Lakes and Ponds

Northern California Climate Change Vulnerability Assessment Synthesis

An Important Note About this Document: *This document represents an initial evaluation of vulnerability for lakes and ponds in northern California based on expert input and existing information. Specifically, the information presented below comprises vulnerability factors selected and scored by regional experts, relevant references from the scientific literature, and peer-review comments and revisions (see end of document for a glossary of terms and brief overview of study methods). The aim of this document is to expand understanding of habitat vulnerability to changing climate conditions, and to provide a foundation for developing appropriate adaptation responses.*

Peer reviewers for this document included Anonymous (U.S. Forest Service), Sam Flanagan (Bureau of Land Management), and Nina Hemphill (U.S. Forest Service). Vulnerability scores were provided by Karen Pop (U.S. Forest Service). Upper Lake workshop participants provided additional comments on the climate change vulnerability of this habitat.

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Habitat Description

Lakes and ponds in northern California occur both naturally and as man-made water bodies, and at a wide range of elevations. They generally occur in inland depressions or dammed riverine channels and are often associated with wetlands and/or riverine habitats (Cowardin et al. 1979; Grenfell 1988). Lacustrine systems typically have lower oxygen content compared to those characterized by running water (Grenfell 1988). Lakes are generally distinguished from ponds by having a greater depth and a correspondingly wider temperature profile (i.e.,

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thermocline) that supports diverse aquatic communities, including fish (Vuln. Assessment Reviewer, pers. comm., 2018). As the size of a water body increases, wind action can also influence ecosystem dynamics (De Meester et al. 2005). Elevation and terrestrial vegetation type and cover also influence aquatic structure and function by affecting temperature, nutrient inputs, and other factors associated with productivity and water quality (Piovia-Scott et al. 2016). These differences result in distinct aquatic communities in cold high-elevation lakes where aquatic productivity is low and warmer lakes at lower elevations that are characterized by high productivity and abundant populations of aquatic organisms (Melack & Schladow 2016; Piovia-Scott et al. 2016).

Executive Summary

The relative vulnerability of lakes and ponds in northern California was evaluated as moderate and moderate-high by regional experts, respectively, due to moderate sensitivity (for lakes) or moderate-high sensitivity (for ponds) to climate and non-climate stressors, moderate-high exposure to projected future climate changes, and moderate adaptive capacity.

Rank (Confidence)	Lakes	Ponds
Sensitivity	Moderate (High)	Moderate-High (High)
Exposure	Moderate-High (Moderate)	Moderate-High (Moderate)
Adaptive Capacity	Moderate (Moderate)	Moderate (Moderate)
Collective Vulnerability	**Moderate (Moderate)**	**Moderate-High (Moderate)**

Sensitivity & Exposure Summary	*Climate and climate-driven factors*: • Precipitation amount and timing, snowpack amount, timing of snowmelt and runoff, drought, water temperature *Disturbance regimes*: • Wildfire *Non-climate stressors*: • Invasive species, pollution (e.g., nutrient loading), dams, timber harvest, recreation

Lakes and ponds are sensitive to climate stressors that alter water levels, water chemistry, and biotic assemblages, including precipitation amount and timing, changes in snowpack amount, timing of snowmelt, drought, and water temperature. Given their location in depressions and valley bottoms, lakes and ponds are also sensitive to climate stressors that increase erosion and sedimentation or alter hydrologic flow within the watershed. Wildfire impacts lakes and ponds through inputs of nutrients and sediment. Introduction of non-native fish into formerly fishless lakes and ponds significantly impacts ecosystem dynamics, and may exacerbate the impacts of climate change in high-elevation lakes. Additional non-climate stressors (e.g., pollution, dams and water diversions, timber harvest, recreation) have also altered many lake and pond habitats, and the resulting changes in habitat structure, hydrology, water quality, and aquatic community assemblages may be further exacerbated by climate change.

Adaptive Capacity Summary	*Factors that enhance adaptive capacity*: + Lacustrine food webs may respond relatively quickly to changing environmental conditions + High-elevation lakes and ponds are generally in better condition than lower-elevation water bodies, due in part to their remote location *Factors that undermine adaptive capacity*: – Anthropogenic changes on the landscape (e.g., presence of dams and roads) reduce habitat connectivity and contribute to changes in hydrology that can degrade lacustrine ecosystems – Lower-elevation lakes and ponds are more vulnerable to accumulation of contaminants and introduction of invasive plants and animals – Small size of ponds makes them more vulnerable to climate and non-climate stressors

The adaptive capacity of ponds and lakes varies based on their size, depth, and hydrologic connectivity across the landscape. Dams, water diversions, and roads have reduced habitat connectivity and disrupted inflow patterns to lakes and ponds. Compared to smaller water bodies, larger ones are likely better able to respond to stressors and disturbances and still maintain highly functioning aquatic biota assemblages, but all water bodies are vulnerable to alteration from small changes in thermal and hydrological regimes. Across the landscape, lakes and ponds represent areas of high regional diversity and may provide stepping-stone habitat for aquatic and terrestrial species as the climate changes. In addition, lacustrine habitats hold high public value and offer many ecosystem services (e.g., water supply, flood control, nutrient cycling, and myriad recreational opportunities). Although directly mitigating changes in water temperatures and other climate stressors is difficult, management of riparian areas to provide shade on the springs or streams that feed lacustrine systems can reduce water temperatures. Maintaining riparian trees and shrubs to slow the flow of nutrients and trap sediment can also benefit lakes and ponds. Additionally, activities that limit nutrient inputs, erosion and sedimentation, and the establishment of invasive species may allow lacustrine habitats to better respond to the impacts of climate change.

Sensitivity and Exposure

Lakes were evaluated by regional experts as having moderate sensitivity to climate and climate-driven factors, changes in disturbance regimes, and non-climate stressors (high confidence in evaluation), while ponds were evaluated as having moderate-high sensitivity (high confidence). Both lakes and ponds were evaluated as having moderate-high overall future exposure (moderate confidence).

Sensitivity and future exposure to climate and climate-driven factors

Regional experts evaluated lakes as having moderate sensitivity to climate and climate-driven factors (high confidence in evaluation), while ponds were evaluated as having high sensitivity (high confidence). Both lakes and ponds were evaluated as having an overall moderate-high future exposure to these factors within the study region (low confidence). Key climatic factors that affect lakes and ponds include precipitation amount and timing, snowpack amount, timing of snowmelt and runoff, drought, and water temperature.[1]

Precipitation amount/timing, snowpack, timing of snowmelt/runoff, and drought

Year-to-year variation in rainfall and snowpack significantly impact the volume (e.g., depth, area) of lacustrine ecosystems (Vincent 2009; Howard & Noble 2018). Hydrological shifts in precipitation, snowpack, and snowmelt are projected to lower water levels in lakes and ponds (Sahoo et al. 2013). Impacts are likely to be particularly significant for snow-dominated systems at middle- and high- elevations where snowpack reductions are expected to be the most extreme (Young et al. 2009). Periods of drought can reduce lake volume significantly (Suchanek et al. 2003; Howard & Noble 2018). For instance, Butte Lake in Lassen Volcanic National Park (outside of the study area for this assessment) declined in total volume by 40% within the 2013–14 water year, which was in the middle of an extreme state-wide drought (Howard & Noble 2018). This resulted in a shift in lake hydrology from an open system (with surface outflow) to a closed system, and overall declines in dissolved oxygen and phytoplankton composition and biodiversity (Howard & Noble 2018). Ponds and shallow lakes may dry completely during severe droughts (Lovich et al. 2017; Purcell et al. 2017; Vuln. Assessment Reviewer, pers. comm., 2019). Extreme conditions such as these can cause collapse of the food web and extirpation of many aquatic and semi-aquatic species (e.g., Lovich et al. 2017).

Increased eutrophication and concentrations of cyanobacteria are associated with drier conditions that lead to warmer and shallower water bodies (Vincent 2009; Howard & Noble 2018; Paerl et al. 2019). An analysis of water quality in Clear Lake during droughts in the 1970s and late 1980s/early 1990s found that periods of drought were strongly correlated with increases in pH and water clarity, as well as significant increases in phosphorus and associated cyanobacteria blooms (Richerson et al. 1994 cited in Suchanek et al. 2003). As water volume and water quality decline, reduced survival and shifts in the composition of aquatic communities can occur (Furey et al. 2006; Vincent 2009).

Regional Precipitation, Snowpack, Snowmelt, and Drought Trends[2]	
Historical & current trends: • 2.6–9.4 cm (1.0–3.7 in) increase in mean annual precipitation between 1900 and 2009 for the Northwestern California, Southern	*Projected future trends:* • 23% decrease to 38% increase in mean annual precipitation by 2100 (compared to 1951–1980) for the North Coast, Northern Coast

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[1] All climate and climate-driven factors presented were ranked as having a moderate or higher impact on this habitat type. To a lesser degree, changes in upland and riparian vegetation associated with warmer air temperatures may also alter nutrient inputs (Greig et al. 2012; Vuln. Assessment Reviewer, pers. comm., 2018).

[2] Trends in climate factors and natural disturbance regimes presented in this and subsequent summary tables are not habitat-specific; rather, they represent broad trends and future projections for the study region. The precipitation, temperature, climatic water deficit, and snowpack projections for this project are derived from the Basin Characterization Model, which uses modified Jepson ecoregions (Flint et al. 2013; Flint & Flint 2014). Projections for all other factors are based on a review of relevant studies in the scientific literature. For this project, exposure was evaluated by calculating the magnitude and direction of projected change within the modified Jepson ecoregions that include habitat distribution within the study geography.

Regional Precipitation, Snowpack, Snowmelt, and Drought Trends[2]	
Cascade, and Great Valley ecoregions (Rapacciuolo et al. 2014) • 15–39% decrease in April 1 snow water equivalent (SWE) between 1951 and 2010 for the Northwestern California and Southern Cascade ecoregions (Flint et al. 2013) • 15–40-day shift towards earlier date of 90% snowmelt across the western U.S. since 1915 (Hamlet et al. 2005) • 10–30-day shift towards earlier timing of snowmelt-driven runoff across the western U.S. since 1948 (Stewart et al. 2005) • Drought years have occurred twice as often over the last two decades compared to the previous century (Diffenbaugh et al. 2015) • 2012–2014 drought set records for lowest precipitation, highest temperatures, and most extreme drought indicators on record (Griffin & Anchukaitis 2014; Diffenbaugh et al. 2015)	Range, Northern Interior Coast Range, Klamath Mountain, Southern Cascade, and Great Valley ecoregions (Flint et al. 2013; Flint & Flint 2014)[3] • Seasonal changes are projected to be more significant as the wet season becomes wetter and shorter (i.e., later onset of fall rains and earlier onset of summer drought) and the dry season becomes drier and longer (Pierce et al. 2018; Swain et al. 2018) • Overall, interannual variability is expected to increase (Pierce et al. 2018; Swain et al. 2018) • Decreases in April 1 SWE by 2100 (compared to 1951–1980; Flint et al. 2013; Flint & Flint 2014): ○ 86–99% decrease on the North Coast ○ 82–99% decrease in the Northern Coast Range ○ 99–100% decrease in the Northern Interior Coast Range ○ 72–94% decrease in the Klamath Mountains ○ 61–89% decrease in the Southern Cascades • Likely 5–15-day shift towards earlier timing of snowmelt-driven runoff in northern California by 2100 (up to 60-day shift across the western U.S.; Stewart et al. 2004; Rauscher et al. 2008) • Drought years are twice as likely to occur over the next several decades due to increased co-occurrence of dry years with very warm years (Cook et al. 2015) • 80% chance of multi-decadal drought by 2100 under a high-emissions scenario (Cook et al. 2015) • Severe droughts that now occur once every 20 years will occur once every 10 years by 2100 and once-in-a-century drought will occur once every 20 years (Pierce et al. 2018)
Summary of Potential Impacts on Habitat *(see text for citations)*	
• Reduced lake and pond depth and area, potentially leading to significant alterations in hydrological regime (e.g., change from open to closed system) • Declines in water quality and altered aquatic community composition and species survival	

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[3] Projections for changes in annual and seasonal precipitation by ecoregion can be found in the full climate impacts table (https://bit.ly/2LHgZaG).

Water temperature

A survey of six large lakes in California, including Clear Lake in Lake County, found that lake water temperatures are warming approximately twice as fast as air temperatures (Schneider et al. 2009). Warmer air temperatures, evaporation during drought conditions, and/or changes in the hydrologic cycle (e.g., reduced snowpack) can lead to lowering of water levels in lakes and ponds and warmer water temperatures (Vincent 2009). In winter, warmer water temperatures may result in fewer ice-covered days, delayed ice formation, and earlier ice-out dates (Stefan et al. 2001; Fang & Stefan 2009). In summer, warmer surface water temperatures may lead to stronger thermocline boundaries, reducing the degree of mixing that can occur as lake waters cool again in the fall and winter (Sahoo et al. 2013). Lakes that fail to completely mix experience very low levels of dissolved oxygen near the bottom (Sahoo et al. 2013), reducing suitable habitat area for invertebrates, fish, and other aquatic organisms (Fang & Stefan 2009). Overall, changes in the thermal regime are likely to contribute to shifts in aquatic species composition as warmwater species expand and coldwater species experience increasing thermal stress (Stefan et al. 2001; Schindler 2009). It is also possible that primary productivity (e.g., plants, algae, some bacteria) will increase due to warmer water temperatures (Petchey et al. 1999; O'Connor et al. 2009). However, the impacts of potential increases in primary productivity on food webs is highly uncertain due to complex interactions among species that occur at the ecosystem level (Petchey et al. 1999).

Warmer water temperatures increase the risk of harmful algal blooms, which are caused by toxic concentrations of cyanobacteria in warm, nutrient-rich waters (Visser et al. 2016; Paerl et al. 2019). Shallow lakes, such as Clear Lake in northern California, are especially vulnerable to increases in water temperatures, particularly in combination with high levels of nutrient inputs from the watershed (Grantham 2018; Paerl et al. 2019). Harmful algal blooms deplete dissolved oxygen, reduce water clarity, alter the food web, and produce toxins that can harm fish, wildlife, pets, and humans (Visser et al. 2016; Grantham 2018; Paerl et al. 2019).[4]

Regional Water Temperature Trends	
Historical & current trends: • 0.05°C (0.09°F) increase per year in summer nighttime surface water temperature of Clear Lake from 1992–2008 (Schneider et al. 2009) • No trends available for pond water temperatures	*Projected future trends:* • No projections available for lake or pond water temperatures
Summary of Potential Impacts on Habitat *(see text for citations)*	
• Increased stress in coldwater fish species, possible reductions in winter fishkill in shallow lakes, and shifts in amphibian and fish breeding phenology due to increasing water temperatures	

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[4] Although routine monitoring programs exist for only a few locations (e.g., Clear Lake), voluntary reports of harmful algae blooms are tracked statewide: https://mywaterquality.ca.gov/habs/where/freshwater_events.html

Regional Water Temperature Trends
• Increased seasonal stratification, reducing dissolved oxygen levels and resulting in associated decreases in habitat suitability for aquatic fauna • May stimulate production of cyanobacteria that form harmful algal blooms

Sensitivity and future exposure to changes in natural disturbance regimes

Regional experts evaluated lakes as having moderate sensitivity to changes in natural disturbance regimes (moderate confidence in evaluation), while ponds were evaluated as having moderate-high sensitivity (moderate confidence). Both lakes and ponds were evaluated as having an overall moderate-high future exposure to these stressors within the study region (moderate confidence). The key natural disturbance regime that affects lakes and ponds is wildfire.

Wildfire

Wildfire has myriad impacts on lakes and ponds, as changes within the watershed affect both the immediate surrounding upland area and the amount and quality of water draining into the system (Schindler 2009). Wildfires reduce the amount of vegetation around lakes and ponds, increasing water surface area exposed to solar radiation, particularly in smaller water bodies (Schindler 2009; Beakes et al. 2014). The loss of vegetation also results in higher amounts of runoff and associated increases in erosion, sedimentation, and nutrient inputs (Spencer et al. 2003; Coombs & Melack 2013). Wildfires can mobilize substantial quantities of nitrogen and phosphorus through smoke and ash fall to lakes and ponds, increasing plankton growth and eutrophication (Goldman et al. 1990; Brass et al. 1996; Spencer et al. 2003; Betts & Jones 2009). This pathway for nutrient transport can extend beyond the valley bottom of a particular fire and affect lakes in other watersheds (Spencer et al. 2003), and the effects of high nutrient inputs can last up to three years (Bayley et al. 1992; Brass et al. 1996). Physical effects can include increased wind stress on small lakes that would normally be protected by the surrounding vegetation (Parker et al. 2009).

High-intensity wildfire, in particular, may act synergistically with other stressors (e.g., drought) to significantly degrade water quality in lakes and ponds, leading to declines in and/or extirpation of aquatic organisms (Lovich et al. 2017). A study of southwestern pond turtles (*Actinemys pallida*) found this type of multiple-impact habitat degradation followed a large, severe wildfire that occurred at a southern California lake during the 2012–2016 drought (Lovich et al. 2017). Following the fire, water quality impacts contributed to the collapse of aquatic food webs, leading to high turtle mortality from starvation and dehydration (Lovich et al. 2017).

Regional Wildfire Trends	
Historical & current trends: • 85% of U.S. Forest Service lands in northern California are burning less frequently	*Projected future trends:* • State-wide, up to 77% increase in mean annual area burned and 50% increase in the frequency

Regional Wildfire Trends

compared to pre-1850 fire return intervals, largely due to fire suppression (Safford & Van de Water 2014)

- Fire size and total area burned increased on U.S. Forest Service lands in northwestern California between 1910-2008, with the highest values occurring after 2000 (Miller et al. 2012)
- Changes in large fires (over 400 ha) in the inland northern California/Sierra Nevada region since the 1970s (Westerling 2016):
  - 184–274% increase in frequency
  - 270–492% increase in total area burned
  - 215% increase in length of the fire season
- Changes in fire size, area burned, and fire frequency over the past several decades remain well below historical tribally-influenced frequency and extent of burning in California (Stephens et al. 2007)
- No significant trends in the average areal proportion of high-severity fire were documented in northwestern CA from 1984–2008 (Miller et al. 2012; Parks et al. 2015; Law & Waring 2015; Keyser & Westerling 2017)
  - The relatively short period of record for fire severity data may obscure long-term trends
  - To date, there are no peer-reviewed studies on trends in northern California fire severity that include data from the last ten years

of extremely large fires (>10,000 ha) by 2100 (Westerling 2018)

  - Greatest increases in burned area (up to 400%) occur in montane forested areas in northern California (Westerling et al. 2011; Westerling 2018)
  - Less significant increases or possible decrease along the North Coast (Westerling et al. 2011)
- Little projected change in fire severity in northwestern California by 2050 in models based solely on historical fire-climate relationships (Parks et al. 2016)
  - However, human activity and fuel buildup from decades of fire suppression have altered historical fire-climate relationships (Taylor et al. 2016; Syphard et al. 2017; Wahl et al. 2019), and projections that incorporate these factors suggest that more significant increases in fire severity and size may occur (Mann et al. 2016; Wahl et al. 2019)
- The majority of impacts to natural and human ecosystems come from extreme fire events (i.e., fires that have a low probability of occurring in any given place and time), which are likely to increase over the coming century (Westerling 2018)
  - Generally, these patterns are not well-represented in studies that evaluate indices of mean fire size, intensity/severity, etc.

Summary of Potential Impacts on Habitat *(see text for citations)*

- Alters water temperature and chemistry, changing aquatic flora and fauna abundance and interactions
- Can reduce soil stability and increase runoff, erosion, sedimentation, and organic nutrient input

Sensitivity and current exposure to non-climate stressors

Regional experts evaluated lakes and ponds as having moderate-high sensitivity to non-climate stressors (moderate confidence in evaluation), with an overall moderate current exposure to these stressors within the study region (high confidence). Key non-climate stressors that affect lakes and ponds include invasive species, pollution (e.g., nutrient loading), dams, timber harvest, and recreation.[5]

Invasive species

In lacustrine habitats, invasive species reduce the abundance and diversity of native flora and fauna through competition, increased predation risk, and/or disease spread (Cucherousset & Olden 2011; Vuln. Assessment Reviewer, pers. comm., 2018). Ultimately, these impacts can result in altered ecosystem dynamics (e.g., food webs), further increasing the sensitivity of lake and pond ecosystems to climate change (Cucherousset & Olden 2011; Vuln. Assessment Reviewer, pers. comm., 2018). In northern California, species of greatest concern include introduced fish (multiple species), American bullfrog (*Lithobates catesbeianus*), signal crayfish (*Pacifastacus leniusculus*), and the New Zealand mudsnail (*Potamopyrgus antipodarum;* CDFW 2015). Bullfrogs, in particular, are a serious threat in ponds and shallow lakes (Vuln. Assessment Reviewer, pers. comm., 2019).

Non-native fish have been stocked in many previously fishless, high-elevation lakes in northern California (Marchetti et al. 2004). In these low-productivity systems, the introduction of non-native fish can substantially increase algal production and increase competition with native fish and amphibians for emerging aquatic insect prey (Schindler et al. 2001; Epanchin et al. 2010). Introduced salmonids in high-elevation lakes in the Sierra Nevada reduced populations of mountain yellow-legged frog (*Rana muscosa*) through predation on tadpoles (Vredenburg 2004) and reduced survival, recruitment, and growth of Cascade frogs (Pope 2008). In the Trinity Alps Wilderness, researchers found that non-native trout removal rapidly increased macroinvertebrate abundance and biomass (Pope et al. 2009; Pope & Hannelly 2013). Non-native fish have also impacted aquatic community composition in lakes that historically hosted native fish; for instance, only four of the original 13 native fish species remain in Clear Lake, where 80% of fish are currently non-native species (Suchanek et al. 2003 and citations therein).

Pollution

Pollutants such as pesticides, excess nutrients, and heavy metals (e.g., mercury) can significantly degrade lake and pond water quality, with potentially severe impacts on aquatic organisms due to direct toxicity or indirectly through effects on the food chain (Suchanek et al. 2003). Excess nutrients (especially phosphorus) have been identified as a major driver of harmful algae blooms (Richerson et al. 1994 cited in Suchanek et al. 2003; Paerl et al. 2019), and are likely to be exacerbated by climate-driven increases in water temperature (Paerl et al. 2019). Pesticides have also been linked to severe declines in breeding waterfowl populations due to bioaccumulation within the food web (Suchanek et al. 2003 and citations therein). In some areas, such as around the Supher Bank Mercury Mine near Clear Lake, arsenic and mercury contamination can have additional impacts on water quality and aquatic organisms (Suchanek et al. 2003 and citations therein).

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[5] Non-climate stressors presented are those ranked as having a moderate or higher impact on this habitat type; additional non-climate stressors that may influence the habitat to a lesser degree include roads/highways/trails.

Dams

Impoundments have been shown to harbor significantly higher levels of aquatic invasive species than naturally formed lakes, and enhance the invasion risk for natural lakes by increasing their proximity to invaded water bodies, effectively serving as stepping-stone habitats for non-native aquatic species (Johnson et al. 2008). Upstream dams also prevent the movement of sediments and nutrients into lakes (Suchanek et al. 2003).

Marijuana (*Cannabis sativa*, *C. indica*) cultivation has also resulted in the construction of many non-engineered dams and water diversions constructed to create small impoundments that function as ponds (Bauer et al. 2015; Carah et al. 2015). These are most common within the North Coast Range, and are associated with many potential negative impacts, including the spread of invasive species (e.g., bullfrogs), the use of pond liners, and the accumulation of nutrient-laden runoff from grow sites (Carah et al. 2015; Vuln. Assessment Reviewer, pers. comm., 2019).

Timber harvest

Timber harvest has been shown to alter water quantity and quality in aquatic habitats, although lakes have been less well-studied than streams (Paterson et al. 1998). The impacts of timber harvest practices such as clearcutting on lakes and ponds are similar to those of severe wildfire, such as increased erosion and sedimentation following the loss of stabilizing vegetation in adjacent upland forests (Vuln. Assessment Reviewer, pers. comm. 2018). Additionally, re-growth in logged areas is often at higher densities that result in greater uptake of water resources, which could affect lake and pond levels (Vuln. Assessment Reviewer, pers. comm. 2018).

Recreation

Lakes and ponds are vulnerable to structural and biotic community changes through recreational impacts, including boating, fishing, swimming, and camping, as well as recreational trails and roads (Mosisch & Arthington 1998; Trombulak & Frissell 2000; Bunn & Arthington 2002). Motorized boating causes multiple impacts in lake and pond habitat (Bunn & Arthington 2002), including increased erosion of banks and shorelines (Mosisch & Arthington 1998) and increased turbidity in shallow areas (Hilton & Phillips 1982; Kirk 1985). Boats can also physically damage aquatic flora and fauna, including fish, by direct impact (Dokulil 2014; Whitfield & Becker 2014). Increasing human visitation to lakes has been associated with a shift in the aquatic food web toward increased algal abundance due to higher nutrient levels (Hadwen & Bunn 2005; Hadwen et al. 2005). Trampling or disturbance of banks of streams, ponds, and lakes can also increase sediment levels (Hayes et al. 2016).

Unpaved roads can supply sediment to lakes, increasing turbidity (Reid & Dunne 1984; Donohue & Garcia Molinos 2009) as well as reducing growth and survival of fish (Newcombe & Jensen 1996). Runoff of salt and other deicing or dust-control chemicals can disrupt lake stratification patterns and ecosystem dynamics (Hoffman et al. 1981; Gjessing et al. 1984).

Adaptive Capacity

Lakes and ponds were evaluated by regional experts as having moderate overall adaptive capacity (moderate confidence in evaluation).

Habitat extent, integrity, continuity, and permeability

Regional experts evaluated lakes and ponds as having a high geographic extent (high confidence in evaluation), low-moderate (at low elevations) or high (at high elevations) structural and functional integrity (high confidence), and low continuity (high confidence).

Landscape permeability for lakes and ponds was evaluated as low-moderate (moderate confidence). Dams and roads/highways/trails were identified as the primary barriers to habitat continuity and dispersal across the study region.[6]

Lake and pond habitats are found throughout California across a wide elevational range, although they are less abundant in drier areas (Grenfell 1988). In general, high-elevation lakes and ponds in the Marble, Trinity, and Klamath Mountains are in better condition than those at lower elevations (Vuln. Assessment Reviewer, pers. comm., 2019), due largely to their remote location and position within the watershed (Finlay & Vredenburg 2007).

Lakes and ponds are isolated habitats by definition, although they are sometimes linked by riparian corridors (Vincent 2009; Vuln. Assessment Reviewer, pers. comm., 2018). Hydrologic connections to other surface water bodies can be degraded or severed by dams, roads, and development (Dudgeon et al. 2006; Vincent 2009). Changes in precipitation have the potential to cause shifts in the connectivity of lakes as well as in erosion rates that could affect hydraulic inflow and outflow dynamics (Vincent 2009). Many lakes and ponds are affected by non-climate stressors that reduce their integrity, including non-native fish, nutrient enrichment, hydrological modification, and stressors from development and recreation (Vincent 2009; CDFW 2015).

Habitat diversity

Regional experts evaluated lakes and ponds as having moderate-high physical and topographical diversity (moderate confidence in evaluation), moderate-high component species diversity (moderate confidence), and moderate-high functional diversity (moderate confidence).

Lakes and ponds vary across the landscape depending on geographic setting and size and depth of the water body (Grenfell 1988). Ranging from large and hydraulically connected to small and isolated, lakes and ponds support a wide range of aquatic species (Scheffer et al. 2006). The distribution of aquatic flora and fauna in lacustrine habitats is influenced by gradations of oxygen, light, and temperature associated with elevation and water depth, with a distinct zonation of life existing from deeper water to shore (Grenfell 1988; Melack & Schladow 2016).

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[6] All barriers presented were ranked as having a moderate or higher impact on this habitat type.

In larger lakes, aquatic flora and fauna also vary along with currents and surface level fluctuations (Bunn & Arthington 2002; De Meester et al. 2005). Where they are present, top predators such as trout can act as keystone species in lacustrine ecosystems due to their influence on aquatic food webs, nutrient cycling, and energy transfer from aquatic to terrestrial habitats (Vuln. Assessment Reviewer, pers. comm., 2018).

In northern California, lakes and ponds are important habitats for myriad species of conservation importance, including mussels (e.g., winged floater [*Anodonta nuttalliana*]), northern red-legged frogs (*Rana aurora*), foothill yellow-legged frogs (*R. boylii*), salamanders (e.g., Pacific giant salamander [*Dicamptodon tenebrosus*]), migratory and resident birds, and anadromous fish, among others (Grenfell 1988; Petranka 1998; CDFW 2015; Howard et al. 2015). Based on their size, ponds contribute disproportionately to regional biodiversity (Oertli et al. 2002), with both natural and artificial ponds providing aquatic habitat and a vital water source to wildlife during the dry summer months (Vuln. Assessment Reviewer, pers. comm., 2019). Warmer, drier climate conditions are likely to impact critical aquatic refugia for invertebrates and amphibians in particular, potentially threatening reproductive success and basic life history needs (e.g., water immersion, invertebrate prey availability, predator evasion capability; Vuln. Assessment Reviewer, pers. comm., 2018).

Resistance and recovery

Regional experts evaluated lakes and ponds as having moderate resistance to climate stressors and natural disturbance regimes (moderate confidence in evaluation) and moderate-high recovery potential (moderate confidence).

In general, ponds exhibit larger changes in composition and/or structure in response to relatively small climate-driven changes (Vuln. Assessment Reviewer, pers. comm., 2018), suggesting low resistance to future climate change.

Ponds and shallow lakes, given their smaller areal extent and depth, respond relatively quickly to stressors and disturbances through changes in structure and biotic assemblages (Vuln. Assessment Reviewer, pers. comm., 2018; Scheffer & van Nes 2007). Slight changes in air and water temperatures and increasing frequency of drought can cause complex and significant changes to lake and pond habitats (Schindler et al. 1996). Recent research has shown that lacustrine food webs respond relatively quickly to changing environmental conditions, such as species adjusting spatial use of habitat (McMeans et al. 2016).

Management potential

Public and societal value

Regional experts evaluated lakes and ponds as having moderate public and societal value (high confidence in evaluation).

Lakes and ponds are a major source of water resource provision in California, and are also highly valued by the public for recreational opportunities such as boating, fishing, swimming, and camping (Grantham 2018; Vuln. Assessment Reviewer, pers. comm., 2018). Despite their high habitat and recreational value, lakes and ponds are rarely considered in economic terms and thus tend to be under-valued when it comes to financial support (Vuln. Assessment Reviewer, pers. comm., 2018). However, many communities depend on fishing and water-based recreational activities to support regional economic stability; for instance, fishing in Clear Lake can generate $1 million in tourism dollars a year (Giusti 2016). Lakes and ponds are protected to some extent through enforcement of the Clean Water Act, but this legislation does not fully protect these habitats from non-point source pollution that can lead to eutrophication and harmful algal blooms (Carpenter 2005; Welch & Cooke 2005).

Management capacity and ability to alleviate impacts[7]

Regional experts evaluated the potential for reducing climate impacts on lakes and ponds through management as low (moderate confidence in evaluation). Regional experts identified use conflicts and/or competing interests for lakes and ponds as non-native fish stocking and damming or diverting water at lake inlets/outlets for human and livestock use (Vuln. Assessment Reviewer, pers. comm., 2018).

Climate-informed management of lakes and ponds would benefit conservation target species (i.e., frogs, fish, and amphibians), maintain high biodiversity sites across the landscape, and provide the public with important water resources and recreational benefits. Management actions that may improve the resilience of lakes and ponds to climate change include:

- Maintaining riparian trees and shrubs to shade the streams and springs that feed lacustrine systems, helping to reduce water temperature (Vuln. Assessment Reviewer, pers. comm., 2019). Restoration of wetlands and riparian areas around lake and pond inputs also slows the flow of nutrients and traps sediment that would otherwise flow into connected lacustrine systems (Grantham 2018; Vuln. Assessment Reviewer, pers. comm., 2019).
- Reduce nutrient inputs to lakes and ponds to minimize eutrophication and limit the risk of harmful algal blooms (Paerl et al. 2019). Options may include improvements to wastewater treatment, supporting no-till agriculture, and maintaining/developing streamside buffer zones (Spencer et al. 2003; Jeppesen et al. 2009).
- Continue monitoring and management of invasive species (i.e., non-native fish, American bullfrog, and crayfish; Schindler et al. 2001; Gherardi et al. 2011). Removal of invasive fishes in previously fishless lakes would likely contribute to the restoration of many amphibian populations and help limit future declines (Pope 2008; Cucherousset & Olden 2011).
- Develop comprehensive, lake-based monitoring programs that would provide early warning of climate-driven changes in both lakes and watersheds (Schindler 2009).
- Capitalize on pond restoration opportunities focused on enhancing groundwater recharge to augment late summer streamflows (this strategy is currently being explored in the upper Mattole watershed; S. Flanagan, pers. comm., 2019).

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[7] Further information on climate adaptation strategies and actions for northern California can be found on the project page (https://bit.ly/31AUGs5).

Ecosystem services

Lakes and ponds provide a variety of ecosystem services, including:

- Provisioning of food, genetic resources, and fresh water;
- Regulation of water purification;
- Support of primary production, nutrient cycling, and water cycling; and
- Cultural/tribal uses for spiritual/religious purposes, knowledge systems, aesthetic values, sense of place, cultural heritage, inspiration, and recreation (Schindler 2009; Tranvik et al. 2009; Vincent 2009; Vuln. Assessment Reviewer, pers. comm., 2018).

Lakes and ponds also serve a role as sentinels and integrators of environmental events (Adrian et al. 2009; Schindler 2009). These water bodies provide information about the effects of climate change on the terrestrial landscape as well as the lake itself, increasing understanding of terrestrial-aquatic linkages (Adrian et al. 2009).

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Further information on the Northern California Climate Adaptation Project is available on the project website (https://tinyurl.com/NorCalAdaptation).

Literature Cited

Adrian R, O'Reilly CM, Zagarese H, Baines SB, Hessen DO, Keller W, Livingstone DM, Sommaruga R, Straile D, Van Donk E. 2009. Lakes as sentinels of climate change. Limnology and Oceanography **54**:2283–2297.

Bauer S, Olson J, Cockrill A, van Hattem M, Miller L, Tauzer M, Leppig G. 2015. Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four northwestern California watersheds. PLoS ONE **10**:e0120016.

Bayley SE, Schindler DW, Beaty KG, Parker BR, Stainton MP. 1992. Effects of multiple fires on nutrient yields from streams draining boreal forest and fen watersheds: nitrogen and phosphorus. Canadian Journal of Fisheries and Aquatic Sciences **49**:584–596.

Beakes MP, Moore JW, Hayes SA, Sogard SM. 2014. Wildfire and the effects of shifting stream temperature on salmonids. Ecosphere **5**:63.

Betts EF, Jones JB Jr. 2009. Impact of wildfire on stream nutrient chemistry and ecosystem metabolism in boreal forest catchments of Interior Alaska. Arctic, Antarctic, and Alpine Research **41**:407–417.

Brass JA, Ambrosia VG, Riggan PJ, Sebesta PD. 1996. Consequences of fire on aquatic nitrate and phosphate dynamics in Yellowstone National Park. Pages 53–57 in J. M. Greenlee, editor. Proceeding of the 2nd Biennial Conference on the Greater Yellowstone ecosystem. Sep. 19-21, 1993, Yellowstone National Park. International Association of Wildland Fire, Fairfield, WA.

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

Copyright EcoAdapt 2019

Carah JK et al. 2015. High time for conservation: adding the environment to the debate on marijuana liberalization. BioScience **65**:822–829.

Carpenter SR. 2005. Eutrophication of aquatic ecosystems: bistability and soil phosphorus. Proceedings of the National Academy of Sciences **102**:10002–10005.

CDFW. 2015. California State Wildlife Action Plan, 2015 Update: a conservation legacy for Californians. Prepared with assistance from Ascent Environmental, Inc. California Department of Fish and Wildlife, Sacramento, CA.

Cook BI, Ault TR, Smerdon JE. 2015. Unprecedented 21st century drought risk in the American Southwest and Central Plains. Science Advances **1**:e1400082.

Coombs JS, Melack JM. 2013. Initial impacts of a wildfire on hydrology and suspended sediment and nutrient export in California chaparral watersheds. Hydrological Processes **27**:3842–3851.

Cowardin LM, Carter V, Golet FC, LaRoe ET. 1979. Classification of wetlands and deepwater habitats of the United States. US Department of the Interior, US Fish and Wildlife Service.

Cucherousset J, Olden JD. 2011. Ecological impacts of nonnative freshwater fishes. Fisheries **36**:215–230.

De Meester L, Declerck S, Stoks R, Louette G, Van De Meutter F, De Bie T, Michels E, Brendonck L. 2005. Ponds and pools as model systems in conservation biology, ecology and evolutionary biology. Aquatic Conservation: Marine and Freshwater Ecosystems **15**:715–725.

Diffenbaugh NS, Swain DL, Touma D. 2015. Anthropogenic warming has increased drought risk in California. Proceedings of the National Academy of Sciences **112**:3931–3936.

Dokulil MT. 2014. Environmental impacts of tourism on lakes. Pages 81–88 in A. Ansari and S. Gill, editors. Eutrophication: causes, consequences and control. Springer, Dordrecht, Netherlands.

Donohue I, Garcia Molinos J. 2009. Impacts of increased sediment loads on the ecology of lakes. Biological Reviews **84**:517–531.

Dudgeon D et al. 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biological Reviews **81**:163.

Epanchin PN, Knapp RA, Lawler SP. 2010. Nonnative trout impact an alpine-nesting bird by altering aquatic-insect subsidies. Ecology **91**:2406–2415.

Fang X, Stefan HG. 2009. Simulations of climate effects on water temperature, dissolved oxygen, and ice and snow covers in lakes of the contiguous US under past and future climate scenarios. Limnology and Oceanography **54**:2359–2370.

Finlay JC, Vredenburg VT. 2007. Introduced trout sever trophic connections in watersheds: consequences for a declining amphibian. Ecology **88**:2187–2198.

Flint LE, Flint AL. 2014. California Basin Characterization Model: a dataset of historical and future hydrologic response to climate change (Ver. 1.1, May 2017). U.S. Geological Survey Data Release. Available from https://doi.org/10.5066/F76T0JPB.

Flint LE, Flint AL, Thorne JH, Boynton R. 2013. Fine-scale hydrologic modeling for regional landscape applications: the California Basin Characterization Model development and performance. Ecological Processes **2**:25.

Furey PC, Nordin RN, Mazumder A. 2006. Littoral benthic macroinvertebrates under contrasting drawdown in a reservoir and a natural lake. Journal of the North American Benthological Society **25**:19–31.

Gherardi F, Aquiloni L, Diéguez-Uribeondo J, Tricarico E. 2011. Managing invasive crayfish: is there a hope? Aquatic Sciences **73**:185–200.

Giusti G. 2016. Understanding the economic value of angling on Clear Lake: a profile of a famous lake. University of California Cooperative Extension, Riverside, CA. Available from http://ucanr.edu/sites/ClearLakeAquaticWebsite/files/247634.pdf (accessed May 14, 2019).

Gjessing E, Lygren E, Berglind L, Gulbrandsen T, Skanne R. 1984. Effect of highway runoff on lake water quality. Science of the Total Environment **33**:245–257.

Goldman CR, Jassby AD, de Amezaga E. 1990. Forest fires, atmospheric deposition and primary productivity at Lake Tahoe, California-Nevada. Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen **24**:499–503.

Grantham T. 2018. North Coast summary report. California's Fourth Climate Change Assessment. Publication number: SUM-CCC4A-2018-001. California Energy Commission, Sacramento, CA.

Greig HS, Kratina P, Thompson PL, Palen WJ, Richardson JS, Shurin JB. 2012. Warming, eutrophication, and predator loss amplify subsidies between aquatic and terrestrial ecosystems. Global Change Biology **18**:504–514.

Grenfell WE Jr. 1988. Lacustrine. In K. E. Mayer and W. F. Laudenslayer Jr., editors. A guide to wildlife habitats of California. California Department of Fish and Game, Sacramento, CA. Available from https://www.wildlife.ca.gov/Data/CWHR/Wildlife-Habitats.

Griffin D, Anchukaitis KJ. 2014. How unusual is the 2012–2014 California drought? Geophysical Research Letters **41**:9017–9023.

Hadwen WL, Bunn SE. 2005. Food web responses to low-level nutrient and 15N-tracer additions in the littoral zone of an oligotrophic dune lake. Limnology and Oceanography **50**:1096–1105.

Hadwen WL, Bunn SE, Arthington AH, Mosisch TD. 2005. Within-lake detection of the effects of tourist activities in the littoral zone of oligotrophic dune lakes. Aquatic Ecosystem Health & Management **8**:159–173.

Hamlet AF, Mote PW, Clark MP, Lettenmaier DP. 2005. Effects of temperature and precipitation variability on snowpack trends in the western United States. Journal of Climate **18**:4545–4561.

Hayes MP, Wheeler CA, Lind AJ, Green GA, Macfarlane DC. 2016. Foothill yellow-legged frog conservation assessment in California. Gen. Tech. Rep. PSW-GTR-248. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.

Hilton J, Phillips GL. 1982. The effect of boat activity on turbidity in a shallow Broadland River. Journal of Applied Ecology **19**:143–150.

Hoffman RW, Goldman CR, Paulson S, Winters GR. 1981. Aquatic impacts of deicing salts in the central Sierra Nevada Mountains, California. Journal of the American Water Resources Association **17**:280–285.

Howard JK et al. 2015. Patterns of freshwater species richness, endemism, and vulnerability in California. PLoS ONE **10**:e0130710.

Howard K, Noble P. 2018. Hydrological perturbations drive rapid shifts in phytoplankton biodiversity and population dynamics in Butte Lake (Lassen Volcanic National Park, California). Lake and Reservoir Management **34**:21–41.

Jeppesen E, Kronvang B, Meerhoff M, Søndergaard M, Hansen KM, Andersen HE, Lauridsen TL, Liboriussen L, Beklioglu M, Özen A. 2009. Climate change effects on runoff, catchment phosphorus loading and lake ecological state, and potential adaptations. Journal of Environmental Quality **38**:1930–1941.

Johnson PT, Olden JD, Vander Zanden MJ. 2008. Dam invaders: impoundments facilitate biological invasions into freshwaters. Frontiers in Ecology and the Environment **6**:357–363.

Keyser A, Westerling AL. 2017. Climate drives inter-annual variability in probability of high severity fire occurrence in the western United States. Environmental Research Letters **12**:065003.

Kirk JT. 1985. Effects of suspensoids (turbidity) on penetration of solar radiation in aquatic ecosystems. Hydrobiologia **125**:195–208.

Law BE, Waring RH. 2015. Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests. Forest Ecology and Management **355**:4–14.

Lovich JE, Quillman M, Zitt B, Schroeder A, Green DE, Yackulic C, Gibbons P, Goode E. 2017. The effects of drought and fire in the extirpation of an abundant semi-aquatic turtle from a lacustrine environment in the southwestern USA. Knowledge & Management of Aquatic Ecosystems **418**:18.

Mann ML, Batllori E, Moritz MA, Waller EK, Berck P, Flint AL, Flint LE, Dolfi E. 2016. Incorporating anthropogenic influences into fire probability models: effects of human activity and climate change on fire activity in California. PLoS ONE **11**:e0153589.

Marchetti MP, Moyle PB, Levine R. 2004. Invasive species profiling? Exploring the characteristics of non-native fishes across invasion stages in California. Freshwater Biology **49**:646–661.

McMeans BC, McCann KS, Tunney TD, Fisk AT, Muir AM, Lester N, Shuter B, Rooney N. 2016. The adaptive capacity of lake food webs: from individuals to ecosystems. Ecological Monographs **86**:4–19.

Melack J, Schladow SG. 2016. Lakes. Pages 693–712 in H. Mooney and E. Zavaleta, editors. Ecosystems of California. University of California Press, Oakland, CA.

Miller JD, Skinner CN, Safford HD, Knapp EE, Ramirez CM. 2012. Trends and causes of severity, size, and number of fires in northwestern California, USA. Ecological Applications **22**:184–203.

Mosisch TD, Arthington AH. 1998. The impacts of power boating and water skiing on lakes and reservoirs. Lakes & Reservoirs: Research & Management **3**:1–17.

Newcombe CP, Jensen JO. 1996. Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact. North American Journal of Fisheries Management **16**:693–727.

O'Connor MI, Piehler MF, Leech DM, Anton A, Bruno JF. 2009. Warming and resource availability shift food web structure and metabolism. PLoS Biology **7**:e1000178.

Oertli B, Joye DA, Castella E, Juge R, Cambin D, Lachavanne J-B. 2002. Does size matter? The relationship between pond area and biodiversity. Biological Conservation **104**:59–70.

Paerl HW, Havens KE, Hall NS, Otten TG, Zhu M, Xu H, Zhu G, Qin B. 2019. Mitigating a global expansion of toxic cyanobacterial blooms: confounding effects and challenges posed by climate change. Marine and Freshwater Research. Available from https://doi.org/10.1071/MF18392.

Parker BR, Schindler DW, Beaty KG, Stainton MP, Kasian SE. 2009. Long-term changes in climate, streamflow, and nutrient budgets for first-order catchments at the Experimental Lakes Area (Ontario, Canada). Canadian Journal of Fisheries and Aquatic Sciences **66**:1848–1863.

Parks SA, Miller C, Abatzoglou JT, Holsinger LM, Parisien M-A, Dobrowski SZ. 2016. How will climate change affect wildland fire severity in the western US? Environmental Research Letters **11**:035002.

Parks SA, Miller C, Parisien M-A, Holsinger LM, Dobrowski SZ, Abatzoglou J. 2015. Wildland fire deficit and surplus in the western United States, 1984–2012. Ecosphere **6**:1–13.

Paterson AM, Cumming BF, Smol JP, Blais JM, France RL. 1998. Assessment of the effects of logging, forest fires and drought on lakes in northwestern Ontario: a 30-year paleolimnological perspective. Canadian Journal of Forest Research **28**:1546–1556.

Petchey OL, McPhearson PT, Casey TM, Morin PJ. 1999. Environmental warming alters food-web structure and ecosystem function. Nature **402**:69–72.

Petranka JW. 1998. Salamanders of the United States and Canada. Smithsonian Institution Press, Washington, D.C.

Pierce DW, Kalansky JF, Cayan DR. 2018. Climate, drought, and sea level rise scenarios for the Fourth California Climate Assessment. California's Fourth Climate Change Assessment. Publication Number: CNRA-CEC-2018-006. California Energy Commission, Sacramento, CA.

Piovia-Scott J, Sadro S, Knapp RA, Sickman J, Pope KL, Chandra S. 2016. Variation in reciprocal subsidies between lakes and land: perspectives from the mountains of California. Canadian Journal of Fisheries and Aquatic Sciences **73**:1691–1701.

Pope KL. 2008. Assessing changes in amphibian population dynamics following experimental manipulations of introduced fish. Conservation Biology **22**:1572–1581.

Pope KL, Hannelly EC. 2013. Response of benthic macroinvertebrates to whole-lake, non-native fish treatments in mid-elevation lakes of the Trinity Alps, California. Hydrobiologia **714**:201–215.

Pope KL, Piovia-Scott J, Lawler SP. 2009. Changes in aquatic insect emergence in response to whole-lake experimental manipulations of introduced trout. Freshwater Biology **54**:982–993.

Purcell KL, McGregor EL, Calderala K. 2017. Effects of drought on western pond turtle survival and movement patterns. Journal of Fish and Wildlife Management **8**:15–27.

Rapacciuolo G et al. 2014. Beyond a warming fingerprint: individualistic biogeographic responses to heterogeneous climate change in California. Global Change Biology **20**:2841–2855.

Rauscher SA, Pal JS, Diffenbaugh NS, Benedetti MM. 2008. Future changes in snowmelt-driven runoff timing over the western US. Geophysical Research Letters **35**:L16703.

Reid LM, Dunne T. 1984. Sediment production from forest road surfaces. Water Resources Research **20**:1753–1761.

Safford HD, Van de Water KM. 2014. Using fire return interval departure (FRID) analysis to map spatial and temporal changes in fire frequency on national forest lands in California. Res. Pap. PSW-RP-266. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.

Sahoo GB, Schladow SG, Reuter JE, Coats R, Dettinger M, Riverson J, Wolfe B, Costa-Cabral M. 2013. The response of Lake Tahoe to climate change. Climatic Change **116**:71–95.

Scheffer M, Van Geest GJ, Zimmer K, Jeppesen E, Søndergaard M, Butler MG, Hanson MA, Declerck S, De Meester L. 2006. Small habitat size and isolation can promote species richness: second-order effects on biodiversity in shallow lakes and ponds. Oikos **112**:227–231.

Scheffer M, van Nes EH. 2007. Shallow lakes theory revisited: various alternative regimes driven by climate, nutrients, depth and lake size. Pages 455–466 in R. D. Gulati, E. Lammens, N. De Pauw, and E. Van Donk, editors. Shallow lakes in a changing world. Developments in Hydrobiology, vol 196. Springer, Dordrecht, Netherlands.

Schindler DE, Knapp RA, Leavitt PR. 2001. Alteration of nutrient cycles and algal production resulting from fish introductions into mountain lakes. Ecosystems **4**:308–321.

Schindler DW. 2009. Lakes as sentinels and integrators for the effects of climate change on watersheds, airsheds, and landscapes. Limnology and Oceanography **54**:2349–2358.

Schindler DW, Bayley SE, Parker BR, Beaty KG, Cruikshank DR, Fee EJ, Schindler EU, Stainton MP. 1996. The effects of climatic warming on the properties of boreal lakes and streams at the Experimental Lakes Area, northwestern Ontario. Limnology and Oceanography **41**:1004–1017.

Schneider P, Hook SJ, Radocinski RG, Corlett GK, Hulley GC, Schladow SG, Steissberg TE. 2009. Satellite observations indicate rapid warming trend for lakes in California and Nevada. Geophysical Research Letters **36**:L22402.

Spencer CN, Gabel KO, Hauer FR. 2003. Wildfire effects on stream food webs and nutrient dynamics in Glacier National Park, USA. Forest Ecology and Management **178**:141–153.

Stefan HG, Fang X, Eaton JG. 2001. Simulated fish habitat changes in North American lakes in response to projected climate warming. Transactions of the American Fisheries Society **130**:459–477.

Stephens SL, Martin RE, Clinton NE. 2007. Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. Forest Ecology and Management **251**:205–216.

Stewart IT, Cayan DR, Dettinger MD. 2004. Changes in snowmelt runoff timing in western North America under a `business as usual' climate change scenario. Climatic Change **62**:217–232.

Stewart IT, Cayan DR, Dettinger MD. 2005. Changes toward earlier streamflow timing across western North America. Journal of Climate **18**:1136–1155.

Suchanek TH et al. 2003. Evaluating and managing a multiply-stressed ecosystem at Clear Lake, California: a holistic ecosystem approach. Pages 1239–1271 in D. J. Rapport, B. L. Lasley, D. E.

Rolston, N. O. Nielsen, C. O. Qualset, and A. B. Damania, editors. Managing for healthy ecosystems. Routledge, Abingdon, UK.

Swain DL, Langenbrunner B, Neelin JD, Hall A. 2018. Increasing precipitation volatility in twenty-first-century California. Nature Climate Change **8**:427.

Syphard AD, Keeley JE, Pfaff AH, Ferschweiler K. 2017. Human presence diminishes the importance of climate in driving fire activity across the United States. Proceedings of the National Academy of Sciences **114**:13750–13755.

Taylor AH, Trouet V, Skinner CN, Stephens S. 2016. Socioecological transitions trigger fire regime shifts and modulate fire–climate interactions in the Sierra Nevada, USA, 1600–2015 CE. Proceedings of the National Academy of Sciences **113**:13684–13689.

Tranvik LJ, Downing JA, Cotner JB, Loiselle SA, Striegl RG, Ballatore TJ, Dillon P, Finlay K, Fortino K, Knoll LB. 2009. Lakes and reservoirs as regulators of carbon cycling and climate. Limnology and Oceanography **54**:2298–2314.

Trombulak SC, Frissell CA. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology **14**:18–30.

Vincent WF. 2009. Effects of climate change on lakes. Pages 55–60 in G. E. Likens, editor. Encyclopedia of Inland Waters. Elsevier, Amsterdam.

Visser PM, Verspagen JMH, Sandrini G, Stal LJ, Matthijs HCP, Davis TW, Paerl HW, Huisman J. 2016. How rising CO_2 and global warming may stimulate harmful cyanobacterial blooms. Harmful Algae **54**:145–159.

Vredenburg VT. 2004. Reversing introduced species effects: experimental removal of introduced fish leads to rapid recovery of a declining frog. Proceedings of the National Academy of Sciences **101**:7646–7650.

Wahl ER, Zorita E, Trouet V, Taylor AH. 2019. Jet stream dynamics, hydroclimate, and fire in California from 1600 CE to present. Proceedings of the National Academy of Sciences **116**:5393–5398.

Welch EB, Cooke GD. 2005. Internal phosphorus loading in shallow lakes: importance and control. Lake and Reservoir Management **21**:209–217.

Westerling AL. 2016. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. Philosophical Transactions of the Royal Society B: Biological Sciences **371**:20150178.

Westerling AL. 2018. Wildfire simulations for California's Fourth Climate Change Assessment: projecting changes in extreme wildfire events with a warming climate. California's Fourth Climate Change Assessment. Publication Number: CCCA4-CEC-2018-014. California Energy Commission, Sacramento, CA.

Westerling AL, Bryant BP, Preisler HK, Holmes TP, Hidalgo HG, Das T, Shrestha SR. 2011. Climate change and growth scenarios for California wildfire. Climatic Change **109**:445–463.

Whitfield AK, Becker A. 2014. Impacts of recreational motorboats on fishes: a review. Marine Pollution Bulletin **83**:24–31.

Young CA, Escobar-Arias MI, Fernandes M, Joyce B, Kiparsky M, Mount JF, Mehta VK, Purkey D, Viers JH, Yates D. 2009. Modeling the hydrology of climate change in California's Sierra Nevada for subwatershed scale adaptation. Journal of the American Water Resources Association **45**:1409–1423.

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Northern California Climate Adaptation Project:
Vulnerability Assessment Methods and Application

Defining Terms

Exposure: A measure of how much of a change in climate or climate-driven factors a resource is likely to experience (Glick et al. 2011).

Sensitivity: A measure of whether and how a resource is likely to be affected by a given change in climate or factors driven by climate (Glick et al. 2011).

Adaptive Capacity: The ability of a resource to accommodate or cope with climate change impacts with minimal disruption (Glick et al. 2011).

Vulnerability: A function of the sensitivity of a particular resource to climate changes, its exposure to those changes, and its capacity to adapt to those changes (IPCC 2007).

Vulnerability Assessment Model

The vulnerability assessment model applied in this process was developed by EcoAdapt (EcoAdapt 2014a; EcoAdapt 2014b; Kershner 2014; Hutto et al. 2015; Gregg 2018),[8] and includes evaluations of relative vulnerability by local and regional stakeholders who have detailed knowledge about and/or expertise in the ecology, management, and threats to focal habitats, species groups, individual species, and the ecosystem services that these resources provide. Stakeholders evaluated vulnerability for each resource by discussing and answering a series of questions for sensitivity and adaptive capacity. Exposure was evaluated by EcoAdapt using projected future climate changes from the scientific literature. Each vulnerability component (i.e., sensitivity, adaptive capacity, and exposure) was divided into specific elements. For example, habitats included three elements for assessing sensitivity and six elements for adaptive capacity. Elements for each vulnerability component are described in more detail below.

In-person workshops were held in Eureka, Redding, and Upper Lake between May and October 2017. Participants self-selected habitat and species group/species breakout groups and evaluated the vulnerability of each resource. Participants were first asked to describe the habitat and/or to list the species to be considered in the evaluation of an overarching species group. Due to limitations in workshop time and participant expertise, multiple resources were not assessed during these engagements. Evaluations for remaining habitats, species groups, and species were completed by contacting resource experts.[9]

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[8] Sensitivity and adaptive capacity elements were informed by Lawler 2010, Glick et al. 2011, and Manomet Center for Conservation Sciences 2012.

[9] Resources evaluated by experts included: coastal bluff/scrub habitats, coastal conifer hardwood forest, true fir forest, lakes/ponds, freshwater marshes, vernal pools, seeps/springs, native insect pollinators, native ungulates, salamanders, frogs, native mussels, marbled murrelet, and northwestern pond turtle.

Stakeholders assigned one of five rankings (High, Moderate-High, Moderate, Low-Moderate, or Low) for sensitivity and adaptive capacity. EcoAdapt assigned rankings for projected future climate exposure. Rankings for each component were then converted into scores (High-5, Moderate-High-4, Moderate-3, Low-Moderate-2, or Low-1), and the scores were averaged (mean) to generate an overall score. For example, scores for each element of habitat sensitivity were averaged to generate an overall habitat sensitivity score. Scores for exposure were weighted less than scores for sensitivity and adaptive capacity because the uncertainty about the magnitude and rate of future change is greater. Sensitivity, adaptive capacity, and exposure scores were combined into an overall vulnerability score calculated as:

Vulnerability = [(Climate Exposure*0.5) x Sensitivity] - Adaptive Capacity

Elements for each component of vulnerability were also assigned one of three confidence rankings (High, Moderate, or Low). Confidence rankings were converted into scores (High-3, Moderate-2, or Low-1) and the scores averaged (mean) to generate an overall confidence score. These approximate confidence levels were based on the Manomet Center for Conservation Sciences (2012) 3-category scale, which collapsed the 5-category scale developed by Moss and Schneider (2000) for the IPCC Third Assessment Report. The vulnerability assessment model applied here assesses the confidence associated with individual element rankings and, from these rankings, estimates the overall level of confidence for each component of vulnerability and then for overall vulnerability.

Stakeholders and decision-makers can consider the rankings and scores presented as measures of relative vulnerability and confidence to compare the level of vulnerability among the focal resources evaluated in this project. Elements that received lower confidence rankings indicate knowledge gaps that applied scientific research could help address.

Vulnerability Assessment Model Elements

Sensitivity & Exposure (Applies to Habitats, Species Groups, Species)

- **Climate and Climate-Driven Factors:** e.g., air temperature, precipitation, freshwater temperature, soil moisture, snowpack, extreme events: drought, altered streamflows, etc.
- **Disturbance Regimes:** e.g., wildfire, flooding, drought, insect and disease outbreaks, wind
- **Future Climate Exposure:** e.g., consideration of projected future climate changes (e.g., temperature and precipitation) as well as climate-driven changes (e.g., altered fire regimes, altered water flow regimes, shifts in vegetation types)
- **Stressors Not Related to Climate:** e.g., tectonic and volcanic events; residential or commercial development; agriculture and/or aquaculture; roads, highways, trails; dams and water diversions; invasive and other problematic species; livestock grazing; fire suppression; timber harvest; mining; etc.

Sensitivity & Exposure (Applies to Species Groups and Species)

- **Dependencies:** e.g., dependencies on sensitive habitats, specific prey or forage species, and the timing of the appearance of these prey and forage species (concern for mismatch)

Sensitivity & Exposure (Applies to Species ONLY)

- **Life History:** e.g., species reproductive strategy, average length of time to reproductive maturity

Adaptive Capacity (Applies to Habitats, Species Groups, Species)

- **Extent, Integrity, and Continuity/Connectivity:** e.g., resources that are widespread vs. limited, structural and functional integrity (e.g., degraded or pristine) of a habitat or health and functional integrity of species (e.g., endangered), isolated vs. continuous distribution
- **Landscape Permeability:** e.g., barriers to dispersal and/or continuity (e.g., land-use conversion, energy production, roads, timber harvest, etc.)
- **Resistance and Recovery:** e.g., *resistance* refers to the stasis of a resource in the face of change, *recovery* refers to the ability to "bounce back" more quickly from the impact of stressors once they occur
- **Management Potential:** e.g., ability to alter the adaptive capacity and resilience of a resource to climatic and non-climate stressors (societal value, ability to alleviate impacts, capacity to cope with impacts)
- **Ecosystem Services:** e.g., provisioning, regulating, supporting, and/or cultural services that a resource produces for human well-being

Adaptive Capacity (Applies to Habitats ONLY)

- **Habitat Diversity:** e.g., diversity of physical/topographical characteristics, component native species and functional groups

Adaptive Capacity (Applies to Species Groups, Species)

- **Dispersal Ability**: i.e., ability of a species to shift its distribution across the landscape as the climate changes
- **Intraspecific/Life History Diversity:** e.g., life history diversity, genetic diversity, phenotypic and behavioral plasticity

Literature Cited

EcoAdapt. 2014a. A climate change vulnerability assessment for aquatic resources in the Tongass National Forest. EcoAdapt, Bainbridge Island, WA. 124 pp.

EcoAdapt. 2014b. A climate change vulnerability assessment for resources of Nez Perce-Clearwater National Forests. Version 3.0. EcoAdapt, Bainbridge Island, WA. 398 pp.

Glick P, Stein BA, Edelson NA. 2011. Scanning the conservation horizon: A guide to climate change vulnerability assessment. National Wildlife Federation, Washington, D.C.

Gregg RM, editor. 2018. Hawaiian Islands climate vulnerability and adaptation synthesis. EcoAdapt, Bainbridge Island, WA. 284 pp.

Hutto SV, Higgason KD, Kershner JM, Reynier WA, Gregg DS. 2015. Climate change vulnerability assessment for the north-central California coast and ocean. Marine Sanctuaries Conservation Series ONMS-15-02. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 473 pp.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Pages 617–652 in M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, editors. Cambridge University Press, Cambridge, UK.

Kershner JM, editor. 2014. A climate change vulnerability assessment for focal resources of the Sierra Nevada. Version 1.0. EcoAdapt, Bainbridge Island, WA. 418 pp.

Lawler J. 2010. Pacific Northwest Climate Change Vulnerability Assessment. From http://climatechangesensitivity.org

Manomet Center for Conservation Sciences and National Wildlife Federation. 2012. The vulnerabilities of fish and wildlife habitats in the Northeast to climate change. A report to the Northeastern Association of Fish and Wildlife Agencies and the North Atlantic Landscape Conservation Cooperative. Manomet Center for Conservation Sciences, Plymouth, MA.

Moss R, Schneider S. 2000. Towards consistent assessment and reporting of uncertainties in the IPCC TAR. In R. Pachauri and T. Taniguchi, editors. *Cross-Cutting Issues in the IPCC Third Assessment Report*. Global Industrial and Social Progress Research Institute (for IPCC), Tokyo.

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