Optimizing Fish Passage Barrier Removal in California While Considering Climate Change Effects

A white paper produced by the California Fish Passage Forum
April 2014

Anadromous fish habitats in California have been heavily impacted by human-caused and natural disturbances, and are experiencing compounded effects as a result of climate change. Climate change is an important driving force on natural systems (Parmesan and Yohe 2003), and can be especially deleterious to anadromous salmonids because of the strong local adaptation to the habitats these fish occupy (Mantua et al. 2010).

This paper summarizes the importance of considering climate change effects while prioritizing fish passage barrier removal as a restoration action in California. The relevance of this topic is essential in light of the state's driest year on record, because climate change is predicted to increase the number and intensity of drought events (Hayhoe et al. 2004), and considering that 28 of the 52 identified evolutionarily significant units of Pacific salmon and steelhead populations along the West Coast of the United States are listed as threatened or endangered under the Endangered Species Act. Removing high-priority fish passage barriers identified through a habitat-based optimization tool will help mitigate the effects of climate change.

Climate Change Effects

The impacts of climate change will vary among species and populations, and will depend on multiple and diverse factors (Dalton et al. 2013); however, climate change pace currently exceeds the rates at which species can colonize new suitable habitat (Comte and Grenouillet 2013). The following are some documented effects of climate change:

- Introduces new stressors and compounds existing stressors on fish as well as increases the frequency and magnitude of extreme floods (Jospe 2013).
- Decreases carrying capacity (Walters et al. 2013) and affects disease resistance, development rates, spawning and migration timing and other biological events, and ocean survival of anadromous fish (Crozier et al. 2011).
- Affects productivity, species distributions, recruitment, and community structure (Osgood 2008), and causes altitudinal shifts, population collapse, local extinctions, failure to migrate, and changes in food availability and food web structure (Portner and Farrell 2008).
- Affects water temperature and the magnitude and timing of stream flows, which affect all aspects of salmon development, rearing, and migration (NOAA-NWFSC 2008).
- Affects nutrient cycling and reciprocal terrestrial-stream subsidy balances (Wenger et al. 2011).

- Affects sea level, air temperature, ocean temperature and circulation patterns, precipitation patterns, air and ocean chemistry (acidification), tropical storm intensities and frequencies, and species abundance and distribution (NOAA 2010).
- Exacerbates non-climate stressors, such as pollution or overharvesting, thus affecting adaptive capacity (Seney et al. 2013).
- Causes habitat loss or alteration, distribution changes, geographic isolation or extirpation of populations unable to adapt or migrate, new interspecific interactions, shifts in phenology, disrupted predator-prey interactions, reduced food supply, increased stress, disease susceptibility, and predation (Seney et al. 2013).
- Increases stream temperatures in rivers. The threat to salmon recovery is great in locations where temperatures are near lethal or sub-lethal thresholds for salmon, but not as significant in rivers where current temperatures are well below those thresholds (Beechie et al. 2012). Altered stream flows and warmer temperatures affect survival and passage through tributaries for anadromous fish that require river systems and coastal regions for all or a portion of their life cycle (Osgood 2008).
- Warms waters, reducing habitat for cold-water species, promotes the introduction and establishment of non-native species typically found in warmer areas, and exacerbates existing stressors, such as habitat loss, pollution, invasive species and disease (NOAA 2010).
- Changes salinity levels for prolonged periods of time, resulting in habitat loss for some species (Burkett and Davidson 2012). Changes in salinity may also facilitate invasion by non-native species better adapted to salinity variations (Hoy et al. 2012).
- Changes water temperatures, flow regimes and salinity concentrations and may result in reduced target species use of restored habitats (e.g., diadromous fish) (NOAA 2010).
- Raises sea level, warms ocean temperatures, and changes freshwater flows, contributing to significant changes in estuarine habitats (Bottom et al. 2005).
- Increases flooding and flash flooding from more intense rainfall events that may cause degradation of the habitat through increased channel erosion, siltation, and destruction of pools and riffles (NOAA 2010).

Changes in Fish Populations as a Result of Climate Change Effects

Globally, scientists are documenting changes in fish populations as a result of climate change. Environmental temperature is a driver for ecosystem responses to climate change, and fish are most susceptible to temperature during their winter reproductive period (Portner and Farrell 2008). Climate change has been implicated in recent and widespread declines in Arctic char (*Salvelinus alpinus*) in the United Kingdom (Winfield et al. 2010), in trout in alpine rivers and streams in Switzerland (Hari et al. 2006), in native western trout species in the United States (Wedekind and Kung 2010), and in North Atlantic cod (*Gadus morhua*) stocks (Portner and Farrell 2008). In the West, at particular risk are juvenile chum (*Onchoryncus keta*) and Chinook (*Onchorynchus tshawytcha*) salmon, which are considered to be the most estuarine-dependent species (Dalton et al. 2013).

A global climate regime shift in 1977–1978 greatly affected marine and freshwater fish in the northern hemisphere (Casselman 2002; Powell and Xu 2012). Adverse effects to major fisheries occurred as a result of the 1988–1992 drought in California (Langridge et al. 2012). In 2014, fishing bans were enacted in many California streams as drought threatened federally endangered Central Coast coho (*Oncorhynchus kisutch*) runs and fall-run Chinook (*Onchorynchus tshawytcha*) (California Department of Fish and Wildlife, pers. comm.). During the next 50 years, changing climate will cause a significant decrease in growth potential of fish assemblages (Cheung et al. 2013).

The diverse spawning, rearing, and migration habitat needs and behaviors of Pacific salmon have been fundamental to their historic resilience, and complicate understanding the effects of climate change (Dalton et al. 2013). Population and life history diversity within individual salmonid species is important in providing a full suite of ecosystem services that include reduced variability in salmon returns, limited predator access to salmon resources, and other effects that contribute to long-term sustainability of these fish populations (Schindler et al. 2010). Biological diversity takes advantage of variations in temperatures, stream flow, ocean conditions, and other habitat features (Mantua et al. 2010); these characteristics shape the ability of anadromous fish to respond to climate change.

Climate change-induced flooding will reduce shallow freshwater areas of rivers, restricting salmon feeding, resting, and refuge from predators, and potentially reduce opportunities for the expression of the full range of life-history strategies (Jorgensen et al. 2013). Factors that prevent fish from exhibiting their full expression of life-history variation reduce their ability to adapt to climate change stressors (Bunn and Arthington 2002; Poff et al. 2007).

Changes in air temperature cause stream warming, resulting in upward shifts in thermal habitat, which will reduce fish populations in lower altitudes (Hari et al. 2006). Biologists predict that altered stream flows and the effects of increased temperatures will result in the additional loss of 58% of native cutthroat trout (*Oncorhynchus clarkii*) habitat, , and 35% loss of rainbow trout (*Oncorhynchus mykiss*) habitat in the western United States (Wenger et al. 2011).

Fish that require rivers for all or a portion of their life cycle are particularly susceptible to changes in climate because they may not be able to avoid suboptimal temperatures, especially during early developmental stages (Wedekind and Kung 2010), and because stream networks typically do not provide alternate routes when human modifications block a migration corridor (Boughton and Pike 2013).

Increased water temperatures, which affect fish embryos, larvae, and fry, were likely responsible for grayling (*Thymallus* spp.) spawning seasons that were delayed for more than three weeks in the last years of a 62-year-long study (Wedekind and Kung 2010). Heavier rainfall and increased flooding in the fall and winter is predicted to scour salmon nests (DeVries 1997). Higher stream temperatures will affect habitat quality for salmon in all of their freshwater life stages (Independent Science Advisory Board 2007). Earlier spring runoff will alter migration timing for salmon smolts in snowmelt-dominated streams (Mantua et al. 2010). Understanding these complexities associated with anadromous fish that rely on freshwater habitats as juveniles before their seaward migration versus those that spend more time in estuarine waters will be necessary to effectively address the added stressors associated with climate change in salmon restoration efforts across the Northwest (Mantua et al 2010).

Local species richness and species turnover of fish communities in streams are influenced by colonization dynamics operating at larger spatial scales, and are thought to be regulated by high extinction rates in headwater streams and high colonization rates in downstream areas (Hitt and Roberts 2012).

Fish populations in the Southwest generally tend to have smaller habitat ranges, which limits their options as conditions change (McDonald et al. 2012). Adaptation strategies and principles of ecosystem resilience include prioritizing connectivity, reducing existing stressors, protecting key ecosystem features, and maintaining diversity (NOAA 2010).

Connectivity/Maintaining Stream Flow

Water diversion and climate change are two key challenges for freshwater ecosystems (Langridge et al. 2013; Walters et al. 2013). Globally, rivers and streams are among the most threatened ecosystems, suffering from declines in biodiversity greater than those in even the most severely affected terrestrial ecosystems (Dudgeon et al. 2006).

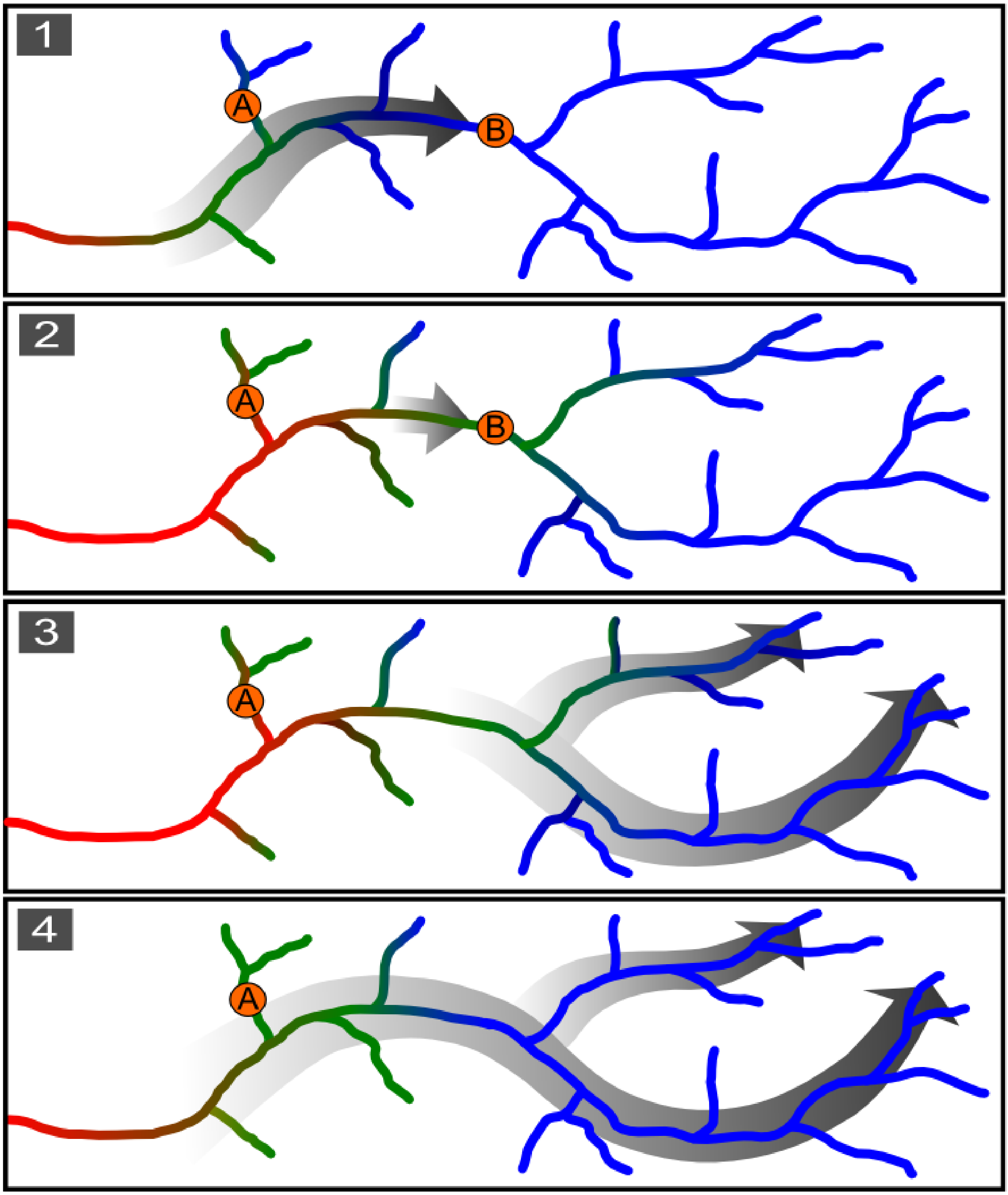
Warming waters reduce fish habitat for cold-water species, provide for the introduction and establishment of non-native species typically found in warmer areas, and exacerbate existing stressors, such as habitat loss, pollution, invasive species and disease (NOAA 2010).

Water diversion causes changes in-stream flow, resulting in habitat loss, increased density dependence, and fewer resources available to combat the challenges imposed (Nislow et al. 2004; Harvey et al. 2006).

Climate change will further shift stream flow and temperature regimes through earlier snowmelt, increased stream flow during winter, and decreased stream flow during late summer and early fall, affecting juvenile salmon growth, movement, and survival (Walters et al. 2013). During drought periods, these issues are exacerbated by lack of adequate snowmelt inputs.

Addressing connectivity has been consistently identified as a high priority, cost-effective approach to protecting and restoring anadromous fish populations. Improperly designed road-stream crossings can fragment stream networks by restricting or preventing aquatic organism passage (Jospe 2013). Physical barriers restrict longitudinal migration in higher altitude regions and reduce habitat available to fish by preventing access to upstream potential thermal habitat (Hari et al. 2006).

Habitat diversity and population resilience can be increased and thus compensate for [or counteract] the effects of climate change-induced reductions in stream flow and increases in temperature by restoring floodplain connectivity, restoring stream flow regimes, and re-aggrading incised channels (Beechie et al. 2012). Restored ecosystem processes that enhance natural habitats and sustain ecosystem services include rehabilitating former floodplains disconnected from rivers by human activity (Boughton and Pike 2013). Increasing connectivity by removing barriers may be one of the most effective ways to mitigate the effects of climate change on aquatic systems, but it is important to remove the right barriers (Jospe 2013), which requires an understanding of connectivity within stream networks (McClurg et al. 2007; Palmer et al. 2008) (Figure 1).



1. Current stream conditions. Anadromous fish are able to utilize habitat below barriers A and B.
2. Climate change leads to warming stream temperatures, reducing the available habitat below barriers A and B.
3. Removing barrier B allows anadromous fish to access cooler habitat. Removing barrier A is a lower priority,as there is little or no suitable habitat available above.
4. Removing barriers may also restore downstream flow, reducing stream temperatures and further increasing available habitat.

Based on findings in Beechie et al. 2012.

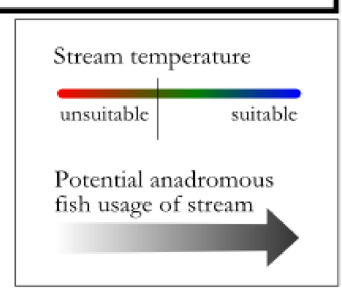


Figure 1. Removing fish barriers may restore downstream flow, reduce stream temperatures, and increase available habitat.

Optimizing Barrier Removal

Limited financial resources drive the need to strategically prioritize barrier removal to maximize accessible upstream fish habitat within a given budget (Gomes and Sabharwal 2009). More simplistic scoring and ranking methods of prioritizing barrier removal have been replaced by optimization-based methods, which offer an objective and systematic framework to address the issue, make efficient use of limited resources, balance multiple and possibly competing objectives and constraints, and incorporate key uncertainties in a coherent fashion (O'Hanley et al. 2013).

Numerous factors are taken into consideration when selecting fish passage barriers for removal, including the amount and quantity of habitat gained for spawning and rearing, barrier passability, the number and type of species that benefit from increased access to upstream habitats, improved connectivity within a watershed and ecosystem, and the cost of the project (BC Ministry of Environment 2009; O'Hanley et al. 2013). The California Fish Passage Forum is supporting the development of an anadromous fish passage barrier prioritization tool (APASS) that maximizes the amount of accessible upstream habitat within a budget (O'Hanley et al. 2012).

Fish Passage Management Considerations

Because human actions have degraded habitats to a greater degree than those predicted from climate change during the next several decades, reversal of degradations to salmon habitats may be able to compensate for expected climate change effects (Battin et al. 2007). Active recovery of an ESA species typically requires the repair of ecosystems modified by people, particularly for species dependent on river ecosystems (Boughton and Pike 2013). Considering biotic interactions and variables other than temperature not only gives us a richer understanding of species-climate relationship, but can inspire a more strategic portfolio of management alternatives (Wenger et al. 2011). This requires that we consider both regional and local variations in climate to adequately assess local fish distributions and fish-habitat associations (Rieman and Isaak 2007).

Rising temperatures threaten to compromise the success of ongoing river and stream restoration efforts in the Southwest, where water withdrawals reduce water levels and increase susceptibility of lakes, streams, and rivers to warming and evaporation (National Wildlife Federation 2013). Land use management and habitat restoration in areas with already degraded habitats may become critical if remnant populations are to retain enough resilience to persist under the challenges posed by even modest climate change (Rieman and Isaak 2007). Some climate change effects, such as warming temperatures, have great predictive certainty, but it may be more important to plan for uncertain climate shifts of likely consequence than to anticipate likely shifts of little consequence (Boughton and Pike 2013).

The California Fish Passage Forum is a consortium of organizations that seek to restore connectivity of freshwater habitats throughout the historic range of anadromy by identifying, assessing, and prioritizing fish passage barriers on public land, and to the extent practical or consistent with landowner goals, private lands (California Fish Passage Forum 2013).

The following management recommendations are based on the life history needs of anadromous fish in California and the anticipated effects of climate change on fish:

- **Conduct a coordinated and comprehensive fish passage improvement program** to restore unimpeded passage for aquatic organisms in anadromous systems (California Fish Passage Forum 2013). Improving connectivity within aquatic ecosystems requires a strategic approach to identifying and prioritizing barrier removal.

- **Prioritize geographic regions and restoration project types** to express a larger suite of life-history strategies, important for species persistence and recovery. Improvements in habitats that support the spectrum of life-history strategies would further support recovery (Jorgensen et al. 2013). Understanding which types of restoration actions are robust to climate change is critical for effective recovery of federally listed populations (NOAA-NWFSC 2008). Because restoration actions focused on in-stream stabilization are unlikely to ameliorate climate change effects, it is important to understand current recovery needs; whether climate change effects will likely alter those needs; whether restoration actions can ameliorate climate change effects; and whether restoration actions can increase ecosystem resilience (Beechie et al. 2013) and ultimately improve overall connectivity within systems.

- **Enhance connectivity by restoring and protecting key ecosystem processes and features** to moderate effects of changes in climate and advance the recovery of endangered species (Boughton and Pike 2013).
  - Offset predicted increases in stream temperatures by maintaining stream flows and protecting and restoring riparian habitats (Wenger et al. 2011).
  - Where inventory in watersheds is lacking, carefully review projects predicted to support spawning and rearing habitats (Rieman and Isaak 2007).

- **Focus regional priorities** on the potential for short-term loss of ecological and evolutionary significance in marginal populations and the potential for long-term persistence in core habitats (Rieman and Isaak 2007).

- **Protect intact freshwater ecosystems by protecting large geographic areas** that serve as buffers and help to promote resilience (Dudgeon et al. 2006). Protection of large areas helps to ensure connectivity among and within stream systems.

References Cited

Battin, J., M. W. Wiley, M. H. Ruckelshaus, R. N. Palmer, E. Korb, K. K. Bartz, and H. Imaki. 2007. Projected impacts of climate change on salmon habitat restoration. *Proceedings of the National Academy of Sciences* **104:**6720–6725.

BC Ministry of Environment. 2009. The strategic approach: Protocol for planning and prioritizing culverted sites for fish passage assessment and remediation.

Beechie, T., M. Collins, P. Roni, and G. Pess. 2013. Incorporating climate change into restoration planning. PowerPoint presentation.

Beechie, T., H. Imaki, J. Greene, A. Wade, H. Wu, G. Pess, P. Roni, J. Kimball, J. Stanford, P. Kiffney, and N. Mantua. 2012. Restoring salmon habitat for a changing climate. *River Research and Applications*. DOI: 10.1002/rra.2590.

Bottom, D. L., C. A. Simenstad, J. Burke, A. M. Baptista, D. A. Jay, K. K. Jones, E. Casillas, and M. H. Schiewe. 2005. Salmon at river's end: The role of the estuary in the decline and recovery of Columbia River salmon. US Department of Commerce, NOAA Technical Memo NMFS-NWFSC-68.

Boughton, D. A., and A. S. Pike. 2013. Floodplain rehabilitation as a hedge against hydroclimatic uncertainty in a migration corridor of threatened steelhead. *Conservation Biology* **27**(6):1158–1168.

Bunn, S. E., and A. H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* **30:**492–507.

Burkett, V. R., and M. A. Davidson, eds. 2012. "Coastal Impacts, Adaptation and Vulnerability: A Technical Input to the 2013 National Climate Assessment." Cooperative Report to the 2013 National Climate Assessment, 150 pp. http://www.coastalstates.org/wp-content/uploads/2011/03/Coastal-Impacts-Adaptation-Vulnerabilities-Oct-2012.pdf.

California Fish Passage Forum. 2013. California Fish Passage Forum Strategic Framework 2013–2018. 44pp.

Casselman, J. M. 2002. Effects of temperature, global extremes, and climate change on year-class production of warmwater, coolwater, and coldwater fishes in the Great Lakes Basin. *In* Fisheries in a Changing Climate (Proceedings of American Fisheries Society Symposium 32), N.A. McGinn, ed. American Fisheries Society, Bethesda, Maryland. pp. 39–59.

Cheung, W. W. L., J. L. Sarmiento, J. Dunne, T. L. Frölicher, V. W. Y. Lam Deng, M. W. Palomares, R. Watson, and D. Pauly. 2013. Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. *Nature Climate Change* **3:**254–258. doi:10.1038/climate1691.

Comte, L. and G. Grenouillet. 2013. Do stream fish track climate change? Assessing distribution shifts in recent decades. *Ecography* **36:**001–011.

Conservation Biology. 2013. Special Section: Incorporating climate change into risk analyses under the U.S. Endangered Species Act. **27**(6):1137.

Crozier, L. G., A. P. Hendry, P.W. Lawson, T. P. Quinn, N. J. Mantua, J. Battin, R. G. Shae, and R. B. Huey. 2011. Potential responses to climate change in organisms with complex life histories: evolution and plasticity in Pacific salmon. *Evolutionary Applications* **1**:252–270.

Crozier, L. G., M. D. Scheuerell, and R. W. Zabel. 2011. Using time series analysis to characterize evolutionary and plastic responses to environmental change: A case study of a shift toward earlier migration date in sockeye salmon. *American Naturalist* **178:**755–773.

Dalton, M. M., P. W. Mote, and A. K. Snover [Eds.]. 2013. Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities. Washington, DC: Island Press. 230pp.

DeVries, P. E. 1997. Riverine Salmonids egg burial depths: Review of published data and implications for scour studies. *Canadian Journal of Fisheries and Aquatic Sciences* **54:**1685–1698.

Dudgeon, D., A. H. Arthington, M. Gessner, Z. Kawabata, D. Knowler, C. Levesque, R. Naiman, A Prieur-Richard, D. Soto, M. L. J. Stiassny, and C. A. Sullivan. Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews* **81**(2):163-182.

Gomes, C.P., and A. Sabharwal. 2009. Optimizing fish passage barrier removal using mixed integer linear programming. Extended Abstract, CROCS-09 Workshop, September 2009.

Hari, R. E., D. M. Livingstone, R. Siber, P. Burkhardt-Holm, and H. Guttinger. 2006. Consequences of climatic change for water temperature and brown trout populations in Alpine rivers and streams. *Global Change Biology* **12:**10–26.

Harvey, B. C., R. J. Nakamoto, and J. L. White. 2006. Reduced stream flow lowers dry-season growth of rainbow trout in a small stream. *Transactions of the American Fisheries Society* **135:**998–1005.

Hayhoe, K., D. Cayan, C. B. Field, P. C. Frumhoff, E. P. Maurer, N. L. Miller, S. C. Moser, S. H. Schneider, K.N. Cahill, E. E. Cleland, L. Dale, R. Drapek, R. M. Hanemann, L.S. Kalkstein, J. Lenihan, C. K. Lunch, R. P. Neilson, S. C. Sheridan, and J. H. Verville. 2004. Emissions pathways, climate change, and impacts on California. Proceedings of the National Academy of Sciences **101**(34):12422–12427.

Hitt, N. P., and J. H. Roberts. 2012. Hierarchical spatial structure of stream fish colonization and extinction. *Oikos* **121:**127–137.

Hoy, M., B. L. Boese, L. Taylor, D. Reusser, and R. Rodriguez. 2012. Salinity adaptation of the invasive New Zealand mud snail (*Potamopyrgus antipodarum*) in the Columbia River estuary

(Pacific Northwest, USA): Physiological and molecular studies. *Aquatic Ecology* **46:**249–260.

Independent Scientific Advisory Board. 2007. Climate change impacts on Columbia River Basin fish and wildlife. Northwest Power and Conservation Council, Portland, OR.

Jorgensen, J. C., M. M. McClure, M. B. Sheer, and N. L. Munn. 2013. Combined effects of climate change and bank stabilization on shallow water habitats of Chinook salmon. *Conservation Biology* **27**(6): 1201–1211.

Jospe, A. 2013. Aquatic barrier prioritization in New England under climate change scenarios using fish habitat quantity, thermal habitat quality, aquatic organism passage, and infrastructure sustainability. M. Sc. Thesis, University of Massachusetts—Amherst. 85pp.

Langridge, R., A. Fisher, A. Racz, B. Daniels, K. Rudestam, and B. Hihara. 2012. Climate Change and Water Supply Security: Reconfiguring Groundwater Management to Reduce Drought Vulnerability. California Energy Commission. Publication Number: CEC-500-2012-017.

Mantua, N., I. Tohver, and A. Hamlet. 2010. Climate change impacts on stream flow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climate Change* **102:**187–223.

McClurg, S. E., J. T. Petty, P. M. Mazik, and J. L. Clayton. 2007. Stream ecosystem response to limestone treatment in acid impacted watersheds of the Allegheny Plateau, West Virginia. *Ecol. Appl.* **17:**1087–1104.

McDonald, R. I., J. D. Olden, J. J. Opperman, W. M. Miller, J. Fargione, C. Revenga, J. V. Higgins, and J. Powell. 2012. Energy, water and fish: Biodiversity impacts of energy-sector water demand in the United States depend on efficiency and policy measures. PloS One 7(11): e50219.

National Oceanic and Atmospheric Administration. 2010. Programmatic framework for considering climate change impacts in coastal habitat restoration, land acquisition, and facility development investments. 55pp.

National Oceanic and Atmospheric Administration (NOAA)-Northwest Fisheries Science Center. 2008. NWFSC research related to climate change. NWR Briefing. 15pp.

National Wildlife Federation. 2013. Swimming upstream: Freshwater fish in a warming world. 34pp.

NMFS. 2012. Regional habitat assessment prioritization for California stocks. Report of the Southwest Regional Habitat Assessment Prioritization Working Group. Internal report, NMFS White Paper. Office of Science and Technology, NMFS, NOAA. Silver Spring, MD. 20pp.

Nislow, K. H., A. J. Sepulveda, and C. L. Folt. 2004. Mechanistic linkage of hydrologic regime to summer growth of age-0 Atlantic salmon. *Transactions of the American Fisheries Society* **133:**79–88.

O'Hanley, J. R. 2012. Development of the APASS Anadromous Fish Passage Barrier Prioritization Tool and Preliminary Findings. California Fish Passage Forum Meeting presentation, April 25, 2012.

O'Hanley, J. R., J. Wright, M. Diebel, M. A. Fedora, and C. L. Soucy. 2013. Restoring stream habitat connectivity: A proposed method for prioritizing the removal of resident fish passage barriers. *Journal of Environmental Management* **125:**19–27.

Osgood, K. E. (editor). 2008. Climate impacts on U.S. living marine resources: National Marine Fisheries Service concerns, activities and needs. U.S. Dep. Commerce, NOAA Tech. Memo. NMFS-F/SPO-89, 118 pp.

Palmer, M. A., R. F. Ambrose, and N. L. Poff. 2008. Ecological theory and community restoration ecology. *Rest. Ecol.* **5:**291–300.

Parmesan, C., and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 432:37–42.

Poff, N. L., J. D. Olden, D. M. Merritt, and D. M. Pepin. 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. P. National Academy of Sciences, **104:** 5732–5737.

Portner, H. O., and A. P. Farrell. 2008. Physiology and climate change. *Ecology* 322:690–692.

Rieman, B. E., and D. Isaak. 2007. Anticipated climate warming effects on bull trout habitats and populations across the interior Columbia River Basin. *Transactions of the American Fisheries Society* **136:**1552–1565.

Powell, A. M., Jr., and J. Xu. 2012. The 1977 global regime shift: A discussion of its dynamics and impacts in the eastern Pacific ecosystem. *Atmosphere-Ocean* **50:**421–436. doi:10.1080/07055900.2012.716023.

Schindler, D. E., R. Hilborn, B. Chasco, C. P. Boatright, T. P. Quinn, L. A. Rogers, and M. S. Webster. 2010. Population diversity and the portfolio effect in an exploited species. *Nature* **465:**609–613, doi:10.1038/nature09060.

Seney, E. E., M. J. Rowland, R. A. Lowery, R. B. Griffis, and M. M. McClure. 2013. Climate change, marine environments, and the U.S. Endangered Species Act. *Conservation Biology* **27**(6):1138–1146.

Walters, A., K. K. Bartz, and M. M. McClure. 2013. Interactive effects of water diversion and climate change for juvenile Chinook salmon in the Lemhi River Basin (U.S.A). *Conservation Biology* **27**(6):1179–1189.

Wedekind, C. and C. Kung. 2010. Shift of spawning season and effects of climate warming on developmental stages of a grayling (Salmonidae). *Conservation Biology* **24**(5):1418–1423.

Wenger, S. J., D. J. Isaak, C. H. Luce, H. M. Neville, K. D. Fausch, J. B. Dunham, D. C. Dauwalter, M. K. Young, M. M. Elsner, B. E. Rieman, A. F. Hamlet, and J. E. Williams. 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. *Proceedings of the National Academy of Sciences*, 10.1073/pans.1103097108. 6pp.

Winfield, I. J., J. Hateley, J. M. Fletcher, J. B. James, C. W. Bean, and P. Clabburn. 2010. Population trends of Arctic charr (*Salvelinus alpinus*) in the UK: assessing the evidence for a widespread decline in response to climate change. *Hydrobiologia* **650:**55–65.