be easily killed. Research and development are also underway for aquatic species, such as the development of pheromones to attract invasive Great Lake lampreys.

Given progress in genetics, novel approaches are being considered to help deter invasive species (Simberloff 2022; van Oppen and Coleman 2022). Methods of particular interest, alone or in various combinations, are gene-silencing, RNA-guided gene drives, and transgenetics. All of these methods are highly controversial and require substantial research and development (Wade 2015). For example, gene drives are an experimental approach to decimate populations of unwanted species. Adverse mutations (e.g., sterility) are introduced into a pest species in a way that the adverse mutation will spread quickly through the population (Bier 2022).

Finally, it is essential that managers be able to detect the presence of non-native species in an ecosystem before they become invasive and cause harm. There have been considerable advances in environmental DNA (eDNA), that can detect and analyze DNA shed by invasive species in the environment. As studies in the Great Lakes region have shown, this technology—essential for early detection—can even reveal the genetic structure and diversity of invasive species, allowing for more precise management (Andres et al. 2023).

Implementation issues

The success of managing aquatic invasive species has been mixed at best (Williams and Grosholz 2008; Simberloff 2022; Conrad et al. 2023). Projects to control invasive freshwater fishes have sometimes succeeded, but they require a challenging commitment to long-term management (Simberloff 2022). Although invasive aquatic weeds are likely the most common group targeted for control, successful control of invasive freshwater plants is uncommon (e.g., Conrad et al. 2023). Invasive invertebrates have rarely been controlled for long periods, and there have been unexpected population rebounds to even higher levels, such as in large-scale green crab removal efforts in California (Grosholz et al. 2021).

Invasive species measures can also generate major environmental, ethical, and social issues. This is particularly true for the most experimental approaches such as genetic methods and robotics. Because gene drives are so controversial and novel, this approach remains focused in laboratory settings (Bier 2022). However, even "conventional" invasive species control methods have major issues. For example, mechanical removal or harvest may result in a major disturbance of the environment, causing mortality or stress for sensitive species. Chemical treatment may also have undesirable environmental effects on other parts of the ecosystem, including human risks (Cailteux 2001).

Case examples

Biological control of aquatic weeds. Alligator weed (*Alternanthera philoxeroides*) is a highly invasive species that it a common invader in the southeastern United States. It was first detected in the Sacramento–San Joaquin Delta in 2017 and is now expanding its distribution (Conrad et al. 2023). The most successful and widely used biocontrol method for Alligator weed is Alligator weed flea beetle (*Agasicles hygrophila*), which has been released for biocontrol in the United States, Australia, China, Thailand, and New Zealand. However, the effectiveness of this method is limited because the beetle does not survive in cold temperatures (Harms and Cronin 2020). Three Alligator weed biological control agents have been approved for release in the southeastern United States but are not yet permitted for release in the Delta (Conrad et al. 2023).

Lake Davis rotenone treatment. For decades, the California Department of Fish and Wildlife Service has used the chemical rotenone to: (a) eradicate unwanted exotic fishes, (b) control fish diseases, (c) restore populations of threatened or endangered fishes, and (d) increase populations of desirable game fishes (Finlayson et al. 2001). The highest-profile example is the 1997 use of rotenone to kill the invasive Northern pike (*Esox Lucius*) in Lake Davis, a reservoir in the headwaters of the Feather River. The invasion from this efficient predator threatened the entire Sacramento Valley watershed and downstream Delta (Lee 2001). The treatment was relatively successful at eliminating Northern Pike, although an additional treatment was needed in 2007 after additional fish were detected.

Robotics. Although Lake Tahoe is famous for its water clarity, this fragile ecosystem is threatened by invasive plants and trash (Keep Tahoe Blue 2023). One of the worst locations is the Tahoe Keys, where the marina is covered with aquatic weeds—Eurasian watermilfoil (*Myriophyllum spicatum*) and Curly-leaf pondweed (*Potamogeton crispus*) (Tahoe Keys Weeds). Keep Tahoe Blue is currently testing a robotic device (Pixiedrone) to harvest and remove these plants.

Gene drive control of pikeminnow. Cal Poly Humboldt researchers are currently researching the potential uses of gene drive technology to rid the Eel River of invasive Sacramento pikeminnow (*Ptychocheilus grandis)*, a predator on local salmon populations (Cal Poly Humboldt). A CalTrout-funded laboratory study will examine whether gene drives could be used to select against the female pikeminnow, disrupting the reproduction of the species.

Use of focused management zones

Since many of California's freshwater ecosystems are vast and resources are often limited, it may not be feasible to protect or improve all parts of every freshwater ecosystem. Focused management zones may be used to try and protect priority regions that support as many species and habitat types as possible (Moyle 2023). The basic idea is to prioritize key regions of each watershed to focus the maximum level of habitat management, including flow augmentations and habitat restoration. This approach is not an excuse to abandon other regions of these important freshwater ecosystems; rather, focused zones are a strategic way to prioritize scarce resources and maintain at least some areas with high-quality habitat.

Implementation issues

The selection of priority areas will be particularly complicated since there are so many potential issues, including ecological benefits, environmental impacts, legal constraints, recreation, and cultural needs. Of particular concern is that focused management in a smaller area may disconnect it from other habitats or populations that would be needed to maintain resiliency. As mentioned above, there is also a risk that Focused Management Zones could be used as an excuse to ignore environmental problems in other parts of the ecosystem.

Case examples

Habitat restoration. Many of the case examples under the habitat support strategy are focused on specific regions of freshwater ecosystems. These include most of the examples under habitat diversity and processes, temperature and water quality improvements, and invasive species control.

Salton Sea Species Conservation Habitat Project. A Focused Management Zone has been created to provide high-quality habitat in a key portion of the Salton Sea. A network of managed ponds and wetlands is being created at the base of the Salton Sea and relies on local flow improvements (through a new water-diversion facility) to maintain suitable salinities.

Strategy 2: Species support

Habitat Support, described in the previous strategy, is essential to improving the resiliency of freshwater populations. For many species, multiple factors make it difficult to rebuild resiliency quickly, particularly considering low population size, long-term habitat issues, and the rapid pace of change in climate and habitat. In these cases, special actions may be needed beyond habitat improvement to both protect species and rebuild population size and genetic diversity. These are organized into three general groups: distribution support, population support, and enhanced genetics and diversity.

Distribution support

Distribution support represents actions that help species overcome barriers to dispersal and migration—this includes anticipating where migration or dispersal will be needed to maintain these populations under future conditions. Barrier removal (e.g., dams, levees) was described in the previous section and represents a high-value approach to improve dispersal and connectivity for aquatic species. Below we also cover tools for locations where no barriers exist (or have been removed), and where barrier removal is not yet feasible.

Some of these tools are already in use, while several need future study and experimentation. These tools are listed roughly in order of the magnitude of management intervention.

Planning for range shifts

Under the best of circumstances, mobile species that are not impeded by barriers (dams, roads, cities, levees) should be able to migrate along waterways in concert with shifting climate and environmental zones. Some of these shifts may be relatively small (e.g., newly inundated areas from sea level rise), while others may be expansive. Managers can identify the added range of these species and the needed support for migration. This tool includes “anticipatory adaptive policy planning,” where new protections or policies are added to protect expected range (Markham 2023). Additional measures may include habitat restoration in the expected zone of range expansion.

Implementation issues

Not surprisingly, the expected range expansion for species can be difficult to predict (Markham 2023). Climate change is expected to have nonlinear effects on habitat conditions and ecological interactions, so the timing and location of potential range expansions are not always clear. In some cases, these barriers may conversely help protect some areas from species invasions.

There are also numerous economic, ecological, and cultural issues with this tool since range expansions may move species into regions dominated by other land uses and species assemblages. Similarly, it may be challenging to develop anticipatory policies—if species have not yet arrived in a new region, typical protections such as endangered species laws may not yet apply. Finally, habitat projects within the expanded range of populations face all the implementation issues listed above for **Habitat support**.

Case examples

Safe Harbor Agreements. In recognition of potential conflicts when species range expands into private property, programs have been developed to encourage landowners to support conservation objectives. Safe Harbor Agreements have been created by California and the federal government. The California State Safe Harbor Agreement (SHA) Program Act (Fish & G. Code, §§ 2089.2-2089.25) is a voluntary program that encourages private landowners to manage for the net conservation benefit of vulnerable species. Landowners agreeing to this program receive authorization for incidental take of vulnerable species. This program is consistent with an analogous federal program.

Bay Area Conservation Planning. The San Francisco Bay Area's diverse habitats (e.g., wildlife corridors, habitat connectivity, rangelands, riparian areas, baylands) are increasingly threatened by climate change, which compounds a litany of long-term environmental issues. *Conservation Lands Network 2.0*, a regional conservation strategy for the San Francisco Bay Area, was developed by a broad group of experts and regional interests to address current and future needs (Bay Area Open Space Council 2019). With emphasis on climate planning, the plan guides strategic investments in land acquisition, stewardship, and other conservation actions.

Helping species access historical habitat

Where barriers to migration occur, biota will need assistance in reaching historic habitat that is more resilient to climate change (NOAA 2021). In addition, barriers can cause isolation of populations, reducing gene flow and increasing the risk of extinction due to inbreeding. Overcoming barriers includes construction of passage structures, improving habitat connectivity through dam and culvert removal, removing barriers between habitats (e.g., connections to wetlands and floodplains), transporting individuals (e.g., migrating spawners) past dams to upstream cold-water habitat, and transporting downstream migrants (e.g., young salmon) past unsuitable areas (reservoirs, high temperature zones: Lusardi and Moyle 2017). This approach also includes transporting plants, invertebrates, fish, and mammals from remnant populations and reestablishing them in their historical habitat. The recently released *California Salmon Strategy* includes examples of each of these approaches (Maven's Notebook 2024).

Implementation issues

Dam removal is particularly challenging, generally taking decades to implement because of economic, technical, ecological, and social issues (see above). The slow pace of planning and construction for these types of projects does not offer immediate relief for struggling populations. In many cases, these reservoirs serve critical water supply, flood, and recreation needs, so removal may not be realistic unless the original functions of the dam are severely degraded or outdated. Removal of barriers and levees to improve habitat connectivity can face similar challenges.

Passage structures are commonly very expensive to build and may not be feasible for some of the tallest dam structures. Moreover, passage structures may not be very effective except for a smaller number of highly mobile species in freshwater ecosystems (e.g., salmonids). Even if passage is possible, species may face huge upstream reservoirs, which may not be readily passable for upstream or downstream migrants that are adapted to riverine habitat. Hence, projects may require both upstream and downstream facilities to move both adults and juveniles (NOAA 2021; Lusardi and Moyle 2017).

There are many potential issues with dispersal support that need to be considered (Lusardi and Moyle 2017), so guidelines have been developed for potential projects (George et al. 2009). Physically moving species can be stressful and may require frequent intervention (NOAA 2021). This approach can require an expensive and labor-intensive commitment to long-term migration support.

Case examples

Klamath dam removals. Four dams on the Klamath River have blocked salmon and steelhead trout from reaching more than 400 miles of habitat, encroached on Indigenous culture, and harmed water quality for people and wildlife (American Rivers 2023). Removal of the four dams in 2023 and 2024 represents the largest such project in US history.

San Clemente dam removal. The San Clemente Dam on the Carmel River historically blocked steelhead trout migration and impacted downstream habitat quality and processes. After the dam was declared unsafe, it was removed to allow the reestablishment of the Carmel River as a free-flowing stream. Additional habitat restoration was required to support downstream habitat quality.

Additional dam removals. As part of the recent *California Salmon Strategy* (Maven's Notebook 2024), Governor Newsom has promised to fast-track the removal of dams from Northern California to Southern California (Beam 2024). These include dams along the Eel River, Malibu Creek, and a tributary to the Ventura River.

Yolo Bypass floodplain. The Yolo Bypass is one of the Sacramento Valley's primary fish nursery areas and migration corridors and is a source of food for the downstream San Francisco Estuary (Sommer et al. 2001). However, its Fremont Weir structure is poorly connected with the Sacramento River, limiting access for fish to this critical habitat and reducing floodplain food exports to the San Francisco Estuary. The Fremont Weir project is being constructed to improve this connectivity and enhance upstream migration of salmon, trout, and sturgeon (USBR and DWR 2019). Additional managed flooding projects are recommended as part of the *California Salmon Strategy* (Maven's Notebook 2024).

Beaver reintroduction. Beavers are well-known ecosystem engineers—their dams help to slow streamflow, enhance groundwater recharge, and encourage wetlands. After being extirpated from much of their range, they are gradually being reintroduced into their historical habitat. A recent example of this is the reintroduction of beavers into a 2,325-acre valley in Plumas County, part of the traditional lands of the Mountain Maidu people (Bartlett 2023). Additional projects are planned as part of the *California Salmon Strategy* (Maven's Notebook 2024).

Winter-run Chinook salmon reintroductions. The Battle Creek project (CDFW 2016) is seeking to reintroduce winter-run Chinook salmon to reliable cold-water habitat within the Battle Creek watershed. 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; Maven's Notebook 2024).

Fish ladders. California's landscape has numerous barriers to fish passage throughout the state. Passage structures have been constructed in many watersheds that can pass at least some species. Passage issues and structures are catalogued in the CDFW Fish Passage Database (CDFW). The recent *California Salmon Strategy* (Maven's Notebook 2024) identifies many locations that will be targeted for fish passage facilities.

Fish cannons. As noted in the previous example, California has many fish passage barriers, making it expensive and challenging to construct traditional fish ladders. A relatively recent technology is the fish cannon: portable and relatively inexpensive pneumatic tubes that may help salmon and other migratory fishes move above dams and other barriers (Garavelli et al. 2019). Initial tests of the technology appear promising, especially when combined with systems to attract migratory fish to a central location. Videos of this unusual technology have generated viral interest on the internet (Daley 2019).

Assisting migration to new geographic ranges

Where climate change makes habitat conditions unsuitable throughout the current range of a species, an option is to transplant species outside their historical range to locations where temperatures and other conditions are suitable (Camacho 2010; Twardek et al. 2023). *Assisted migration* is an approach to avoid extinction by intentionally moving species to areas where the species has never existed. The technique—also called translocation—involves moving seedings, embryos, juveniles, or adults to totally new regions. This process may also involve additional work in the new habitat to make conditions more suitable for colonization of the transplanted species.

Assisted migration has been used for decades to expand sport fishing opportunities in various parts of the state (Dill and Cordone 1997). Unintentional introductions have also been common (see Invasive Species section above).

This climate change adaptation tool has already received substantial attention for terrestrial species, leading to the development of policies and guidelines for these projects (e.g., Williams and Dumroese 2013). Notably, USFWS (2022) has developed a new rule to make it easier for fish and wildlife managers to use assisted migration as a last resort for conservation.

Implementation issues

In the scientific literature there is notable hesitancy to implement assisted migration for conservation (Twardek et al. 2023). This is a result of the potential unknowns and risks associated with this activity, particularly with respect to possible negative impacts on habitats and resident biota. While assisted migration has been conducted experimentally and accidentally in California (e.g., Dill and Cordone 1997), this approach has not been commonly implemented as a conservation tactic. Consequently, there are substantial legal, policy, cultural, ethical, and ecological issues. To try and address these issues, there are guidance and policy documents to direct testing and implementation of assisted migration (George et al. 2009; Willimas and Dumroese 2013; USFWS 2022).

Case examples

Sacramento perch transplantation. Sacramento perch (*Archoplites interruptus*) are California's only native species of sunfish. They were once found in the Sacramento–San Joaquin Delta and Clear Lake in northern California, but have been displaced from their historical range because of competition from non-native sunfish, including bluegill and green sunfish (Moyle 2002). To support their conservation, they were transplanted to lakes in the eastern Sierra Nevada (Crowley Lake and Bridgeport Reservoir in Mono County). They appear to be thriving—the transplanted populations are sufficiently abundant that they support popular sport fisheries. Recently, the species was transplanted into San Diego County to support urban fishing and their conservation (CDFW 2023a).

Threespine stickleback transplantation. The endangered unarmored threespine stickleback (*Gasterosteus aculeatus*) lives in just a few streams in Santa Barbara. A recent project is designed to help the species survive in the face of current and future threats, particularly climate change (CDFW 2022). A first step in the project was to drain the introduction site, Bluff Lake Reserve, to eliminate all invasive fish. After Bluff Lake was refilled, more than 200 stickleback were captured with nets and traps at a nearby donor lake, then released into Bluff Lake. Additional translocations are planned for this site.

High Sierra lake stocking of rainbow trout. Rainbow trout (*Oncorhynchus mykiss*) is native to California, but its distribution has been expanded outside its native range to support recreational fishing (Dill and Cordone 1997; Moyle 2002). High Sierra lakes were historically fishless, but stocking of trout began in the late 1800s to support fisheries. The practice was expanded after World War II with aerial transplants supported by numerous hatcheries.

Trout stocking is a cautionary tale about the risks of assisted migration. While the trout and the mountain fisheries thrived, there were major ecological consequences since the fish ate native invertebrates and amphibians (CDFW 2018). Stocking of trout has been a major cause of the decline in Sierra Nevada yellow-legged frogs (*Rana sierrae*), which have vanished from approximately 92 percent of their historical habitat. Regional efforts are now underway to suspend stocking and remove trout from target lakes.

Refuges

Climate change is expected to severely reduce or eliminate habitat in some areas. To safeguard against extinction, special refuges may be needed to protect the most sensitive populations. In this relatively common conservation strategy, a portion of the target species are removed from their natural habitat and moved to a potentially safer, intensively managed location. These range from relatively natural constructed outdoor habitats within the historic range of the species to indoor conservation hatcheries, nurseries, and rearing facilities. Particularly for conservation hatcheries, there is a need to develop culture or nursery techniques so that the population can be relatively self-sustaining—i.e., reducing the need to remove more wild stock from the natural environment. The recent Salmon Resilience Strategy (Maven's Notebook 2024) proposes to construct four new conservation hatcheries to support salmonids.

Implementation issues

There are always major risks when species are removed from their natural habitats and maintained in wholly new habitat, so there are substantial legal, technical, ecological, and ethical issues with refuges (George et al. 2009). It is often hard to recreate suitable conditions in captive environments, so species may not reproduce or feed successfully. Refuge conditions and management practices may cause domestication, resulting in inbred stocks that are not suitable for future reintroductions. Capture and transfer of individuals to refuges can also deplete wild populations. In some cases, refuges create a reduced emphasis on other more important habitat measures in the wild. Numerous safeguards (e.g., genetics planning), extensive outreach, and long-term commitments to science and management are therefore needed for this tool.

Case examples

Spring-run salmon captive broodstock. Spring-run Chinook salmon are one of the most endangered aquatic species in California. The remnant wild populations in Deer Creek, Mill Creek, and Butte Creek have declined due to multiple factors, particularly recent heat waves and low-flow conditions. In 2023, the California Department of Fish and Wildlife and the National Oceanic and Atmospheric Administration took the unprecedented step of moving wild juvenile spring-run salmon to captivity to safeguard the fish against extinction (James 2023). The captive fish are currently being held at the UC Davis Center for Aquatic Biology and Aquaculture for the next two years, while managers decide where and if to release them.

Naturalized refuges for Devils Hole pupfish. The Devils Hole pupfish (*Cyprinodon diabolis*) is an endangered fish found only in Devils Hole, a spring-filled cavern close to the California-Nevada Border (Kolbert 2021). Since it naturally occurs at only this location, it is an especially vulnerable species. 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 taken from Devils Hole (Kolbert 2021).

Mojave Tui Chub naturalized refuges. Mohave tui chub (*Siphateles bicolor mohavensis*) is a small, rare native fish that has almost been eradicated from its native habitat in the Mohave River by interbreeding, habitat loss, and competition. The Mohave tui chub still exists as genetically pure populations in man-made habitats outside the river's course—in Mojave National Preserve, the Mohave Chub Spring, and Lake Tuendaeboth. Recent translocations to Morning Star Mine Pond and restoration of West Pond appear to have been successful—as of July 2018, five populations have been in existence for more than five years (National Park Service).

Population support

Addressing habitat issues, including distribution support, will not be sufficient to conserve some aquatic species, especially those with low population sizes, in the face of long-term environmental problems and climate change. Population support includes actions to bolster populations of native species to increase overall resiliency. Many of these are already in use in response to long-term decline in populations. These approaches are described roughly in increasing level of management intervention, with higher biological risks for the latter options.

Reduce sources of mortality

In addition to **Habitat and Distribution Support** (see above), populations harmed by climate change can be boosted by reducing other sources of mortality. These include stopping illegal harvest (i.e. poaching), stricter regulations in sport and commercial fisheries, reducing losses at water diversion structures, and measures to prevent excessive predation.

Many types of inland and coastal fishes and invertebrates support recreational harvest—the most popular include trout, salmon, striped bass, black bass, sturgeon, halibut, mussels, and crayfish (Moyle 2002). Hunting for water fowl is also a popular activity in many parts of the state. Inland harvest is protected by an extensive set of state regulations (CDFW 2023c). When these populations decline or harvest is considered excessive, the California Fish and Game Commission can modify the regulations or implement new ones.

Chinook salmon are the only commercially harvested species common to inland freshwater ecosystems (Moyle 2002). However, other species like Dungeness crabs (*Metacarcinus magister*) and Starry flounder occur in brackish estuaries. The coastal fishery for Chinook salmon is managed by the Pacific Fishery Management Council, who can reduce harvest or implement full closures when the species is at risk (e.g., Bland 2023). The recent *California Salmon Strategy* recognizes the need to include harvest management in planning for salmon resilience under climate change (Maven's Notebook 2024).

Poaching is a periodic problem for the state's sport and commercial fisheries, and for waterfowl hunting. The magnitude of the issue is difficult to quantify since data are only available on violators that have been cited, and because warden field activities focus on enforcement, not on data collection. However, news of poachers being caught is relatively common. California Department of Fish and Wildlife employs wardens throughout the state to enforce fishing regulations, including efforts to prevent illegal harvest (CDFW).

It is well recognized that some freshwater ecosystems have predation "hotspots," where there are excessive losses of species (Lehman et al. 2019). Removing artificial structures from waterways (e.g., pilings, debris) can help to address this issue. Harvest of non-native predators is also a common habitat restoration technique in lakes and streams in California, often using nets, electrofishing, or chemicals (e.g., Rotenone) (Finlayson et al. 2001). Predator control is being considered in the Bay-Delta and its watershed as a potential tool to reduce mortality rates of target fishes, particularly Chinook salmon (Grossman 2016).

Water diversions are a well-known predation hot spot (Lehman et al. 2019) and can also cause direct mortality of aquatic animals that are swept into pumps and pipes (Moyle and Israel 2011). Screening of water diversions and the development of operational criteria have therefore been a major approach to protecting species against losses at municipal, agricultural, and industrial water diversions (Moyle and Israel 2011). The highest profile example of diversion impacts are the state and federal water export facilities in the Bay-Delta (Grimaldo et al. 2009). Each location has operational criteria to reduce losses during critical fish movement periods—fish screens and salvage facilities have also been constructed to try and rescue a portion of the entrained individuals. However, mortality at these water diversions remains a contentious issue (Moyle et al. 2018).

Implementation issues

Enhanced regulations on legal harvest, including fishery closures, can have devastating effects on industries, local communities, and cultural groups (Bland 2023). The current level of poaching is largely unknown except for the periodic capture of violators, so it is difficult to assess the impact of poaching on populations. The high value of some of the animals can make the activity highly lucrative—one news article claimed that the value of poaching of fish and wildlife is likely more than $100 million/year (Jensen 2014). Still, poaching is a highly cryptic activity, making enforcement very difficult.

Limiting water diversions to protect species against entrainment can have major effects on agricultural and municipal economies that rely on diverted water. The population impacts of fish screening projects are difficult to assess, so the potential benefits of fish screen installations are usually highly uncertain. Moyle and Israel (2005) did a major review of fish screen projects in California's Central Valley and found that few projects tried to evaluate the effectiveness of screens in preventing the mortality of fish, and even fewer assessed population impacts. They concluded that: “The limited published literature suggests that this lack of evaluation is typical throughout the western United States, despite millions of dollars spent annually on screens and their maintenance.”

Predator control faces many of the issues described above for invasive species control. Removal of non-native predator hot spots can be a successful approach, particularly when done in an isolated area (e.g., threespine stickleback example above) and it halts further range expansions (e.g., see Lake Davis example above). However, removal efforts have had mixed success, especially in larger bodies of water like rivers and estuaries where predators are highly mobile and removal is difficult (Grossman 2016). For example, harvest of one predator group may simply result in a rapid expansion of another predator, so net mortality may not increase. In some cases, control may result in higher levels of predators than existed earlier (Grosholz et al. 2021).

Case examples

Closure of the Chinook salmon fishery. In 2008, 2009, and 2023–24, the Pacific Fishery Management Council took the extreme step of totally closing both the commercial and recreational fisheries in California (Bland 2023).

Delta water project regulations. The state and federal Water Projects in the Sacramento–San Joaquin Delta provide water to over 25 million people and support a multibillion-dollar agricultural industry. The diversions are located in core rearing and migration habitat for several threatened and endangered fishes (Grimaldo et al. 2009; Moyle 2018). Diversion regulations are in place to protect these fishes, but are highly controversial.

Delta predator removal. Cavallo et al. (2013) conducted predator removal experiments on the Mokelumne River and examined the response of tagged migrating juvenile salmon. Predator removal was also tested along experimental reaches of the lower San Joaquin River by National Marine Fisheries Service, but there was no evidence that their manipulations resulted in a change in salmon survival or relative predation rates (Michel et al. 2019).

Southern California lake drainage to control non-native predators. See unarmored threespine stickleback example above.

Clifton Court Forebay predator removal. In 2016 the Department of Water Resources started a three-year study to investigate whether electrofishing and relocating predatory fish in Clifton Court Forebay helped improve the survival of Chinook salmon and Central Valley steelhead trout (DWR). Predators congregate near the State Water Project diversion facilities in Clifton Court Forebay.

Sherman Island fish screen evaluation project. The Sacramento–San Joaquin Delta has approximately 2,000 water diversions, the majority of which are unscreened. Department of Water Resources installed fish screens in multiple locations across Sherman Island, which is surrounded by habitat for many endangered fishes (DWR). Unlike most other regional fish screening projects (Moyle and Israel 2011), the fish screens are undergoing a detailed evaluation of their effectiveness.

Remediate diseases

Climate change will increase the prevalence of diseases in native populations through overcrowding and reducing habitat quality, particularly through temperature increases (Karvonen et al. 2010). Many of the previously described habitat actions (e.g. flow, connectivity, water quality) can help alleviate these issues. Potential higher-level management interventions include veterinary treatment of individuals. California already has a long history of marine and terrestrial wildlife rehabilitation centers dedicated to treating animals struggling with disease, contaminant exposures, or injuries (see case examples below).

Implementation issues

Disease treatment in species typically involves removing individuals from their natural habitats, which may not be practical in many cases and can create substantial stress. For example, if not all individuals can be treated, the population may be subject to repeated reinfections. Therefore, this approach can have major technical and legal obstacles.

Therapeutic veterinary methods have been developed for a relatively small percentage of species—mostly marine mammals, birds, and sport fishes—so much more research is needed for broad applications. A related issue is that major resources are needed to develop therapeutic approaches and to treat individuals. Although there is currently a network of wildlife rehabilitation centers in California (see below), these sites are focused on select species—the current resources are not sufficient for conservation of the full range of freshwater species.

Case examples

Fungus treatment of mountain yellow-legged frogs. In California, US Fish and Wildlife Service is working to combat *Batrachochytrium dendrobatidis*, a chytrid fungus that kills mountain yellow-legged frogs, an endangered species highly susceptible to the fungus (Snow 2020). The team has developed extensive protocols to guide the process, including field safety procedures and monitoring.

Thiamine deficiency in Pacific salmon. In 2019, several hatcheries in California's Central Valley observed multiple abnormalities and high mortality in juvenile fall-run Chinook salmon (Bell 2022; Suffridge et al. 2023). The problem was traced to thiamine deficiency in their parents, likely due to their feeding patterns in the Pacific Ocean. Thiamine treatment of hatchery spawners appears to resolve this problem in hatchery juveniles (Bell 2022). Recent studies indicate that thiamine generated from microbes in spawning gravels could generate thiamine in rivers (Suffridge et al. 2023). This raises the possibility that nutrient supplementation or habitat management could help reduce thiamine deficiency.

Marine Mammal Center. The Marine Mammal Center operates the largest marine mammal hospital in the world. The center has a team of veterinarians and volunteers to provide state-of-the-art medical care to marine mammals that have been rescued. While the center focuses on marine and coastal mammals, some types—such as harbor seals—frequent estuaries and freshwater rivers.

California wildlife rehabilitation centers. The state has a broad network of wildlife rehabilitation centers that focus on different species groups. These provide focused services for several groups native to our freshwater ecosystems: mammals, birds, amphibians, and reptiles.

Population supplementation

Climate change acts in ways that can trigger populations to rapidly slide towards extinction. One of the highest-level management interventions is to supplement imperiled populations with hatchery- or nursery-grown individuals (Trushenski et al. 2018). This requires establishing methods to culture species, as well as strategies for reintroduction. Another approach is to collect wild individuals and move them to safer, controlled environments before release back into the wild. Although it is widely used for salmon and trout, there have been substantial issues, including fitness of hatchery fish, competition and spawning with wild fish, and straying into non-natal watersheds.

A growing trend is the development of partnerships with private industry to support conservation supplementation (Ridlon et al. 2023). Publicly funded hatcheries and refuges often do not have the facilities or other resources to support the broad suite of species that may need to be conserved. This has led to collaborations with private aquaculture companies, who may have the facilities to hold and produce species. Private nurseries have been used for decades as a tool to support restoration of terrestrial ecosystems.

Implementation issues

Population supplementation can boost populations and form the basis for harvest by sport and commercial fishing. Conservation hatcheries are also increasingly being used to help boost at-risk populations (Flagg et al. 2005). However, there are widespread concerns about the negative effects of supplementation from hatcheries (Allendorf 1991; Trushenski et al. 2018). A recent global synthesis of the topic by McMillan et al. (2023) revealed that adverse genetic effects on diversity were common. There were also multiple examples of effects on productivity and abundance from ecological and genetic changes. The study reported that there are few published studies supporting beneficial hatchery effects on wild salmonids.

A less intrusive approach is to collect wild individuals and place them in specially designed nurseries (e.g., constructed ponds) to maximize their survival before reintroduction (see examples below). However, this approach can deplete natural populations, and removal of natural selective pressures may not produce individuals that are well-suited to the wild. This also may result in major permitting and ecological issues.

Case examples

A streamside nursery for Klamath suckers. Shortnose suckers (*Chasmistes brevirostris*) and Lost River suckers (*Deltistes luxatus*) are two endangered fish in the Klamath River watershed. Streamside acclimation facilities are being tested to help young suckers acclimate before being released (Grable 2023). US Fish and Wildlife Service and the Klamath Tribes have been capturing wild larvae and rearing suckers in specially constructed ponds that are rich in food and have better water quality than their typical lake habitat.

McCloud River salmon egg incubator. As part of the effort to reintroduce Chinook salmon into the McCloud River, the Winnemen Wintu Tribe and fish biologists have designed a salmon egg incubator to enhance supplementation by better mimicking river conditions (Dadigan 2023). The incubator is a protected place for eggs to hatch, and hatchlings to acclimate to river currents. The system also allows young fish to leave on their own when they are ready to enter the McCloud River.

Marine aquaculture for conservation. Conservation aquaculture is already being tested in marine environments, where private aquaculturists are helping to support conservation projects (Ridlon et al. 2023). A highly relevant example for California is the use of aquaculture to support rare oyster populations, and to promote reef conservation as part of broader habitat restoration projects. Similar approaches are also being tested to rebuild coral reefs in more tropical climates.

Delta Smelt population supplementation. Delta smelt (*Hypomesus transpacificus*) is a small, endangered fish that only lives in the San Francisco Estuary. It is impacted by many factors, including water diversions, invasive species, disease, habitat loss and contaminants. To safeguard against extinction, university researchers developed methods to grow Delta smelt in hatcheries (Lindberg et al. 2013). In 2021, the first experimental release of cultured Delta smelt was conducted by a consortium of university and agency scientists (Bacher 2021). Larger-scale supplementation is scheduled to occur in 2024.

Genetic support

This strategy includes actions that seek to either take advantage of existing genetic diversity or to introduce genetic diversity into existing populations. This diversity is essential for adapting to changing conditions (Bernhardt et al. 2013)—many of the tools previously described in the habitat strategy can help to maintain diversity and resilience. Dispersal support and assisted migration are critical to maintaining gene flow and to avoid inbreeding. However, if populations are very low and species are too genetically homogenous, they may not be able to cope with major changes like heat waves or flow changes without additional support to maintain genetic diversity. Many of these tools are highly experimental and need further assessment, particularly considering legal, cultural, and ethical issues. However, in a recent article Fitzpatrick et al. (2023) argue that "genetic rescue" tools are not used often enough to manage species at risk of extinction.

Here we examine genetic support tools. They are roughly organized by the level of management intervention.

Diversity protection

For species currently produced in hatcheries (e.g., salmon and steelhead), state-of-the-art breeding programs can be used to maximize genetic diversity in hatchery stocks (e.g., Maven's Notebook 2024). Where there is evidence that hatchery practices have adverse effects (e.g., homogenization, inbreeding), there may be situations when the diversity of wild river populations could be better protected by suspending hatchery fish stocking (Quiñones et al. 2013; McMillan et al. 2023). There is historical precedent for the closure of some hatchery stocking, such as the effort to protect mountain yellow-legged frogs (see example above).

Another option is to relocate hatcheries to seaward locations, so that hatchery fish are less likely to interfere with the spawning and rearing of wild fish. This approach may require a shift in where harvest is allowed. For example, most California hatcheries are located relatively inland, while other northwest locations such as the Oregon Coast have more seaward facilities (NOAA Fisheries). California's recently released *California Salmon Strategy* briefly notes the potential need for hatchery relocation (Maven's Notebook 2024).

In addition to hatchery reform, resource managers can support freshwater ecosystems by managing for diversity in populations. This typically involves using tools such as genetics to identify critical populations in need of protection and targeted measures. Habitat diversity and distribution support are some of the most powerful tools to support species diversity in wild populations, but for some species with very low population and genetic diversity, additional steps may be necessary.

Implementation issues

Resources may not be available in all hatchery locations to develop state-of-the-art breeding programs, which can involve substantial genetic analyses, labor, and fish-holding facilities. Suspension of hatchery programs may face substantial opposition from the public and commercial fishing groups, who see hatchery production as an important tool to maintain strong fisheries. There may also be regulatory hurdles—several hatcheries are part of mitigation obligations for water and power agencies to compensate for lost habitat upstream of their dams.

Closure of hatcheries may do little to protect wild stocks of fish if river and ocean habitat conditions remain poor, a possible scenario under climate change. Finally, the relocation of hatcheries depends on the availability of suitable locations in seaward locations, which generally have major competing land and water uses in this populous state. Relocation of Central Valley hatcheries, for example, would therefore be quite challenging.

Case examples

Salmon hatchery genetic management plans. USFWS (2016) developed a comprehensive genetic management plan to maximize the diversity of the highly imperiled winter-run Chinook salmon. Additional hatchery genetic management plans are proposed as part of the *California Salmon Strategy* (Maven's Notebook 2024).

Delta smelt hatchery genetic management. The UC Davis Fish Conservation and Culture Lab (FCCL) and Genomic Variation Lab (GVL) of UC Davis have developed a breeding and rearing plan to manage hatchery Delta smelt, which are currently being used for pilot supplementation in the Bay-Delta (See example above). The approach is using modern genetic methods and hatchery facilities to ensure that the hatchery stock is relatively diverse, and to minimize the deviation from the wild population (FCCL).

Potential hatchery reform. Changes in hatcheries operations have been recommended for many years (California Hatchery Scientific Review Group 2012). Recently, hatchery operations have been identified as a key issue facing salmon in the *California Salmon Strategy*. Multiple potential changes to hatcheries are included, such as the possibility of reforms to operations and relocation.

Mountain yellow-legged frogs. See example above describing how the stocking of hatchery fish was suspended in order to protect stocks of threatened amphibians.

Assisted evolution

Even with large, diverse populations, the pace of natural selection may be insufficient to cope with climate-driven changes in habitat (Beaulieu and Rainville 2005; USGS 2023). Moreover, California's native aquatic species already have low diversity and abundance, greatly reducing their ability to adapt.

Assisted evolution represents a very high-level intervention to select for individuals that can better survive warmer and drier conditions under climate change (van Oppen and Coleman 2022). Selective breeding is a traditional tool in hatcheries and nurseries, but future applications might include highly experimental approaches to influence how genes are expressed (epigenetics) or the introduction of new genes.

Selective breeding has been used for millennia by humans to select for desirable traits in plants and animals, especially for agricultural, horticultural, racing (horses, dogs), and pets (United Nations Environment Program). The basic approach for selective breeding takes advantage of the existing genetic diversity of populations.

Selective breeding is rare for all but aquatic species with commercial or recreational value (Lind et al. 2012; Azra et al. 2022). Examples from aquaculture include seaweeds, microalgae, bivalves, abalone, crustaceans, and many fishes.

The genes of an organism determine its traits, including environmental tolerances. However, the specific genes that are expressed can depend on the environmental conditions (e.g., temperature, pH, food) that individuals are exposed to. This process, called *epigenetic*s, is a set of mechanisms by which organisms respond to the environment by changing their behavior, physiology, and life history transitions (McCaw et al. 2020). Epigenetics is therefore a candidate tool that could help organisms survive under climate change. Notably, it does not involve changing the genome of a species; rather, it changes the expression of existing genes. For example, exposure of species to warmer conditions in a lab or a hatchery during reproduction could trigger increased temperature resistance in their offspring (e.g., Roy et al. 2021).

Gene editing is increasingly being considered as a tool for conservation, especially following the development of powerful approaches such as CRISPR technology (van Oppen and Coleman 2022). This approach can allow the removal of deleterious genes, or the insertion of beneficial ones. CRISPR could therefore be tested as a way to improve temperature tolerance. As described above for the Invasive Species tools, “gene drives” are also a potential tool to combat invaders. Gene editing has been tested on fish, invertebrates, and algae; however, its potential application to conservation remains conceptual or highly experimental.

Implementation issues

Assisted Evolution is likely the most controversial of all of the tools discussed here because it involves such a high level of intervention, especially for gene editing. This tool is therefore expected to generate major social, cultural, ethical, and legal issues. Withers and Jenkins (2023) report a journal-based poll that concluded that 70 percent of US adults felt that gene editing could be misused in the context of conservation. However, public perceptions are complex—Berseth (2022) reported that public support for selective breeding of Pacific salmon varied substantially depending on the context.

Since several of the technologies are so new, they still require substantial research and development that will require a major resource commitment, especially epigenetics and gene editing (van Oppen and Coleman 2022). These new technologies are likely prone to unintended consequences or errors, which could have serious ecological consequences such as the introduction of unwanted genes and their contamination in other populations. Even selective breeding, a tool with a long human history, is a major challenge because this approach has not been widely tested for aquatic conservation.

Since assisted evolution involves laboratory-, hatchery-, or nursery-based interventions, all the implementation issues described for supplementation apply to assisted evolution (e.g., Lind et al. 2012).

Case examples

Pearl oyster epigenetics. Aquatic heat waves are an increasing issue for many aquatic species, including bivalves. To test the potential for epigenetic approaches to protect oysters, He et al. (2021) exposed pearl oysters to repeated heatwaves in the laboratory and found that this approach enhanced their thermal tolerance.

Coastal oyster acclimation. In addition to the direct effects of heat, climate change can enhance susceptibility to disease. To examine potential ways to protect Australian oysters, Scanes et al. (2023) acclimated oysters to four treatment levels of temperature, including an antibiotic treatment, and then exposed all treatments to a simulated heat wave. They found that acclimation helped reduce pathogen load and enhance survival.

Shellfish selective breeding. 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 aquaculture farms as well as shellfish restoration projects (Tan and Zheng 2020).

Coral selective breeding. Florida's coral reefs are suffering from high temperatures, which causes bleaching and starvation. A new program is using selective breeding to try and develop strains of coral that are more resistant to high temperatures (Newborn 2023).

Hybridization

Another relatively extreme conservation action is to crossbreed races or closely related species as a potentially beneficial way to spread beneficial alleles among populations. Plant hybridization is commonly used to generate specific desirable traits such as fast growth, appearance, and disease resistance for agriculture and agronomy (Goulet et al. 2017). More recently, hybridization has also been used in commercial aquaculture for fish and invertebrates (Bartley et al. 2000). A similar strategy might be used in conservation in situations where individual species are unable to adapt quickly to climate change.

Chan et al. (2019) suggest that hybridization is worthy of consideration for climate adaptation because it may enhance the adaptive potential of a population, allowing species to invade new niches and expand their distribution ranges. The intentional use of hybridization for aquatic conservation remains largely experimental, though. Therefore, we do not list any case examples below based on the directed use of this approach for aquatic conservation.

Implementation issues

As with assisted evolution, public concerns about using hybridization for genetic and evolutionary rescue have hindered its application (Chan et al. 2019). Most of the issues described above for assisted evolution therefore apply to hybridization. Some of the key potential risks include less fit offspring (outbreeding depression) and the loss of parental species because of genetic mixing. Chan et al. (2019) also suggest that the uncertain legal status of hybrids has also impeded their use in conservation. To help navigate these issues, Chan et al. (2019) have developed a decision tree to guide the potential use of hybrids for conservation.

Case examples

California tiger salamander hybrids. The decline of California tiger salamander populations is thought to be due to drought, loss of breeding habitats, and the presence of non-native predators such as American bullfrogs. The species is increasingly influenced by interbreeding with the introduced barred tiger salamander (*Ambystoma tigrinum mavortium*), perhaps for as long as 50–60 years (Fitzpatrick et al. 2007). Researchers have found strong evidence of hybrid vigor between the two types, including higher survival rates. Since these hybrids are capable of breeding, it is possible that these more robust hybrids may eventually replace the historically pure California tiger salamander and potentially provide an evolutionary advantage under climate change.

Chinook salmon hybrids. Araujo et al. (2021) found evidence that two Pacific salmon (Chinook and Coho) occasionally produce hybrids in the northwest. They believe that hybridization has been a naturally occurring event, likely exacerbated by extended drought conditions. Hybridization may therefore be linked to both habitat and climatic changes.

American chestnut hybrids. European and American chestnut trees (Castanea) have been decimated by chestnut blight (*Cryphonectria parasitica*) for more than a century. Clark et al. (2016) tested whether hybrids between the disease-resistant Chinese chestnut could be used as a conservation approach. They found that the hybrids showed improved disease resistance and could be considered as a restoration tool.

Strategy 3. Contingency actions

There is a closing window of opportunity to preserve at-risk groups—many types of fish, amphibians, invertebrates, and wildlife are already on a trajectory towards extinction (Howard et al. 2015). Controversial as it may be, contingency actions are needed to prepare for a highly uncertain future. This includes tools to preserve knowledge about habitat and life history traits of native species along with their genomes. These approaches are used widely today in terrestrial conservation and adaptation programs but are much less common in freshwater aquatic systems. In addition, contingency actions should tackle what to do when key species—especially those protected under state and federal Endangered Species Acts—are no longer viable in their historic habitat. A key point is that this strategy is not an excuse to put less emphasis on other conservation strategies; rather, it represents a form of bet-hedging in case the best efforts are not successful.

Historical conservation

California has a strong legacy of scientific inquiry, but there are large gaps in understanding of freshwater biota, particularly for species that are not vertebrates, are not harvested commercially or for recreation, or do not have special legal status (e.g., threatened and endangered). Historical conservation is the collection of baseline information about current species and habitats—this includes the collection of as much information as possible about species (e.g., diets, behaviors, physiology) and habitats (e.g., structure, substrate, soundscapes) before these resources are potentially lost to climate change and degraded habitat. Collection of this type of information is common across the state's universities, agencies, and other organizations (see examples below), although the data are generally not being collected in an organized, systematic way for conservation purposes.

Implementation issues

Historical conservation by itself does not save species; however, understanding the status and trends of species in aquatic ecosystems through research and monitoring is critical for the development of suitable climate adaptation approaches. Presentations of this information to the public (see virtual reality example below) can help generate support for conservation. As noted above, this tool is not intended as an alternative to focused management interventions—it is a complementary approach to other management interventions.

Even though there has been substantial progress in field collection methods (e.g., new sampling techniques, genetics, acoustics, telemetry), historical conservation can be expensive and time consuming because there are so many different aquatic ecosystems in California. Some species and habitats are very hard to study because they are rare and sensitive. Hence, permitting, logistics, and funding could be major limiting factors.

Case examples

Interagency ecological program (IEP). The IEP is a consortium of state and federal agencies that do research and monitoring on the San Francisco Estuary and its watershed. This long-term program (60+ years) is a primary source of information about the distribution, status, trends, and habitat use of many types of species in marine, brackish, and freshwater ecosystems. This information has been essential to understanding the role of various threats (water diversions, invasive species, habitat loss, contaminants, climate change) and supporting management activities such as water distribution, flood management, recreation, fisheries, water quality, invasive species control, and habitat restoration.

Sierra Nevada Aquatic Research Laboratory (SNARL). SNARL was originally established in 1935 to focus on hatchery trout responses to transplantation. However, the lab has evolved over time and includes broad ecological research in eastern and central California and western Nevada. SNARL is part of an extensive habitat preserve and includes a modern laboratory and an experimental stream complex. The program has been responsible for cataloguing many of the species in the neighboring streams, rivers, lakes, wetlands, and pools.

California Natural Diversity Database (CNDDB). The CNDDB is an inventory of the status and locations of rare plants and animals in California. The project maintains current lists of rare species and a database of their locations using GIS-mapping.

Virtual R\reality. A novel type of historical conservation is the use of virtual reality to allow people to observe simulations of species in their habitats. The Sacramento Zoo developed a nighttime exhibit where the public could observe relatively realistic simulations of extinct and rare animals (Tubbs 2023).

Tissue archives

Tissue archives are a valuable source of information about species because they can provide insight into multiple factors including genetics, diversity, habitat use, environmental exposures, pathology, and life history (Goodale et al. 2023). There has been a proliferation of chemical and genetic techniques that allow scientists to learn much about species with small samples of their tissues. Whole organism preservation has been a common technique used in museums and research labs for many decades. Archives of plant and animal tissues are common for terrestrial species, but are rarer for California's aquatic species other than high-profile types such as salmonids and amphibians.

Tissue archives differ from seed banks (below) in that they do not necessarily involve the archiving of reproductive materials. Instead, the samples can use the whole organism (e.g., frozen, dried, pickled, pressed) or multiple tissues: fins, bones, skin, and muscle in animals or leaves, roots, pollen, and stems in plants (e.g., Pence et al. 2017). There are many approaches to preservation such as freezing, drying, and storage in chemical solutions (White and Dusek 2015).

Implementation issues

This initiative is already underway in California at a relatively large scale (see below); however, much more work and resources will be needed to catalogue the state's freshwater biota. Preservation techniques still have not been evaluated for the broad suite of species, so substantial research and development is needed. Also, preservation needs to progress in a more organized way to ensure conservation of aquatic resources for all watersheds in the state.

This method requires samples from the target species, which may be challenging to collect because of their rarity, sensitivity, and associated legal constraints.

Case examples

Genome 10K. The Genome 10K is a UC Santa Cruz-based scientific collaboration for the preservation and understanding of genetic diversity in animals. Their stated goal is "to assemble a genomic zoo that will live forever as a basis for the science and preservation of life." The specific activities include coordination of tissue collection for subsequent large-scale sequencing and analysis projects. The project focuses on vertebrates, primarily terrestrial species.

Salmon tissue archives. Biobanking of salmon fin clips (adipose or caudal fins) has been used for decades to conserve the genetic diversity of Chinook salmon and as a resource to support specific programs, such as the Livingston Stone hatchery for winter-run Chinook salmon (USFWS 2016) and parentage-based (genetic) tagging (CDFW 2023b).

Genetic libraries

Effective management and conservation of species depends on access to reliable information about their genetics and diversity. Genetic libraries are commonly used to record the diversity of populations (van Oppen and Coleman 2022) and are critical to the development of conservation plans, including the prioritization of efforts to conserve specific populations. They represent the analytical results of genetic analyses conducted on species' tissues and can be used to record the genetic legacy of biodiversity. These technologies have been expanding rapidly and are increasingly cost effective.

Implementation issues

Genetic libraries are already being established in California (see below); however, much more work and resources will be needed to catalogue the full suite of species in the state's freshwater ecosystems. Despite the widespread availability of genomic methods, applications of genomics still lag behind the collection and storage of other environmental data (van Oppen and Coleman 2022). The data also need to be collected in a more organized way so that the full range of California's aquatic ecosystems are covered.

This method requires samples from target species, which may be challenging to collect because of their rarity, sensitivity, and associated legal constraints.

Case examples

California Genomics Conservation Project (CGCP). The CGCP is a consortium of genetic experts working to support conservation science in California. This state-funded initiative seeks to produce the most comprehensive multispecies genomic dataset ever assembled, with the goal of helping manage and protect regional biodiversity in the face of climate change. The project reports that they are generating full genome sequences for approximately 22,000 individual plants, vertebrates, and invertebrate animals representing nearly 150 genera and selected species. A major goal is to identify critical populations and locations to help prioritize conservation.

Genome 10K. See Genome 10K example above, which is designed to coordinate and support large-scale genomic sequencing and analysis projects.

Seed banks

Seed banks are increasingly common in terrestrial conservation (Goodale et al. 2023) but are relatively rare for California's aquatic species. The tool involves developing live or cryopreserved archives of embryos, gametes, and seeds. These resources can be critical reservoirs of diversity needed to support conservation projects and potential "de-extinction" at a later time when habitat conditions are suitable.

Implementation issues

Preservation techniques still have not been developed for the broad suite of species from California's aquatic ecosystems, so substantial research and development is needed. This includes developing methods for long-term viability and maintaining genetic diversity. The approach still needs to be implemented in a broader, more systematic way so that all California's watersheds are covered.

Substantial resources are typically needed for large-scale preservation of reproductive tissues. Current government facilities are insufficient to conserve the freshwater biodiversity in California. For this reason, partnerships with private groups, including aquaculturists, are increasingly being used for live seed banks.

There are also numerous obstacles to reestablishing populations based on laboratory embryos—just because seed stock is available does not ensure that it won't become altered under laboratory conditions (e.g., Finger et al. 2018) or that habitat conditions will be suitable anytime in the future.

Finally, there are many permitting hurdles for the collection and preservation of special-status species.

Case examples

Frozen Zoo. The Frozen Zoo is a San Diego-based facility to store seed stock from a wide variety of species. The facility purports to be the largest and most diverse collection of its kind in the world, with "over 10,000 living cell cultures, oocytes, sperm, and embryos representing nearly 1,000 taxa." Although the project focuses on terrestrial species, it includes several key examples from California's freshwater ecosystems (e.g., mountain yellow-legged frog). The purpose of the facility is to provide an archive that could be used for conservation, population supplementation, evolutionary biology, and the development of medical treatments.

Salmon cryopreservation. Cryopreservation of salmon milt (sperm) has been used for decades to conserve the genetic diversity of winter-run Chinook salmon and as a resource to support the Livingston Stone hatchery program (USFWS 2016).

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 reported to 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, who state that the project is intended as a service to the world.

Marine Conservation for Aquaculture. See example above.

Plan for novel ecosystems and loss of some species

Even with aggressive action, climate change will result in the loss of original species assemblages and habitat features (Staudinger et al. 2021). This scenario is consistent with the USGS (2023) "Acceptance" scenario to respond to climate change—resource managers may have to accept that it is not feasible to protect some populations because of ecological, economic, or societal barriers.

The loss of species—particularly those protected by state and federal Endangered Species Acts—does not mean, however, that ecosystems should be ignored. There will still likely be options to maintain the multiple benefits that come from healthy ecosystems and these new, novel ecosystems will support a new species assemblage (Moyle 2013). For example, many aquatic ecosystems in California are struggling with invasive species that adversely affect native species. Yet some of these invasive species are very desirable for recreation (e.g., striped bass, largemouth bass) or have other aesthetic value.

Under this option, resource managers would develop contingency actions that include alternative ecosystem management goals and objectives like water quality, recreation, and aesthetics, depending upon projected changes in these ecosystems (Moyle 2013). This likely involves less reliance on managing ecosystems using endangered species laws and more on other regulatory tools (e.g., Clean Water Act and the Porter-Cologne Act).[2] Our upcoming companion report will describe some of these potential legal and policy tools in much greater detail.

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[2] The Porter-Cologne Act is the principal law governing water quality in California (Maven's Notebook 2020). It was adopted in 1969, three years prior to the federal Clean Water Act. The Act established the nine regional water boards who oversee water quality on a local and regional level. One of the most relevant provisions is that the regional water boards must prepare and periodically update basin plans, which define beneficial uses and establish water quality standards to protect those uses. Hence, these plans are a potential tool to manage for novel ecosystems and beneficial uses; however, major updates may be necessary to facilitate an ecosystem approach (Gray et al. 2022).

Implementation issues

As for the other approaches under contingency actions, there is a risk that this tool could be interpreted as "giving up." Therefore, managers need to be very clear that this tool is intended as a backstop in case other options do not work or are not feasible.

Although there are strong environmental laws that could be used to manage novel ecosystems, all existing frameworks would require at least regulatory amendment to work properly, because they have a particular flaw or are missing some key element (e.g., Gray et al. 2022). This issue will be described in much more detail in our companion report.

Perhaps of greatest concern is that novel ecosystems are inherently unpredictable. Since, by definition, these ecosystems have no historical analogue, it may be difficult to develop management strategies. There may also be unintended consequences, such as the proliferation of highly undesirable species.

Case examples

California rivers. There are limited case examples of how ecosystem management changes once species disappear. Moyle (2013) describes three California river systems (Putah Creek, Cosumnes River, Eel River) that are so highly altered that attempting to restore them to an historic condition (or a stable state) is largely not possible. Moreover, climate change will only exacerbate these issues. Moyle (2013) argues that resource managers should change their focus away from historical conditions and towards novel ecosystems with desirable features, including a mix of native and non-native species.

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