Focal Resource: AQUATIC SYSTEMS

CWHR Types[1]: N/A

General Overview of Process

EcoAdapt, in collaboration with the U.S. Forest Service and California Landscape Conservation Cooperative (CA LCC), convened a 2.5-day workshop entitled *A Vulnerability Assessment Workshop for Focal Resources of the Sierra Nevada* on March 5-7, 2013 in Sacramento, California. Over 30 participants representing federal and state agencies, non-governmental organizations, universities, and others participated in the workshop[2]. The following document represents the vulnerability assessment results for the **AQUATIC ECOSYSTEM**, which is comprised of evaluations and comments from a participant breakout group during this workshop, peer-review comments following the workshop from at least one additional expert in the subject area, and relevant references from the literature. The aim of this synthesis is to expand understanding of resource vulnerability to changing climate conditions, and to provide a basis for developing appropriate adaptation responses. The resulting document is an initial evaluation of vulnerability based on existing information and expert input. Users are encouraged to refer to the Template for Assessing Climate Change Impacts and Management Options (TACCIMO, http://www.taccimo.sgcp.ncsu.edu/) website for the most current peer-reviewed literature on a particular resource. This synthesis is a living document that can be revised and expanded upon as new information becomes available.

Geographic Scope

The project centers on the Sierra Nevada region of California, from foothills to crests, encompassing ten national forests and two national parks. Three geographic sub-regions were identified: north, central, and south. The north sub-region includes Modoc, Lassen, and Plumas National Forests; the central sub-region includes Tahoe, Eldorado, and Stanislaus National Forests, the Lake Tahoe Basin Management Unit, and Yosemite National Park; and the south sub-region includes Humboldt-Toiyabe, Sierra, Sequoia, and Inyo National Forests, and Kings Canyon/Sequoia National Park.

Key Definitions

Vulnerability: Susceptibility of a resource to the adverse effects of climate change; a function of its sensitivity to climate and non-climate stressors, its exposure to those stressors, and its ability to cope with impacts with minimal disruption[3].

Sensitivity: A measure of whether and how a species or system is likely to be affected by a given change in climate or factors driven by climate.

Adaptive Capacity: The degree to which a species or system can change or respond to address climate impacts.

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[1] From California Wildlife Habitat Relationship (CWHR) habitat classification scheme http://www.dfg.ca.gov/biogeodata/cwhr/wildlife_habitats.asp

[2] For a list of participant agencies, organizations, and universities please refer to the final report *A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada* available online at: http://ecoadapt.org/programs/adaptation-consultations/calcc.

[3] Glick, P., B.A. Stein, and N.A. Edelson, editors. 2011. Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment. National Wildlife Federation, Washington, D.C.

Exposure: The magnitude of the change in climate or climate driven factors that the species or system will likely experience.

Methodology

The vulnerability assessment comprises three vulnerability components (i.e., sensitivity, adaptive capacity, and exposure), averaged rankings for those components, and confidence scores for those rankings (see tables below). The sensitivity, adaptive capacity, and exposure components each include multiple finer resolution elements that were addressed individually. For example, sensitivity elements include: direct sensitivity of the system to temperature and precipitation, sensitivity of component species within the system, ecosystem sensitivity to disturbance regimes (e.g., wind, drought, flooding), sensitivity to other climate and climate-driven changes (e.g., snowpack, altered hydrology, wildfire), and sensitivity to non-climate stressors (e.g., grazing, recreation, infrastructure). Adaptive capacity elements include: ecosystem extent, integrity, and fragmentation; ecosystem ability to resist or recover from stressors; landscape permeability; ecosystem diversity (e.g., physical, topographical, component species, functional groups); and ecosystem value and management potential. To assess exposure, participants were asked to identify the climate and climate-driven changes most relevant to consider for the ecosystem and to evaluate exposure to those changes for each of the three Sierra Nevada geographic sub-regions. Climate change projections were provided to participants to facilitate this evaluation[4]. For more information on each of these elements of sensitivity, adaptive capacity, and exposure, including how and why they were selected, please refer to the final methodology report *A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada*[5].

During the workshop, participants assigned one of three rankings (High (>70%), Moderate, or Low (<30%)) to each finer resolution element and provided a corresponding confidence score (e.g., High, Moderate, or Low) to the ranking. These individual rankings and confidence scores were then averaged (mean) to generate rankings and confidence scores for each vulnerability component (i.e., sensitivity, adaptive capacity, exposure score) (see table below). Results presented in a range (e.g. from moderate to high) reflect variability assessed by participants. Additional information on ranking and overall scoring can be found in the final methodology report *A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada*[5].

Recommended Citation

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This document is available online at EcoAdapt (http://ecoadapt.org/programs/adaptation-consultations/calcc).

[4] Geos Institute. 2013. *Future Climate, Wildfire, Hydrology, and Vegetation Projections for the Sierra Nevada, California: A climate change synthesis report in support of the Vulnerability Assessment/Adaptation Strategy process.* Ashland, OR. http://ecoadapt.org/programs/adaptation-consultations/calcc.
[5] Kershner, J.M., editor. 2014. *A Climate Change Vulnerability Assessment for Focal Resources of the Sierra Nevada.* Version 1.0. EcoAdapt, Bainbridge Island, WA. http://ecoadapt.org/programs/adaptation-consultations/calcc.

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Overview of Vulnerability Component Evaluations

SENSITIVITY

Sensitivity Factor	Sensitivity Evaluation	Confidence
Direct Sensitivities – Temperature	**3 High**	**2 Moderate**
Direct Sensitivities – Precipitation	**3 High**	**2 Moderate**
Component Species	**3 High**	**2 Moderate**
Disturbance Regimes	**3 High**	**2 Moderate**
Climate-Driven Changes	**3 High**	**2 Moderate**
Non-Climatic Stressors – Current Impact	**3 High**	**2 Moderate**
Non-Climatic Stressors – Influence Overall Sensitivity to Climate	**3 High**	**2 Moderate**
Other Sensitivities	**No answer provided by participants**	**No answer provided by participants**

Overall Averaged Confidence (Sensitivity)[6]: Moderate

Overall Averaged Ranking (Sensitivity)[7]: High

ADAPTIVE CAPACITY

Adaptive Capacity Factor	Adaptive Capacity Evaluation	Confidence
Extent and Integrity – Distribution	**3 High**	**3 High**
Extent and Integrity – Fragmentation	**3 High**	**1 Low**
Resistance and Recovery	**No answer provided by participants**	**3 High**
Landscape Permeability	**1 Low**	**2 Moderate**
System Diversity – Physical/Topographical	**3 High**	**3 High**
System Diversity – Component Species/Functional Groups	**3 High**	**1 Low**
System Value	**3 High**	**2 Moderate**
Specificity of Management Rules	**3 High**	**2 Moderate**
Other Adaptive Capacities	**No answer provided by participants**	**No answer provided by participants**

Overall Averaged Confidence (Adaptive Capacity)[6]: Moderate

Overall Averaged Ranking (Adaptive Capacity)[7]: High

EXPOSURE

Relevant Exposure Factor	Confidence
Temperature	**1 Low**
Precipitation	**1 Low**

[6] Overall confidence is an average of the confidence column for sensitivity, adaptive capacity, or exposure, respectively.

[7] Overall sensitivity, adaptive capacity, and exposure are an average of the sensitivity, adaptive capacity, or exposure evaluation columns above, respectively.

Relevant Exposure Factor	Confidence
Dominant vegetation type	**1 Low**
Snowpack	**1 Low**
Runoff	**1 Low**
Timing of flows	**1 Low**
Low flows	**1 Low**
High flows	**1 Low**
Stream temperature	**1 Low**
Other – water quality	**1 Low**

Exposure Region	Exposure Evaluation (2010-2080)	Confidence
Northern Sierra Nevada	**No answer provided by participants**	**No answer provided by participants**
Central Sierra Nevada	**No answer provided by participants**	**No answer provided by participants**
Southern Sierra Nevada	**No answer provided by participants**	**No answer provided by participants**

Overall Averaged Confidence (Exposure)[6]: Not applicable

Overall Averaged Ranking (Exposure)[7]: Not applicable

Sensitivity

1. Direct sensitivities to changes in temperature and precipitation.

a. Sensitivity to temperature (means & extremes): High

i. Participant confidence: Moderate

b. Sensitivity to precipitation (means & extremes): High

i. Participant confidence: Moderate

Additional comments: More specific analysis on the sensitivity of aquatic systems could be determined by incorporating elevation and climatic zones information.

References:
Temperature: Stream temperatures have increased in recent decades as air temperatures have increased (Hari et al. 2006, Webb and Nobilis 2007, Kaushal et al. 2010 cited in Null et al. 2012).

Stream temperatures are strongly correlated with climate (Morrill et al. 2005). Relationship between air and stream temperature is not linear, particularly as stream temperature exceeds 20˚C, when evaporative cooling slows heating (Null et al. 2012). Stream temperatures directly influence the biological, physical, and chemical properties of lotic ecosystems, including metabolic rates and life histories, dissolved oxygen levels, nutrient cycling, productivity, and rates of chemical reactions (Vannote and Sweeney 1980; Poole and Berman 2001). Stream warming may alter stream habitat conditions, change the distribution and abundance of native species, drive local extinctions, reduce community biodiversity, and ease the introduction of invasive species (Eaton and Scheller 1996, Rahel and Olden 2008 cited in Null et al. 2012). In addition, warming temperatures influence the partitioning of precipitation between rain, snow, runoff and infiltration, and these changes in the nature, frequency, and abundance of precipitation also impact water temperature (Null et al. 2012).

Precipitation: Mean precipitation at watershed outlets of 15 streams (5-7 Strahler stream order) in the Sierra Nevada averaged 1080 mm/yr (42.5 in/yr) and ranged between 560-1675 mm/yr (22-66 in/yr) (Null et al. 2012). The frequency, abundance and nature of precipitation events impact water temperature (Null et al. 2012), level, and velocity (Meyers et al. 2010). Flow changes may result in altered channel topography and substrate (Yarnell et al. 2010), ephemeral streams, and altered dynamics of salmon redd scour and dewatering (Meyers et al. 2010).

Changes in precipitation can also impact primary productivity in lakes (Coats 2010; Sadro and Melack 2012).

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2. Sensitivity of component species.

a. Sensitivity of component species to climate change: High

i. Participant confidence: Moderate

Additional comments: Coldwater species won't be able to adapt to temperature changes because they are physically restricted to their river and cannot move to a new one.

The number of endemic fishes in the Sierra Nevada is high for both warm and cold water species. Many of these fish and amphibians have reduced ranges and are sensitive to large-scale disturbances and warming temperatures.

References: Aquatic species in California are likely to be impacted by changes associated with climate change, including changes in water temperature, quality, and the frequency, intensity and timing of stream flow (Coats 2010; Null et al. 2010; Yarnell et al. 2010; Kiernan and Moyle 2012). Most native fish species requiring cold water (<22˚C) and all native anadromous fish were rated highly or critically vulnerable to climate change (Moyle et al. 2012). Fishes in the families *Cyprinodontidae*, *Embiotocidae*, *Osmeridae*, *Petromyzontidae*, *Salmonidae*, for example, were almost all rated highly or critically vulnerable to climate change (Moyle et al. 2012). However, uncertainty remains regarding temperature thresholds for coldwater guild species, and thresholds are variable by life stage, previous acclimation, duration of thermal maxima and minima, food abundance, competition, predation, body size and condition (McCullough 1999). All California salmonid populations are adversely impacted by the shrinking availability of coldwater habitats (Katz et al. 2012). Because they are at the southern boundary of their range, small thermal increases in summer water temperatures can result in suboptimal and lethal conditions with consequent reductions in distribution and abundance of California's endemic salmon, trout and steelhead (Katz et al. 2012). The maximum thermal tolerance for Chinook salmon (*O. tshawytscha*) and steelhead trout is reported as 24˚C (Eaton and Scheller 1996), although both can tolerate warmer temperatures for shorter periods (Myrick and Cech 2001). Water temperatures above 20˚C can have adverse spawning and rearing effects in Chinook salmon (Yates et al. 2008). The egg and alevin life stages require <24˚C temperatures for optimal growth and survival. Bull trout (*Salvelinus confluentus*) in North America have an optimal temperature range lower than other salmonids, and are threatened by climate change directly through thermally stressful temperatures and indirectly by increased competitive ability of other trout species (Rahel et al. 2008).

Freshwater fish species native to California tend to be more affected by climate change than alien fish species (Moyle et al. 2012). Longer warm, low-flow seasons may expand abundance of nonnative fauna (Yarnell et al. 2010). Amphibians that breed in ephemeral and often isolated bodies of water (e.g., vernal pools and intermittent headwater streams) are especially vulnerable to changes in temperature and precipitation (Blaustein et al. 2010). Downstream species, such as the delta smelt (*Hypomesus transpacificus*), may also be particularly vulnerable to temperature changes. Rising temperatures are likely to reduce spawning season, or eliminate spawning entirely (Hanak and Lund 2011).

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3. Sensitivity to changes in disturbance regimes.

a. Sensitivity to disturbance regimes including: Wildfire, drought, flooding, disease
b. Sensitivity to these disturbance regimes: High
    i. Participant confidence: Moderate

Additional comments: Post-fire impacts represent a considerable disturbance.

References:
Flooding and drought: The frequency, abundance and nature of precipitation events impact water temperature (Null et al. 2012), level, and velocity (Meyers et al. 2010). Flow changes may result in altered channel topography and substrate (Yarnell et al. 2010), ephemeral streams, and altered dynamics of salmon redd scour and dewatering (Meyers et al. 2010).

Disease: Stream warming is projected to magnify the distribution and virulence of disease organisms and parasites, increasing the impact on native salmonids (Rahel et al. 2008).

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4. Sensitivity to other types of climate and climate-driven changes.

a. Sensitivity to climate and climate-driven changes including: Altered fire regimes, evapotranspiration and soil moisture, altered hydrology, extreme temperature or precipitation events, water temperature, storms, air pollution/ozone, other – disease, water pollution
b. Sensitivity to these climate and climate-driven changes: High
    i. Participant confidence: Moderate

Additional comments: Each non-climate factor listed above contributes to changes in water temperature, sediment load, inorganic / organic nutrient load, oxygen deficiencies, resulting in lower habitat availability and lower overall biodiversity in aquatic systems. These factors also lead to reduced primary productivity in lakes. In addition, wildfire can impact pH of the system.

References:
Altered hydrology: Predicted quick pulses of higher winter rainfall in contrast to slower snowmelt will change how sediments are sorted and deposited, resulting in more homogenous channel substrates; channel bars may become more steeply sloped, creating less habitat availability and less overall biodiversity (Yarnell et al. 2010). Reduced streamflow may shift some streams into intermittent flow (Perry et al. 2012), which could affect coldwater species (including amphibians and macro-invertebrates) (Blaustein et al. 2010; Null et al. 2012). Increased terrestrial inputs to Sierran lakes, precipitated by increased frequency of rain events, may result in reduced primary production, increased periods of hypoxia and anoxia, and shift toward net heterotrophy during ice-free seasons (Coats 2010; Sadro and Melack 2012).

Water temperature: According to modeling by Null et al. (2012), average annual stream temperatures warmed approximately 1.6˚C for each 2˚C rise in average annual air temperature. The greatest rise in stream temperatures in response to air temperatures was projected at mid elevation (1500-2500 m) (4921-8202 ft), where climate warming shifted precipitation from snowmelt to rainfall. The largest thermal change occurred during spring in the models, when stream warming could exceed 5˚C for each 2˚C rise in air temperature (Null et al. 2012). Stream temperatures are also affected by riparian vegetation species, height, density and location, as well as stream orientation (LeBlanc and Brown 2000) and topographic shading (Null et al. 2012). However, above 2750 m (9022 ft) elevation, shading may be negligible due to short growing season and poor soils (Null et al. 2012).

In turn, stream temperatures directly influence the biological, physical, and chemical properties of lotic ecosystems, including metabolic rates and life histories, dissolved oxygen levels, nutrient cycling, productivity, and rates of chemical reactions (Vannote and Sweeney 1980; Poole and Berman 2001). Predicted reduction in the magnitude of snowmelt rate is forecast to cause longer, warmer low-flow seasons, with shorter duration of cold water in the system (Yarnell et al. 2010). Stream warming may alter stream habitat conditions, reduce community biodiversity, change the distribution and abundance of organisms, drive local extinctions, and ease the introduction of invasive species (Null et al. 2012). Warmer stream temperatures may inhibit distribution and survival of coldwater species, including abundance of aquatic insects (Perry et al. 2012) and amphibian species that breed in vernal pools and intermittent headwater streams (Blaustein et al. 2010). Modeling results indicate that habitat for coldwater species declined with climate warming (Null et al. 2012). In lakes, increased temperature decreases the solubility of gases, and processes such as denitrification and nitrogen fixation are accelerated. Such changes can lead to water quality problems in Lake Tahoe and other lakes (Coats 2010).

Wildfire: Changes in wildfire regimes may also impact temperature, sediment load and pH of aquatic systems. Wildfires alter riparian vegetation and stream shade (Dwire and Kauffman 2003, Pettit and Naiman 2007 cited in Isaak et al. 2010), and combined with altered forest and riparian communities, may change inputs of sediment and large wood (Miller et al. 2003, Barnett et al. 2008 cited in Rieman and Isaak 2010).

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5. Sensitivity to impacts of other non-climate stressors.

a. Sensitivity to other non-climate stressors including: Residential and commercial development, agriculture and aquaculture (e.g., logging and grazing), energy production and mining (e.g., hydropower dams and water diversions), transportation and service corridors, biological resource use (e.g., fish stocking), human intrusions and disturbance, natural system modifications (e.g., hydropower dams and water diversions), invasive and other problematic species, pollution and poisons

b. Current effects of these identified stressors on system: High
    i. Participant confidence: Moderate
c. Degree stressors increase sensitivity to climate change: High
    i. Participant confidence: Moderate

Additional comments: Aquatic systems are highly sensitive to the impacts of various resource uses (e.g., fish stocking, logging, and grazing), natural system modification (hydropower facilities and dams), and residential and commercial development. Aquatic systems are also highly sensitive to transportation and service corridors, human intrusions and disturbance, pollution and poisons, and agriculture. Aquatic systems have low sensitivity to invasive species, aquaculture, energy production, and mining (due to a moratorium on mining).

References identified by participants: State of Sierra Waters: A Sierra Nevada Watersheds Index[8].

References: Non-climate stressors include biological resource use, such as fish stocking (Null et al. 2012); natural system modification, such as water diversion and hydropower production (Yoshiyama et al. 1998; Null et al. 2012); and residential and commercial development (Null et al. 2012). Rivers above 2000 m (6562 ft) on the western slope of the Sierra Nevada were mostly fishless prior to stocking with native rainbow trout (*Onchorhynchus mykiss*) and golden trout (O. *mykiss aguabonita*), as well as non-native brown trout (*Salmo truta*) and brook trout *(Salvelinus fontinalis*) (Null et al. 2012). Water regulation and land use changes have altered the thermal regime of Sierra Nevada rivers, degrading habitat and creating a dispersal barrier to cold water assemblages (Null et al. 2012; Perry et al. 2012). After construction of large dams, salmon runs, once among the most productive on the Pacific coast, have largely been extirpated from Sierra Nevada rivers (Yoshiyama et al. 1998).

Grazing and timber harvest intensifies mercury contamination moving from mining areas into rivers and streams in northern Sierra Nevada catchments (Alpers et al. 2005 cited by Viers and Rheinheimer 2011). Timber harvest and grazing also results in erosion, which degrades or eliminates fish spawning habitat (Moyle 2002 cited in Viers and Rheinheimer 2011).

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6. Other sensitivities.

a. Other critical sensitivities not addressed: no answer provided by participants
    i. Participant confidence: no answer provided by participants
b. Collective degree these factors increase system sensitivity to climate change: no answer provided by participants

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7. Overall user ranking.

a. Overall sensitivity of this system to climate change: High
    i. Participant confidence: Moderate

References: Scenarios run by Moyle et al. (2012) identify most native species requiring cold water (<22°C) as highly or critically vulnerable to climate change.

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[8] http://www.sierranevadaalliance.org/publications/db/pics/1143036971_22153.f_pdf.pdf

Adaptive Capacity

1. **System extent and integrity.**
    a. System extent throughout the Sierra Nevada (e.g., widespread to narrow distribution): High
        i. Participant confidence: High
    b. Level of fragmentation across the Sierra Nevada: High
        i. Participant confidence: Low

Additional comments: The many dams in the Sierra Nevada region contribute to the fragmentation of aquatic systems.

References:
Geographic extent: Outlets of major watersheds in the Sierra Nevada range in elevation from 39-4418 m (128-14495 ft) (Null et al. 2010). Water regulation and land use changes have altered the thermal regime of Sierra Nevada rivers, degrading habitat and creating a dispersal barrier to cold water assemblages (Null et al. 2012; Perry et al. 2012).

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2. **Resistance, recovery, and refugia.**
    a. Ability of system to resist or recover from impacts: no answer provided by participants
        i. Participant confidence: High
    b. Suitable microclimates within the system that could support refugial communities: Yes, deep pools and dense riparian zones.

Additional comments: Aquatic systems have been able to recover from past climatic fluctuations however, recovery is not guaranteed in the future.

References: It is likely that southern salmonid gene pools reflect a history of resilience as well as adaptations to watersheds characterized by aridity and extreme seasonal variation (Nielsen et al. 1999). Modeling results suggest the American and Mokelumne Rivers are most vulnerable to the three metrics run by Null et al. (2010), and that the Kern River is the most resilient, in part due to the high elevations of the watershed.

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3. **Landscape permeability.**
    a. Degree of landscape permeability: Low
        i. Participant confidence: Moderate
    b. Potential types of barriers to dispersal that apply: agriculture, industrial or urban development, suburban or residential development, geologic features, culverts, dams

Additional comments: Participants are confident concerning the low permeability among aquatic systems, but are less confident on how to gauge the impact of the barriers to dispersal to the aquatic system.

References: Reduced streamflow may shift some streams into intermittent flow (Perry et al. 2012). Increasing temperatures may result in a thermal block for coldwater species migration, such as Chinook salmon (Null et al. 2012). Dams operating without consideration of thermal management, and without adequate passage to coldwater habitat, impact coldwater fish populations (Null et al. 2012). As stream flows become more variable and water temperature and quality change, fish extinction rates are likely to increase (Moyle et al. 2011).

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4. **System diversity.**
    a. Level of physical and topographic diversity: High

        i. Participant confidence: High

b. Level of component species/functional group diversity: High
    i. Participant confidence: Low
c. Description of diversity: no answer provided by participants

Additional comments: Diversity in the aquatic system is great across the Sierra Nevada, but within individual streams and rivers, diversity is limited. The geographic isolation of rivers and lakes makes it difficult to evaluate diversity.

References:
Component species diversity: Evidence exists that fishes can adapt relatively quickly to changing conditions through behavioral or phenotypic plasticity and rapid evolution (Crozier et al. 2008 cited in Rieman and Isaak 2010). Many salmonids can exploit new habitats almost as they become available (Isaak and Thurow 2006, Isaak et al. 2007, Milner 1987, Milner et al. 2000, 2008 cited in Rieman and Isaak 2010). This may be due in part to a diversity of life histories. Multiple life histories within a population or closely allied populations of sockeye salmon (*Oncorhynchus nerka*), for example, may stabilize overall numbers, as certain life histories are better suited to emerging conditions (Hillborn et al. 2003 cited in Rieman and Isaak 2010). Changes in thermal conditions may also lead to local adaptations in thermal tolerances. For example, fall Chinook salmon in the Snake River appear to be evolving novel rearing and migration timing in response to changes in flow and temperature caused by water development over the last 40 years (Williams et al. 2008 cited in Rieman and Isaak 2010). The capacity for rapid evolution in thermal tolerance, however, is unclear and may be more limited than with others (McCullough et al. 2009).

In addition, the southernmost steelhead (*O. mykiss*) populations are characterized by a relatively high genetic diversity compared to populations further north (McCusker et al. 2000 cited in Katz et al. 2012). It is likely that southern salmonid gene pools reflect a history of resilience as well as adaptations to watersheds characterized by aridity and extreme seasonal variation (Nielsen et al. 1999). Extinction of these highly endangered southern populations will likely result in loss of traits adapted to the very environmental characteristics that embody predicted climatic changes to watersheds further north (Katz et al. 2012).

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5. Management potential.

a. Value level people ascribe to this system: High
    i. Participant confidence: Moderate
b. Specificity of rules governing management of the system: High
    i. Participant confidence: Moderate
c. Description of use conflicts: Dams, logging, grazing, development, water diversions.
d. Potential for managing or alleviating climate impacts: There is high potential for management of aquatic systems, because there is a great deal of public interest in water issues, especially pertaining to water needs for residential and agriculture use.

Additional comments: The potential exists to manage roads to improve habitat connectivity as well as to manage grazing and logging for the functioning of sensitive watersheds. In addition, restoration will improve the adaptive capacity of meadows and streams to adjust to floods and droughts. However, the inherent geographic isolation of bodies of water is a barrier to species distribution and movement in the steeply dissected Sierra Nevada. Also, it is important to define the biological diversity of aquatic systems, including cold and warm water fishes, amphibians, reptiles, birds, and mammals dependent on functioning and healthy aquatic systems.

References: The effects of human development have largely eroded the mechanisms that support adaptive capacity in aquatic populations (i.e. connectivity among habitats and populations, local adaptations, and genetic and phenotypic diversity) (Rieman and Dunham 2000, McClure et al. 2008, Bisson et al. 2009 cited in Rieman and Isaak 2010). In the future, climate-induced flow reductions in the northern Sierra Nevada will likely stress traditional water uses for irrigation and urban water storage, as well as aquatic and riparian ecosystems (Null et al. 2010).

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6. Other adaptive capacity factors.

a. Additional factors affecting adaptive capacity: no answer provided by participants
   i. Participant confidence: no answer provided by participants

b. Collective degree these factors affect the adaptive capacity of the system: no answer provided by participants

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7. Overall user ranking.

a. Overall adaptive capacity of the system: High
   i. Participant confidence: Moderate

References: Despite the high level of projected climate stress, California has landscape features that may reduce exposure of species to climate change, including high topographic diversity, abundant perennial water sources, broad elevation and climatic gradients, and long riparian corridors (Klausmeyer et al. 2011).

Exposure

1. **Exposure factors[9].**
    a. Factors likely to be most relevant or important to consider for the system: Temperature, precipitation, dominant vegetation type, snowpack, runoff, timing of flows, low flows, high flows, stream temperature, other – water quality
        i. Participant confidence: Low (all)

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2. **Exposure region.**
    a. Exposure by region: no answer provided by participants
        i. Participant confidence: no answer provided by participants

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3. **Overall user ranking.**
    a. Overall exposure of the species to climate changes: no answer provided by participants
        i. Participant confidence: no answer provided by participants

References:

Temperature: Over the next century, temperatures in California are expected to rise (Hayhoe et al. 2004: Cayan et al. 2008), with the lower range of warming projected between 1.7-3.0°C, 3.1-4.3°C in the medium range, and 4.4-5.8°C in the high range (Cayan et al. 2008). Temperatures along the western slope of the Sierra Nevada are forecast to increase between 0.5-1^{o}C by 2049, and 2-3^{o}C by 2099 (Das et al. 2011). On average, summer temperatures are expected to rise more than winter temperatures throughout the Sierra Nevada region (Hayhoe et al. 2004; Cayan et al. 2008; Geos Institute 2013). Temperature projections using global coupled ocean-atmospheric models (GDFL[10] and PCM[11]) predict summer temperatures to increase 1.6-2.4˚C by mid- century (2049), with the least increases expected in the northern bioregion, and greatest increases expected in the southern bioregion (Geos Institute 2013). By late century (2079), summer temperatures are forecast to increase 2.5-4.0˚C, with changes of least magnitude occurring in the central bioregion (Geos Institute 2013). Winter temperatures are forecast to increase 2.2-2.9˚C by late century (2079), with changes of least magnitude occurring in the central bioregion (Geos Institute 2013). Associated with rising temperatures will be an increase in potential evaporation (Seager et al. 2007).

The effects of a 2°C or 4°C increase in climate temperature on stream temperature will be temporally and spatially variable, depending on coldwater inputs, summer low flows, and vegetative cover—but they would not be greater than the increase in air temperature (Meyers et al. 2010). Scenarios modeling increased atmospheric temperatures at 2°C, 4°C and 6°C run by Null et al. (2010) forecast that, overall, watersheds in the northern Sierra Nevada are most vulnerable to decreased mean annual flow, southern-central watersheds are most susceptible to runoff timing changes, and the central portion of the range is most affected by longer periods with low flow conditions. Increasing atmospheric temperatures, coupled with reductions in summer flows, will increase water temperatures and potentially the suitability of stream reaches as habitat for temperature-sensitive aquatic species (Myrick and Cech 2004). On the South Fork American River in the Sierra Nevada, model results of projected air temperature increases of 2°C, 4°C and 6°C reduced available coldwater habitat (with stress threshold

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[9] Participants were asked to identify exposure factors most relevant or important to the species but were not asked to evaluate the degree to which the factor affects the species.
[10] Delworth, T. L., Broccoli, A. J., Rosati, A. et al. (2006) GFDL's CM2 Global Coupled Climate Models. Part I: Formulation and Simulation Characteristics. Journal of Climate, 19:643-674.
[11] Washington, W. M., Weatherly J. W., Meehl G. A. et al. (2000) Parallel climate model (PCM) control and transient simulations. Climate Dynamics 16:755-744.

21°C) by 57%, 91% and 99.3%, respectively (Null et al. 2012). Warming may cause thermal refuges to disappear from streams in many areas, leaving coldwater fishes no escape from unfavorable conditions (Moyle et al. 2011). Yates et al. (2008) suggest that cold pool reservoirs, such as Shasta, may offset the impacts of 2°C warming throughout the 21st century, but maintenance of a cold pool with warming of 4°C could be challenging.

Overall precipitation: Precipitation has increased slightly (~2%) in the Sierra Nevada over the past 30 years compared with a mid-twentieth century baseline (1951-1980) (Flint et al. 2013). Projections for future precipitation in the Sierra Nevada vary among models; some demonstrate little to no change (e.g. PCM) while others demonstrate more substantial changes (e.g. GFDL). In general, annual precipitation is projected to exhibit only modest changes by the end of the century (Hayhoe et al. 2004; Dettinger 2005; Maurer 2007; Cayan et al. 2008; Geos Institute 2013), with some precipitation decreases in spring and summer (Cayan et al. 2008; Geos Institute 2013). Frequency of extreme precipitation, however, is expected to increase in the Sierra Nevada between 11-49% by 2049 and 18-55% by 2099 (Das et al. 2011).

Snow volume and timing: Overall, April 1st snowpack in the Sierra Nevada, calculated as snow water equivalent (SWE), has seen a reduction of 11% in the last 30 years (Flint et al. 2013), as a consequence of earlier snowmelt (Cayan et al. 2001; Stewart et al. 2005; Hamlet et al. 2007), increased frequency of melt events (Mote et al. 2005), and increased rain:snow ratio (Knowles et al. 2006). However, trends in snowpack in the Sierra Nevada have displayed a high degree of interannual variability and spatial heterogeneity (Mote et al. 2005; Safford et al. 2012). SWE in the southern Sierra Nevada has actually increased during the last half-century, due to increases in precipitation (Mote et al. 2005; Mote 2006; Moser et al. 2009; Flint et al. 2013).

Despite modest projected changes in overall precipitation, models of the Sierra Nevada region largely project decreasing snowpack (Miller et al. 2003; Dettinger et al. 2004b; Hayhoe et al. 2004; Knowles and Cayan 2004; Maurer 2007; Young et al. 2009) and earlier timing of runoff center of mass (Miller et al. 2003; Knowles and Cayan 2004; Maurer 2007; Maurer et al. 2007; Young et al. 2009), as a consequence of early snowmelt events and a greater percentage of precipitation falling as rain rather than snow (Dettinger et al. 2004a, 2004b; Young et al. 2009; Null et al. 2010).

Annual snowpack in the Sierra Nevada is projected to decrease between 64-87% by late century (2060-2079) (Thorne et al. 2012; Flint et al. 2013; Geos Institute 2013). Under scenarios of 2-6˚C warming, snowpack is projected to decline 10-25% at elevations above 3750 m (12303 ft), and 70-90% below 2000 m (6562 ft) (Young et al. 2009). Several models project greatest losses in snowmelt volume between 1750 m to 2750 m (5741 ft to 9022 ft) (Miller et al. 2003; Knowles and Cayan 2004; Maurer 2007; Young et al. 2009), because snowfall is comparatively light below that elevation, and above that elevation, snowpack is projected to be largely retained. The greatest declines in snowpack are anticipated for the northern Sierra Nevada (Safford et al. 2012), with the current patterns of snowpack retention in higher-elevation southern Sierra Nevada basins expected to continue through the end of the century (Maurer 2007).

Average fractions of total precipitation falling as rain in the Sierra Nevada can be expected to increase by approximately 10% under a scenario of 2.5˚C warming (Dettinger et al. 2004b). Increased rain:snow ratio and advanced timing of snowmelt initiation are expected to advance the runoff center of mass by 1-7 weeks by 2100 (Maurer 2007), although advances will likely be non-uniformly distributed in the Sierra Nevada (Young et al. 2009). Snow provides an important contribution to spring and summer soil moisture in the western U.S. (Sheffield et al. 2004), and earlier snowmelt can lead to an earlier, longer dry season (Westerling et al. 2006). A shift from snowfall to rainfall is also expected to result in flashier runoff with higher flow magnitudes, and may result in less water stored within watersheds, decreasing meal annual flow (Null et al. 2010). Mean annual flow is projected to decrease most substantially in the northern bioregion (Null et al. 2010). Changes in stream flow and temperature are expected to be most significant in streams fed by the relatively lower elevation Cascades and northern Sierra Nevada (Katz et al. 2012).

Flows: A reduction in the magnitude of flow at the start of spring snowmelt also implies lower redistribution of sediment, creating large abiotic changes in stream systems (Yarnell et al. 2010). In contrast, predicted quick pulses of higher winter rainfall in California's Mediterranean-montane basins, in contrast to slower snowmelt, may change how sediments are sorted and deposited. Channel substrates may become more homogenous; channel bars may be more steeply sloped, creating less habitat availability (Yarnell et al. 2010). A flashy spring hydrograph may lead to a system dominated by two flow stages (i.e., flood and low-flow), rather than multiple stages, resulting in a stream with greater habitat homogeneity and less overall biodiversity (Yarnell et al. 2010). A flashier runoff with higher flow magnitudes is also expected to result in less water stored within watersheds and decreased mean annual flow (Null et al. 2010). Mean annual flow is projected to decrease most substantially in the northern bioregion (Null et al. 2010).

During summer and fall, rising water temperatures are exacerbated by lower base flows resulting from reduced snowpack (Stewart et al. 2004; Hamlet et al. 2005; Stewart et al. 2005). Reduced summer base flow may result in shorter duration of cold water in the system, and increased frequency or duration of warm, low-flow and zero-flow periods, lower water tables, and reduce riparian wetland inundation (Seavy et al. 2009; Yarnell et al. 2010).

Climatic water deficit: Increases in potential evapotranspiration will likely be the dominant influence in future hydrologic cycles in the Sierra Nevada, decreasing runoff even under forecasts of increased precipitation, and driving increased climatic water deficits (Thorne et al. 2012). Climatic water deficit, which combines the effects of temperature and rainfall to estimate site-specific soil moisture, is a function of actual evapotranspiration and potential evapotranspiration. In the Sierra Nevada, climatic water deficit has increased slightly (~4%) in the past 30 years compared with the 1951-1980 baseline (Flint et al. 2013). Future downscaled water deficit projections using the Basin Characterization Model (Thorne et al. 2012; Flint et al. 2013) and IPCC A2 emissions scenario predict increased water deficits (i.e., decreased soil moisture) by up to 44% in the northern Sierra Nevada, 38% in the central Sierra Nevada, and 33% in the southern Sierra Nevada (Geos Institute 2013).

Lower late-spring and summer flows on snow-melt rivers, and groundwater declines, may reduce survival and growth of shallow-rooted plants, such as seedlings and juveniles trees, as well as phreatophytic trees, when water tables drop too far or too quickly. Surviving phreatophytes may increase root depth in response to declining low flows, shifting plant community composition toward more drought tolerant native and introduced species (Shafroth et al. 2000, Rood et al. 2003, and Rood et al. 2008 cited in Perry et al. 2012).

Many riparian plants are adapted to hydrologic and geomorphic disturbances and tolerate both seasonal and annual variation in environmental conditions (Naiman and Decamps 1997 cited in Seavey et al. 2009). Long-term reduction in sediment transport and deposition and rates of channel migration and abandonment eventually shrinks the areas where pioneer species establish (Scott et al. 1996, Friedman et al. 1998, Shafroth et al. 2002 cited in Perry et al. 2012).

Salmonid species: Where mountain ranges provide 'islands' of habitat and species cannot easily migrate to higher latitude reaches, climate warming is likely to reduce total habitat for coldwater species such as salmonids (Null et al. 2012). Consequently, an elevational shift in the distribution of cold- and warm-water fish species will occur as cold-water species are limited to higher elevations (Yarnell et al. 2010).

Exposures of Chinook salmon (*Oncorhynchus tshawytscha*) to water temperatures above 20°C can result in adverse effects during spawning and rearing (Yates et al. 2008). Increased water temperatures in the Sacramento Valley could jeopardize Chinook (*O. tshawytscha*), particularly in drought years. Temperatures exceeding 24°C are expected slightly earlier in the spring, and to last later into August and September, when peak numbers of fall-run Chinook, the most abundant run in California, historically immigrated into freshwater streams (Yates et al. 2008). Yates et al. (2008) predict the percentage of years in which temperatures at stream outlets will exceed 24°C (for at least 1 week) is likely to increase with climate change. If air temperatures rise by 6°C, most Sierra Nevada rivers are expected to exceed 24°C at watershed outlets for several weeks each year, with the Feather River a notable exception (Null et al. 2012). It is possible that a majority of California's endemic salmon, trout and steelhead could become extinct within the next 50 to 100 years, particularly pink salmon (*Onchorhynchus gorbuscha*) and chum salmon (*Oncorhynchus. keta*) (Katz et al. 2012).

According to the model run by Jager el at. (1999), a shift to earlier high streamflows had a strong positive effect on brown trout (*Salmo trutta*) abundance in the Sierra Nevada. This shift increased redd scouring for winter spawning brown trout, but construction of redds during lower fall flows mitigated dewatering and compensated for scouring. Under a scenario of 2°C increase in average annual temperature, brown trout populations increased in upstream reach and decreased in the downstream reaches of the Sierra Nevada (Jager et al. 1999). In spite of an increased incidence of summer starvation of brown trout in the upstream reach (with elevated temperature of 2°C), growth and fecundity of the survivors was enhanced.

For spring-spawning rainbow trout (*O. mykiss*), on the other hand, the Jager et al. (1999) model predicted that a shift to earlier high streamflows would lead to reduced redd scouring, but increased dewatering events as spring flow was reduced (Jager et al. 1999). Rainbow trout increase in upstream reaches under the 2°C increase is attributed to better growth conditions and therefore, lower predation mortality. Increased temperatures during incubation of rainbow trout caused them to spawn earlier (Jager et al. 1999).

In the Jager et al. (1999) model, temperature in the Tule River had significant effects on the timing of spawning and incubation. For brown trout, spawning was delayed by several weeks, but eggs and alevins developed faster and fry emerged earlier. For rainbow trout, spawning was earlier, particularly in warmer downstream reaches (Jager et al. 1999). However, in these simulations, the effects of streamflow and temperature were not additive, as shown by the tremendous increase in rainbow trout abundance in upstream reach when both temperature and flow (higher winter flows during rain-on-snow events) effects were simulated (Jager et al. 1999).

Under 2°C and 4°C warming scenarios run by Meyers et al. (2010) a shift to increased winter floods predicted a likely long-term decline in the number of brook trout (*Salvelinus fontinalis*) and increase in number of rainbow trout (*O. mykiss*) in Sagehen Creek. In the Sagehen Creek scenarios, brook trout were less able to recover between winter flood events, which were expected to increase both in intensity, and to increase in frequency five-fold under moderate 2°C warming (Meyers et al. 2010). While it is unlikely that temperatures will exceed the functional range of rainbow trout (25°C) in Sagehen Creek, maximum temperatures already surpass functional maximum temperatures (19°C) of brown trout (Meyers et al. 2010).

<u>Disease:</u> Stream warming will magnify the distribution and virulence of disease organisms and parasites (Marcogliese 2001) that are temperature dependent, increasing the impact on native salmonids (Rahel et al. 2008).

More information on downscaled projected climate changes for the Sierra Nevada region is available in a separate report entitled *Future Climate, Wildfire, Hydrology, and Vegetation Projections for the Sierra Nevada, California: A climate change synthesis in support of the Vulnerability Assessment/Adaptation Strategy process* (Geos Institute 2013). Additional material on climate trends for the system may be found through the TACCIMO website (http://www.sgcp.ncsu.edu:8090/). Downscaled climate projections available through the Data Basin website (http://databasin.org/galleries/602b58f9bbd44dffb487a04a1c5c0f52).

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Literature Cited

Blaustein, A. R., S. C. Walls, B. A. Bancroft, J. J. Lawler, C. L. Searle and S. S. Gervasi (2010). "Direct and Indirect Effects of Climate Change on Amphibian Populations." Diversity **2**(2): 281-313.

Cayan, D., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio and D. H. Peterson (2001). "Changes in the Onset of Spring in the Western United States." Bulletin of the American Meteorological Society **82**(3): 399-145.

Cayan, D. R., E. P. Maurer, M. D. Dettinger, M. Tyree and K. Hayhoe (2008). "Climate change scenarios for the California region." Climatic Change **87**(S1): 21-42.

Coats, R. (2010). "Climate change in the Tahoe basin: regional trends, impacts and drivers." Climatic Change **102**(3-4): 435-466.

Das, T., M. D. Dettinger, D. R. Cayan and H. G. Hidalgo (2011). "Potential increase in floods in California's Sierra Nevada under future climate projections." Climatic Change **109**(S1): 71-94.

Dettinger, M. D. (2005). "From climate-change spaghetti to climate-change distributions for 21st Century California." San Francisco Estuary and Watershed Science **3**(1): Article 4.

Dettinger, M. D., D. R. Cayan, N. Knowles, A. Westerling and M. K. Tyree (2004a). Recent Projections of 21st-Century Climate Change and Watershed Responses in the Sierra Nevada, USDA Forest Service. **Gen. Tech. Report PSW-GTR-193**.

Dettinger, M. D., D. R. Cayan, M. K. Meyer and A. E. Jeton (2004b). "Simulated Hydrologic Responses to Climate Variations and Change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900–2099." Climate Change **62**: 283-317.

Eaton, J. G. and R. M. Scheller (1996). "Effects of Climate Warming on Fish Thermal Habitat in Streams of the United States." Limnology and Oceanography **41**(5): 1109-1115.

Flint, L. E., A. L. Flint, J. H. Thorne and R. Boynton (2013). "Fine-scale hydrologic modeling for regional landscape applications: the California Basin Characterization Model development and performance." Ecological Processes ***2***: 25.

Geos Institute (2013). Future Climate, Wildfire, Hydrology, and Vegetation Projections for the Sierra Nevada, California: A climate change synthesis in support of the Vulnerability Assessment/Adaptation Strategy (VAAS) process, Available online at: http://www.geosinstitute.org/climatewiseservices/completed-climatewise-projects.html.

Hamlet, A. F., P. W. Mote, M. P. Clark and D. P. Lettenmaier (2007). "Twentieth-Century Trends in Runoff, Evapotranspiration, and Soil Moisture in the Western United States*." Journal of Climate **20**(8): 1468-1486.

Hamlet, A. F., P. W. Mote, M. P. Clark and D. P. Lettermaier (2005). "Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western United States." Journal of Climate **18**: 4545-4561.

Hanak, E. and J. R. Lund (2012). "Adapting California’s water management to climate change." Climatic Change **111**(1): 17-44.

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.

Isaak, D. J., C. H. Luce, B. E. Rieman, D. E. Nagel, E. E. Peterson, D. L. Horan, S. Parkes and G. L. Chandler (2010). "Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network." Ecological Applications **20**(5): 1350-1371.

Jager, H. I., W. Van Winkle and B. D. Holcomb (1999). "Would Hydrologic Climate Changes in Sierra Nevada Streams Influence Trout Persistnece." Transactions of the American Fisheries Society **128**: 222-240.

Katz, J., P. B. Moyle, R. M. Quiñones, J. Israel and S. Purdy (2012). "Impending extinction of salmon, steelhead, and trout (Salmonidae) in California." Environmental Biology of Fishes.

Kiernan, J. D. and P. B. Moyle (2012). "Flows, droughts, and aliens: factors affecting the fish in a Sierra Nevada, California, stream." Ecological Applications **22**(4): 1146-1161.

Klausmeyer, K. R., M. R. Shaw, J. B. MacKenzie and D. R. Cameron (2011). "Landscape-scale indicators of biodiversity's vulnerability to climate change." Ecosphere **2**(8): art88.

Knowles, N. and D. Cayan (2004). "Elevational dependence of projected hydrologic changes in the San Francisco Estuary and Watershed." Climate Change **62**: 319-336.

Knowles, N., M. D. Dettinger and D. Cayan (2006). "Trends in Snowfall versus Rainfall in the Western United States." Journal of Climate **19**(18): 4545-4559.

LeBlanc, R. T. and R. D. Brown (2000). "The use of riparian vegetation in stream-temperature modification." Water and Environment Journal **14**: 297-303.

Marcogliese, D. J. (2001). "Implications of climate change for parasitism of animals in the aquatic environment." Canadian Journal of Zoology **79**(8): 1331-1352.

Maurer, E. P. (2007). "Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios." Climatic Change **82**(3-4): 309-325.

Maurer, E. P., I. T. Stewart, C. Bonfils, P. B. Duffy and D. Cayan (2007). "Detection, attribution, and sensitivity of trends toward earlier streamflow in the Sierra Nevada." Journal of Geophysical Research **112**(D11).

McCullough, D. A. (1999). A Review and Synthesis of Effects of Alterations to the Water Temperature Regime on Freshwater Life Stages of Salmonids, with Special Reference to Chinook Salmon, EPA.

McCullough, D. A., J. M. Bartholow, H. I. Jager, R. L. Beschta, E. F. Cheslak, M. L. Deas, J. L. Ebersole, J. S. Foott, S. L. Johnson, K. R. Marine, M. G. Mesa, J. H. Petersen, Y. Souchon, K. F. Tiffan and W. A. Wurtsbaugh (2009). "Research in Thermal Biology: Burning Questions for Coldwater Stream Fishes." Reviews in Fisheries Science **17**(1): 90-115.

McKenzie, D., Z. Gedalof, D. L. Peterson and P. W. Mote (2004). "Climate Change, Wildfire, and Conservation." Conservation Biology **18**(4): 890-902.

Meyers, E. M., B. Dobrowski and C. L. Tague (2010). "Climate Change Impacts on Flood Frequency, Intensity, and Timing May Affect Trout Species in Sagehen Creek, California." Transactions of the American Fisheries Society **139**(6): 1657-1664.

Miller, N. L., K. E. Bashford and E. Strem (2003). "Potential impacts of climate change on California hydrology." Journal of American Water Resources Association **39**(4): 771-784.

Morrill, J. C., R. C. Bales and M. H. Conklin (2005). "Estimating Stream Temperature from Air Temperature: Implications for Future Water Qaulity." Journal of Environmental Engineering **131**(1): 139-146.

Moser, S. C., G. Franco, S. Pittiglio, W. Chou and D. Cayan (2009). The Future Is Now: An Update On Climate Change Science Impacts And Response Options For California, Prepared for: California Energy Commission, Public Interest Energy Commission. **CEC-500-2008-071**.

Mote, P. W. (2006). "Climate-Driven Variability and Trends in Mountain Snowpack in Western North America." Journal of Climate **19**(23): 6209-6220.

Mote, P. W., A. F. Hamlet, M. P. Clark and D. P. Lettenmaier (2005). "Declining Mountain Snowpack in Western North America*." Bulletin of the American Meteorological Society **86**(1): 39-49.

Moyle, P. B., J. V. E. Katz and R. M. Quiñones (2011). "Rapid decline of California's native inland fishes: A status assessment." Biological Conservation **144**(10): 2414-2423.

Moyle, P. B., J. D. Kiernan, P. K. Crain and R. M. Quiñones (2012). Projected Effects of Future Climates on Freshwater Fishes of California. C. E. Commission. **CEC-500-2012-028**.

Myrick, C. A. and J. J. Cech, Jr., (2004). "Temperature effects on juvenile anadromous salmonids in California's central valley: what don't we know?" Review in Fish Biology and Fisheries **14**(113-123).

Myrick, C. A. and J. J. Cech Jr. (2001). Temperature effects on Chinook salmon and steelhead: a review focusing on California's Central Valley populations. Bay-Delta Modeling Forum **Technical Publication 01–1:** Available online at: http://www.cwemf.org/Pubs/TempReview.pdf.

Nielsen, E. E., M. M. Hansen and V. Loeschcke (1999). "Genetic Variation in Time and Space: Microsatellite Analysis of Extinct and Extant Populations of Atlantic Salmon." Evolution **53**(1): 261-268.

Null, S. E., J. H. Viers, M. L. Deas, S. K. Tanaka and J. F. Mount (2012). "Stream temperature sensitivity to climate warming in California's Sierra Nevada: impacts to coldwater habitat." Climatic Change **116**(1): 149-170.

Null, S. E., J. H. Viers and J. F. Mount (2010). "Hydrologic response and watershed sensitivity to climate warming in California's Sierra Nevada." PLoS One **5**(4).

Perry, L. G., D. C. Andersen, L. V. Reynolds, S. M. Nelson and P. B. Shafroth (2012). "Vulnerability of riparian ecosystems to elevated CO2 and climate change in arid and semiarid western North America." Global Change Biology **18**(3): 821-842.

Poole, G. C. and C. H. Berman (2001). "An Ecological Perspective on In-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human-CausedThermal Degradation." Environmental Management **27**(6): 787-802.

Rahel, F. J., B. Bierwagen and Y. Taniguchi (2008). "Managing aquatic species of conservation concern in the face of climate change and invasive species." Conserv Biol **22**(3): 551-561.

Rieman, B. E. and D. J. Isaak (2010). Climate Change, Aquatic Ecosystems, and Fishes in the Rocky Mountain West: Implications and Alternatives for Management, US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Sadro, S. and J. M. Melack (2012). "The Effect of an Extreme Rain Event on the Biogeochemistry and Ecosystem Metabolism of an Oligotrophic High-Elevation Lake." Arctic, Antarctic, and Alpine Research **44**(2): 222-231.

Safford, H., M. North and M. D. Meyer (2012). Chapter 3: Climate Change and the Relevance of Historical Forest Condition. Managing Sierra Nevada Forests, USDA Forest Service, Pacific Southwest Research Station. **Gen. Tech. Rep. PSW-GTR-237**.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H. P. Huang, N. Harnik, A. Leetmaa, N. C. Lau, C. Li, J. Velez and N. Naik (2007). "Model projections of an imminent transition to a more arid climate in southwestern North America." Science **316**(5828): 1181-1184.

Seavy, N. E., T. Gardali, G. H. Golet, F. T. Griggs, C. A. Howell, R. Kelsey, S. L. Small, J. H. Viers and J. F. Weigand (2009). "Why Climate Change Makes Riparian Restoration More Important than Ever: Recommendations for Practice and Research." Ecological Restoration **27**(3): 330-339.

Sheffield, J., G. Goteti, F. Wen and E. F. Wood (2004). "A simulated soil moisture based drought analysis for the United States." Journal of Geophysical Research: Atmospheres (1984-2012) **109(D24)**.

Stewart, I., D. Cayan and M. D. Dettinger (2004). "Changes In Snowmelt Runoff Timing in Western North America under a 'Business as Usual' Climate Change Scenario." Climatic Change **62**: 217-232.

Stewart, I., D. Cayan and M. D. Dettinger (2005). "Changes toward Earlier Streamflow Timing across Western North America." Journal of Climate **18**: 1136-1155.

Thorne, J. H., R. Boynton, L. Flint, A. Flint and T.-N. G. Le (2012). Development and Application of Downscaled Hydroclimatic Predictor Variables for Use in Climate Vulnerability and Assessment Studies, Prepared for California Energy Commission, Prepared by University of California, Davis. **CEC-500-2012-010**.

Vannote, R. L. and B. W. Sweeney (1980). "Geographic analysis of thermal equilibria: a conceptual model for evaluating the effect of natural and modified thermal regimes on aquatic insect communities." American naturalist: 667-695.

Viers, J. H. and D. E. Rheinheimer (2011). "Freshwater conservation options for a changing climate in California's Sierra Nevada." Marine and Freshwater Research **62**: 266-278.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan and T. W. Swetnam (2006). "Warming and earlier spring increase western U.S. forest wildfire activity." Science **313**: 940-943.

Yarnell, S. M., J. H. Viers and J. F. Mount (2010). "Ecology and Management of the Spring Snowmelt Recession." BioScience **60**(2): 114-127.

Yates, D., H. Galbraith, D. Purkey, A. Huber-Lee, J. Sieber, J. West, S. Herrod-Julius and B. Joyce (2008). "Climate warming, water storage, and Chinook salmon in California's Sacramento Valley." Climatic Change **91**(3-4): 335-350.

Yoshiyama, R. M., F. W. Fisher and P. B. Moyle (1998). "Historical Abundance and Decline of Chinook Salmon in the Central Valley Region of California." North American Journal of Fisheries Management **18**(3): 487-521.

Young, C. A., M. I. Escobar-Arias, M. Fernandes, B. Joyce, M. Kiparsky, J. F. Mount, V. K. Mehta, D. Purkey, J. H. Viers and D. Yates (2009). "Modeling The Hydrology Of Climate Change In California's Sierra Nevada For Subwatershed Scale Adaptation." Journal of American Water Resources Association **45**(6): 1409-1423.

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