FINAL REPORT: SYNTHESIS OF AQUATIC CLIMATE CHANGE VULNERABILITY ASSESSMENTS FOR THE INTERIOR WEST

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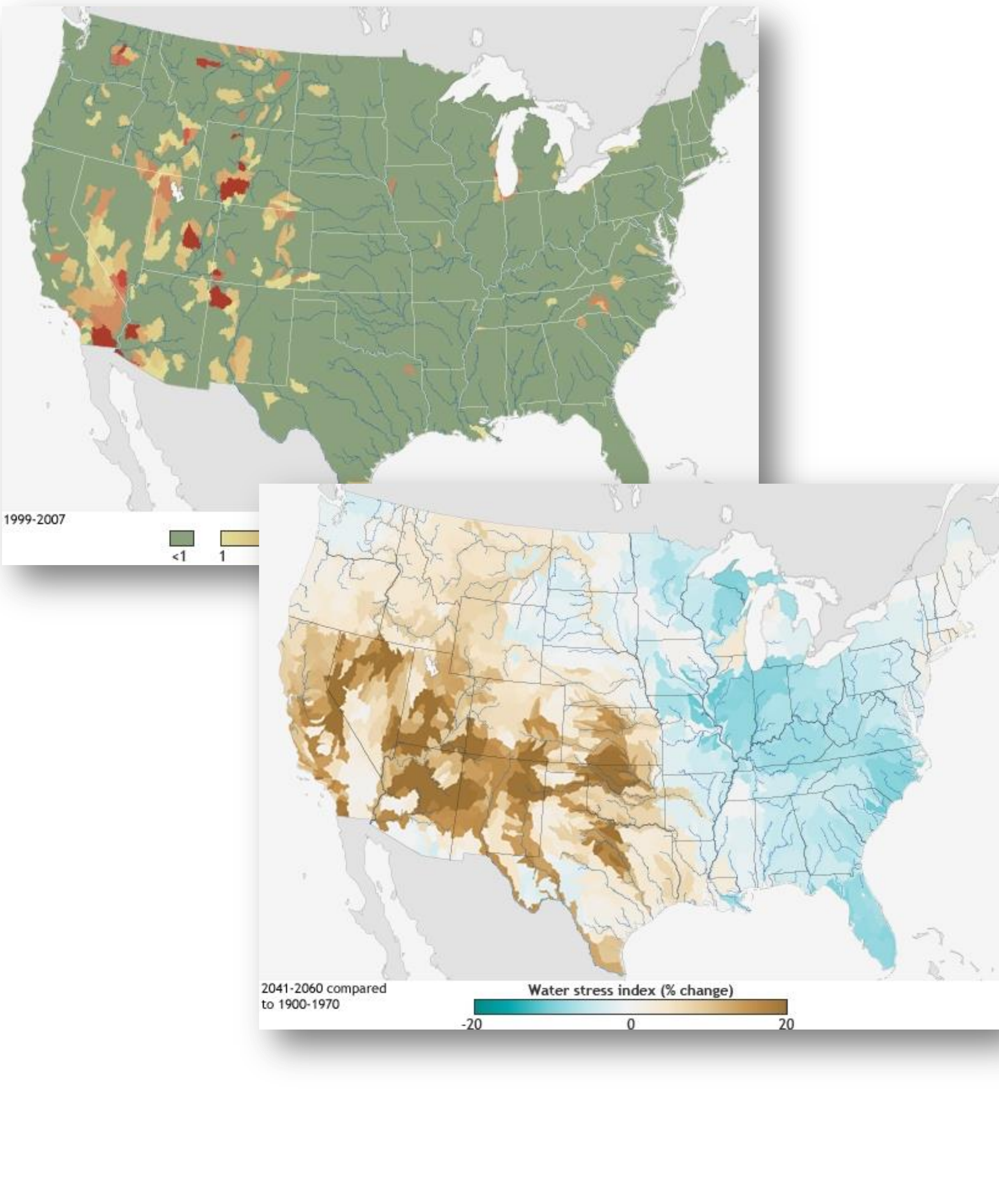

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EXECUTIVE SUMMARY

Climate change challenges the management of western water resources. Water is expected to become more limited with increased evaporation, drought, and changing precipitation regimes. Climate change vulnerability assessments provide a method to compare the causes and consequences of changing conditions for species, habitats, and ecosystems. Within the aquatic sector, vulnerability assessments have long been used to gauge the impact of threats on important ecosystems services that provision both human and ecological needs. We synthesize the current body of literature that assesses the vulnerability of western U.S. aquatic systems to climate change. Specifically, we summarize the assessments that consider the relative impacts of climate change among resource variables, systems, or processes within the Southern Rockies Landscape Conservation Cooperative (SR LCC). We distinguish between impact studies that describe ecosystem or hydrological response to a disturbance and climate change vulnerability assessments that aim to quantify the relative impacts and sensitivities of aquatic systems to climate effects. Several frameworks and approaches are described that represent recent advances in efforts to measure vulnerability.

We identified 43 vulnerability assessments and 225 impact studies that address climate change and aquatic systems in the western U.S. Some general findings from our review include:

- Targets and methods to measure vulnerability vary widely among vulnerability assessments. The place-based nature of vulnerability assessments helps tailor them to local management needs but hinders meaningful comparative analysis at larger scales.
- Aquatic vulnerability assessments tend focus on the innate qualities of ecosystems or hydrological processes that indicate high sensitivity. Further, external non-climate stressors are often identified as the most problematic sources of vulnerability of aquatic systems and species under future conditions. In particular, over allocation (demand exceeding natural flow) and disrupted natural flows (e.g. dams) were commonly implicated issues. This focus and its apparent importance for predicting aquatic system vulnerability indicates a need for management activities that aim to reduce the impact of non-climate stressors.
- The majority of assessments (19) consider water resources in context of the provision of services to the human sector. As a result, many aquatic assessments include considerations for both human and ecosystem vulnerability.
- Scale has an important influence on the degree to which aquatic ecosystems are considered at risk of negative impact due to climate change effects. Local scale impacts may lead to habitat or species loss that is not captured by more generalized, large scale assessments.
- Biophysical characteristics were most predictive of vulnerability at larger scales. Location, elevation, parent materials, and even latitude related directly to the innate sensitivity of systems to climate related changes. Biota, water quality, and exposure to stressors were more commonly used to determine the resiliency of the system to disturbances at local scales.

Approaches for conducting vulnerability assessments were diverse, reflecting the diversity of ways in which aquatic systems might be disrupted by changing conditions. Though the diversity of assessments precludes meaningful comparisons, we note that the several studies identify the southern Great Plains and lower elevation watersheds as highly vulnerable to climate change. Watersheds in southern states tend to be more vulnerability to climate impacts corresponding to projections of dryer conditions and more severe climate impacts. For watersheds in northern states (e.g. Colorado, Utah, Wyoming) climate projections tend towards wetter scenarios and vulnerability often related more to current condition and the presence of stressors (modified flows, invasive species) that limit resilience to climate impacts.

INTRODUCTION

Water is a critical resource for humans and ecological systems in the western United States. Aquatic ecosystems including lakes, rivers, riparian areas and wetlands, are at high risk of climate impacts because they experience relatively high exposure to climate fluctuations and extremes. In turn, impacts arising from climate change are far reaching because these systems tend to support a disproportionate amount of the biodiversity and ecological services in the landscapes within which they exist (Capon et al., 2013). A number of reviews are available that detail threats to riparian and aquatic ecosystems (Spears et al., 2013; Poff et al., 2011; EPA 2011). The Bureau of Reclamation's Managing Water in the West report (Spears et al., 2013), ***Third Edition of the Literature Synthesis on Climate Change Implications for Water and Environmental Resources***, provides a comprehensive synthesis specific to climate impacts for the Western U.S. Within this report expected trends and relevant studies are reviewed and summarized for each region within the U.S. (e.g. Lower Colorado, Upper Colorado, and Mid-Pacific) and include an overview of potential changes and likely impact. A comprehensive review of literature pertaining to California and surrounding areas can be found in Kiparksy and Gleick (2003). Two recent climate assessments consider impacts to aquatic ecosystems and water resources for the entire U.S. and the southwestern U.S. (Melillo et al., 2014 and Garfin et al., 2015, respectively).

Despite the body of literature on potential climate impacts, there remain shortcomings with respect to science and assessments that can guide adaptive management for aquatic ecosystems and species. Vulnerability assessments can be a valuable tool that increases our understanding of how systems are susceptible to changing climate conditions so that we can identify management targets or issues, potential options for mitigation, and prioritize management and research efforts (EPA 2011). Climate change vulnerability assessments are commonly used to integrate current knowledge into actionable management strategies (Friggens et al., 2013). However, the diversity of methods and outputs found within the vulnerability assessment literature can limit efforts to identify relevant studies and challenges the development of effective adaptation options.

This synthesis reviews and discusses the vulnerability assessment literature focused on riparian and aquatic systems in the Western U.S. Our purpose is to describe the state of vulnerability assessments and methods for assessing aquatic systems with particular focus on those found within the Southern Rockies Landscape Cooperative (SR LCC) boundary. This is a working document that allows interested parties to survey the current status and results of vulnerability assessments and related literature. As part of the effort to identify relevant information sources, we also provide a review of literature that describes studies, syntheses and management approaches for aquatic systems in the Interior West (Appendix 1). This review provides a basis upon which we can begin to assess the utility of current methods and measures and determine what is still needed to improve our knowledge of climate change impacts for hydrologic cycles, water quality, and aquatic ecosystems (e.g., Bates et al., 2008; Lettenmaier 2009; Kundzewicz et al., 2007; Miller and Yates 2005; Poff et al., 2011). An accessory document to this report reviews common approaches and strategies for implementing adaptation management within western aquatic ecosystems. These documents form the core knowledge that is summarized and presented on the project webpage. Collectively, these products describe the current status of knowledge regarding the vulnerability of aquatic ecosystems to climate change.

VULNERABILITY ASSESSMENTS

Vulnerability assessments are a fundamental tool available to many disciplines and sectors but are particularly applicable to management of natural resources, the focus of this document. Here we define vulnerability according the Intergovernmental Panel on Climate Change (IPCC 2007) as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitudes and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity". Aquatic based assessments, like social sector studies, tend to focus on components relating to system sensitivity or response to disturbance. Adaptive capacity is realized through increasing system resilience to perturbation.

Riparian and other aquatic systems are likely to experience relatively high levels of exposure to climate effects because they are influenced both directly and indirectly by temperature and precipitation changes. Additionally, because these ecosystems are tightly tied to the very variables expected to change, many are likely to be highly sensitive to changing conditions. However, adaptive capacity might be relatively high for the organisms and processes associate with aquatic systems because they have evolved under conditions marked by extreme variation. Importantly, the impact of climate change on aquatic systems is directly influenced by their ability to adapt or cope with changing conditions (Capon et al., 2013). Still, it is likely the ability for a system to adapt to new conditions will be constrained, in part, by the level of exposure experienced by the system and the sensitivity of its components.

Sensitivity of aquatic systems can be inferred by the degree of change in a measured condition in response to a change in environmental conditions. It may also be interpreted as the likelihood that a system will pass a threshold or critical state. The EPA (2011) describes the tendency for biophysical vulnerability to relate to exposure and sensitivity, whereas socioeconomic vulnerability is related more to adaptive capacity. Social vulnerability, when included in an assessment of climate change vulnerability, is measured through assessing the properties of the system that help it cope with an event rather than the exposure to the event. Among aquatic vulnerability assessments, current condition or stress is a primary component used to gauge sensitivity (e.g., Forest Service WSA, Furniss et al., 2012).

Environmental indicators of ecosystem health, functionality or stress are commonly used in vulnerability assessments and to prioritize management actions and research (Hurd et al., 1999; EPA 2011). Some indicators are used in multiple ways. For instance, quantifying species at risk in an area can be used to indicate the level of impact (for example loss of high valued species, Hurd et al., 1999) or as an indication of resource value (Furniss et al., 2012 and associated case studies). Several studies are available that focus on indicators for determining the vulnerability of aquatic systems (EPA 2011), of perma- and aquaculture (Barsley et al., 2013), of riparian ecosystems (Theobold et al., 2010; Capon et al., 2013), and watersheds (Furniss et al., 2012). Lukas et al., 2014 provides a synthesis and instructions for using data in vulnerability assessments for Colorado aquatic ecosystems.

VULNERABILITY ASSESSMENT APPROACHES

Climate change vulnerability assessments provide a direct mechanism for identifying and prioritizing adaptive management options for the conservation and preservation of ecosystems and their services. Vulnerability analyses are often described as one of two approaches, “top down” or “bottom up.” The “top down” approach uses downscaled global climate change models to forecast impacts on water quality and supply. These “top down” approaches are most appropriate for landscape or regional assessment because the resolution is limited to that of the global climate change models. Top down approaches commonly generate data on future climate conditions and use hydrology, management or demand models to translate global climate effects to realized responses (EPA 2010). Within the top-down category are sensitivity analyses (e.g. Woodbury et al., 2012) that examine a range of conditions and measure response of one or more variables. Bottom up approaches focus more on indicators or “cause-effect” pathways that reflect how climate change impacts valued resources. Bottom up approaches tend to focus on elements of the water system itself and involve qualitative assessments of components that are sensitive to climate change.

Vulnerability assessments are context specific and it is important to clearly describe the scale and focus of the assessment at the onset of the assessment process (Friggens et al., 2013a; Gleick et al., 2012). Since vulnerability is location specific, different habitats within a single wetland ecosystem can vary in their expected response to climate impacts. Selecting the appropriate scale of assessment is critical to addressing management issues or questions. The future conditions also need careful consideration to account for uncertainties in model projections. Scenario based assessments that consider a range of possible outcomes are recommended to identify potential management options (Gitay et al., 2011) though evidence-based approaches focused on the most likely future are advised in some situations (EPA 2010). A vulnerability analysis may require data on a number of key attributes, including the location and characteristics of a watershed or river system, water demand, storage capacity, flexibility of water supply sources, flood management operations, high value resources and their condition, and water quality impacts. Availability of data sources is often a driving limitation to the type of assessment conducted for a study system.

In this section we review a few studies that demonstrate approaches for conducting vulnerability assessments within aquatic systems. These studies were selected based on their potential relevance for systems within the SRLCC but do not deal specifically with systems in the western U.S. and, therefore, are not included in our review of vulnerability assessments. We also list a variety of tools and guidance documents for conducting vulnerability assessments across a wide range of study systems (Appendix 3). This review is not comprehensive but meant to demonstrate a range of approaches and provide references for future efforts. The second stage of this project will detail vulnerability approaches for specific targets of interests as well as present adaptive management strategies that derive from these efforts.

- Nelson et al. (2009) provides a review of the major elements important for assessment of aquatic systems. Though not specific to climate change, these reflect basic components that can be used as indicator of aquatic systems: Location and watershed characteristics, allocation, storage versus runoff ratio, flood management, diversity of water supply, shared regional water sources, water quality impacts. They also distinguish between assessing water demand vulnerabilities versus environmental and water quality requirements. The use of indicators like these is common to many of the assessments discussed in this report (e.g. Greir et al., 1990; Lane et al., 1999; Hurd et al., 1999 and EPA 2011).

- The Ramsar report (Gitay et al., 2011) outlines a conceptual framework for conducting aquatic risk assessments that incorporates concepts of vulnerability and risk assessments. They note that vulnerability is dynamic for a single system and can change given different starting conditions and the timing of climate events. Therefore, assessing vulnerability from the present condition of a wetland may not provide the most accurate measure of long-term vulnerability. Gitay et al. (2011) also note that management responses must consider other pressures or drivers of change.

- Downing and Doherty (2004) and Bayless et al. (1997) present examples of an aquatic vulnerability assessment that centers on stakeholder engagement and can be applied to a variety of systems. Bayless et al. (1997) describe four steps in their process: 1) Delineate affected area, 2) Stakeholder identification, 3) Responses developed, and 4) Identify information gaps.

- The Environmental Protection Agency's comprehensive report (EPA 2011) provides a comprehensive review of potential indicator variables for use in climate change vulnerability assessments in aquatic systems. The EPA describes in detail 53 indicators relevant to spatially cohesive water areas (e.g. watersheds, catchments, and rivers).

- Hlohowskyj et al. (1996) describe a method to rapidly assess climate change impacts for aquatic fish. Briefly this framework includes three steps: 1) predict changes in thermal structure of lakes and streams; 2) predict effects of temperature changes on physiological processes like growth and feeding, and 3) predict impacts of changes in physical habitat features to important life history stages such as migration periods and spawning times. They outline a 4 step process for developing these predictions:

    1. Collect GCM predictions;
    2. Link climate changes to environmental conditions (surface water temp, hydrographs, etc.);
    3. Identify habitat parameters vulnerable to predicted changes in freshwater conditions and collect appropriate data;
    4. Implement assessment approach.

  As an example, they develop empirical models to predict fish yields from historic data and GCM climate predictions. Using habitat suitability models they then predict fisheries response to changes in habitat quality and evaluate changes in growth using bioenergetics model and temperature-process relationships. Through this process they predict changes in habitat abundance and thermal suitability. Though their case study involves two types of modeling approaches, Hlohowskyj et al. (1996) specifically identify methods that are readily implemented, straightforward, do not require specialized computing power or expertise and can be applied to a variety of habitats and species in a timely manner. They also present detailed information the methods for estimating each environmental parameter as well (lake levels, flows, etc.). Importantly, they advocate for a weight of evidence approach (EPA 1992) for evaluating climate change effects.

- Crook et al. (2010) assesses the attributes of fish species that lend them to increased vulnerability to drought conditions. They considered characteristics that would reflect both resistance and resilience to drought for 15 species. The greatest indicator of vulnerability was historic declines in populations. This article also presents a conceptual framework to address climate change vulnerability. The framework focuses on: 1) quantifying spatial variation in the severity of drought impacts on particular habitats (rivers, wetlands etc.); 2) assembling information on drought sensitivities of regionally important species; 3) identifying high risk areas (based on species sensitivity and drought severity); 4) determining and implementing appropriate management actions (pre-emptive, responsive); 5) monitoring outcomes, and 6) disseminating information on outcomes. Their efforts support the consensus that the greatest threats to aquatic systems and species falls not from climate impacts but from the extremely reduced capacity of these systems to deal with disturbance under other anthropogenic stresses.

METHODS FOR SYNTHESIS

We reviewed literature from multiple datasets and search engines to identify relevant publications, reports, and project descriptions describing vulnerability assessments of aquatic systems within the west. Studies and reports were identified from searches using the Template for Assessing Climate Change Impacts and Management Options (TACCIMO), Forest Service data libraries services, the Pacific Institute, Google Scholar, and personal reference. Our intent was to review and synthesize information on climate change vulnerabilities for aquatic ecosystems within the Interior West. Studies and reports were selected based on the following criteria:

1) The study assessed, analyzed or discussed climate change impacts for aquatic systems or components;

2) The study involved a system, habitat or species that resides within the SR LCC boundaries;

We included studies and assessments outside the SR LCC boundary when they provided relevant information not otherwise covered by sources from the Interior west. Because human and ecological water needs are intermingled, we include studies that discuss socioeconomic impacts. However, it was not our intent to compile socioeconomic information and this document and associated tools should not be taken as an authority on the subject. Similarly, we did not focus on studies that assess vulnerability of water utilities to climate impacts. For a review of considerations relevant to water utilities and efforts to assess climate impacts for drinking and wastewater facilities we refer the reader to the EPA (2011) report or to the articles and websites listed in Appendix 1.

We classified documents according to whether they represented studies of impact (Appendix 1), syntheses (Appendix 1), ongoing projects, or a climate change vulnerability assessment (Table 1). We used criteria as described in Friggens et al. (2013a) to distinguish between impact studies and vulnerability assessments. Vulnerability assessments and impact studies were further classified according to their focal geographic and subject area. We present the result of our literature search in Tables 1, 2 and Appendix 1. In addition, the next section presents a brief review each of the vulnerability assessments in chronological order under five focal areas: Fish, Terrestrial Animals, Aquatic Ecosystems, Water Resources, and Comprehensive.

VULNERABILITY ASSESSMENTS FOR THE WESTERN U.S.

We identified 43 climate change vulnerability assessments that discuss aquatic systems either within the Southern Rockies LCC or with relevance to this area (Tables 1, 2). These studies and assessments discuss or measure climate effects across a broad array of ecosystems. Most assessments focused on aquatic ecosystems (watersheds, river and streams, lakes) or habitats though a few focused more on terrestrial and human systems (labeled comprehensive here). The majority of assessments focused on water resources, defined here as the cumulative social and ecological assessment of vulnerability. Relatively few assessments focus on fish and none were found that directly discussed invertebrate fauna (but see Appendix 1 for impact studies and EPA (2011) for use of invertebrates as a vulnerability indicator).

Table 1. Forty-three vulnerability assessments or studies with relevance to the aquatic systems of the Southern Rockies LCC. Geographic scale refers to the level at which the assessment was conducted. . Global assessments have the largest coverage; National assessments are focused within North America; Regional studies are primarily within the Western United States; State and local assessments typically involve approaches based on specific systems. Some studies develop a broadly applicable tool that is demonstrated at a more local scale (e.g. Local/Global and Local/Regional). Focal systems refer to the primary assessment target and are organized as increasing hierarchy. Fish and Terrestrial species assessments deal primarily with populations. Aquatic ecosystem assessments consider vulnerability of riparian habitat and may or may not include references to animal species. Water Resource assessments consider the result of hydrological change on a wider variety of natural and socioeconomic resources. Comprehensive assessments consider vulnerability of multiple sectors including water resources.

Geographic Scale of Assessment	Focal System of Assessment					
	Fish	Terrestrial Species	Aquatic Ecosystems	Water Resources	Comprehensive	Total
Global		1		1		2
Local	2	1	1	2		6
Local/Global	1					1
Local/Regional			1			1
National			1	5	1	7
Regional	1	1	2	10	2	16
State		1	3	1	1	6
State/Local		2				2
West Hemisphere		2				2
Total	**4**	**8**	**8**	**19**	**4**	**43**

FISH

Vulnerability assessments focused on North American fish fauna are limited with notable exceptions for California and the Pacific Northwest (Appendix 1). We did not find climate change vulnerability assessments for fish populations residing within the SR LCC boundary. Here we describe four assessments from other areas that provide guidance or relevant information for efforts within the interior West. As recently pointed out by several studies, climate change is likely to have detrimental effects for fish population (Jaeger et al., 2014; Moyle et al., 2013; Vörösmarty et al., 2010). The IUCN (Reid et al., 2013) reports that freshwater fish are the most threatened group of vertebrates. Issues facing this group include habitat modification, destruction and fragmentation, as well as invasive species, overfishing and climate change. The interactive effects of climate change and invasive fish species has been cited as a threat to native fish populations within the Colorado Basin (Rahel et al., 2008).

- Chu et al., (2005) compared the vulnerability of cold water and warm water fish species in Canada that may have relevance to species in the SR LCC. The primary species assessed included brook trout (*Salvelinus fontinalis*), walleye (*Sander vitreus*), smallmouth bass (*Micropterus dolomieu*), pugnose shiner (*Notropis anogenus*), and arctic char (*Salvelinus alpinus*). Logistic regressions were developed for each species using data from the Canadian Global Coupled Model 2 (CGCM2) climate change model to predict the change in species occurrence in multiple watersheds. Cold water species were considered likely to be extirpated from their present range and cool water and warm water species were likely to shift distributions northward. However, these expansions could be hindered by current ecological and physical barriers. They note that cold water fish may remain in deeper waters that could become more isolated under climate change. Chu et al. (2005) also note that the potential for smallmouth bass to expand northward could be catastrophic for native populations as it would increase predation on populations already experiencing habitat loss.

- Though not focused on North American fish species, Chessman's (2013) analysis, based in Australia, describes a method for estimating fish vulnerability to drought and climate change with potential applications for North American species. Chessman (2013) identified 14 traits associated with either positive or negative response of fish populations to drought. They measure these traits for 36 species made over two time periods at 839 sites and correlated traits to population trend (decline or increase). Eleven traits describing aspects of diet, life history and physiological tolerance proved to be most important for predicting population trends across all species. Adaptation to warm environments, expressed as a high minimum spawning temperature and heat tolerance, was associated with better drought tolerance. Omnivores did better than obligate invertivores. In general fish that did better over the course of a drought had traits associated with "periodic" or seasonally consistent strategies: delayed maturation, large adult size, briefer spawning season, greater fecundity and planktonic eggs. Though this would seem counterintuitive since drought stricken systems often represent a more variable environment, prolonged droughts may have a heavier impact on short lived species (Bagne et al., 2012). Importantly, Chessman et al. (2013) note that traits important to the recovery of fish populations after a drought are likely to be as relevant to the overall observed response as traits that allow species to survive drought conditions. Chessman et al. (2013) specifically notes that their system based on the Murray-Darling basin is not likely to be transferable to estuarine systems and are probably only relevant to systems that hold a similar assemblage of fish groups and food chains. However, these traits may be consistent enough across fish functional groups that they provide a good starting point for assessing other systems.

- Moyle et al. (2013) developed a systematic assessment approach for fish using expert knowledge to determine status and future vulnerability of freshwater fish. This system, based upon the EPA (2011) method for assessing watersheds, includes baseline vulnerability and climate change vulnerability components. Baseline indicators for vulnerability include: current population size, long term population trend, current population trend, long-term range trend, current range trend, current vulnerability to stressors other than climate change, future vulnerability to stressors other than climate change, life span, reproductive plasticity, vulnerability to stochastic events, and current dependence on human intervention. Indicators of climate vulnerability included: physiological/behavioral tolerance to temperature increase, physiological/behavioral tolerance to precipitation change, vulnerability to change in frequency of degree of extreme weather events, dispersive capability, degree of physical habitat specialization, likely future habitat change, ability of species to shift at same rate as habitat, availability of habitat within new range, dependence on exogenous factors, and vulnerability to alien species. Moyle et al. (2013) used these indicators to determine vulnerability and score 121 native and 43 alien species within Californian water systems. Overall, native species were more vulnerable to future conditions. Anadromous species also tended to be more vulnerable. Steelhead trout (*Oncorhynchus mykiss*) were the single most vulnerable species. Vulnerability scores for baseline and climate change impacts tended to be correlated and, in turn, vulnerability scores tended to be correlated with the protected status of species. Moyle et al. (2013) also note that vulnerability was similar among species within a family and propose that family level scores could be representative of the species. They also discuss the implications of modified streams for community composition. For instance, modifications may favor species that prefer slow water (e.g. lake species).

- Quiñones and Moyle (2014) calculated scores representing baseline and climate change influences using a rubric described in Moyle et al. (2014). Their study scored 25 native and 23 alien species in the estuary system of California. Fish were divided into two broad categories in this area; estuary-dependent and stream based fish. None of the alien species were found to be vulnerable to climate effects on habitat and four species may benefit from climate change. Eight native species were classified as critically vulnerable and nine native species had highly vulnerable scores; no native species were expected to benefit from climate effects. As found for other aquatic assessments, fish appear to be more threatened by ongoing issues than by climate change though the difference between each threat category was small. Of the non-climate threats, the highest (most vulnerable) species were predicted to be negatively impacted by estuarine alteration. The discussions and findings of Moyle et al. (2013) and Quiñones and Moyle (2014) provide a basis for considering similar outcomes among fish populations in the interior West.

Table 2. Climate change vulnerability assessments for natural aquatic systems in the Southern Rockies LCC. Location refers to the site in which the assessment or study was conducted. Application scale identifies the scope of the project or methods. Assessments used one or more of four main approaches to assess vulnerability of the focal system: Quantification of traits or indicators of vulnerability; Quantification and comparison of impacts; Synthesis of risks or impacts used to compare vulnerability among sites or systems; the development and demonstration of a method for estimating vulnerability. See text for more details on each assessment.

Authority	Location	Focal system	Application Scale	Time frame	Approach
Adrian et al., 2010	na	Lakes	Global	na	Quantifies/Describes traits indicating vulnerability
Austin et al., 2000	Arizona-San Pedro River	Water Resources	Local	na	Quantifies and compares degree of impact
Bagne and Finch 2012	Southern Arizona	Terrestrial animal species/Plant species	State/ Local	30-50 year future window	Quantifies traits indicating vulnerability
Barnett et al., 2004	Colorado	Water resources	Regional	1st half of the 21st century	Quantifies and compares degree of impact
Capon et al., 2013	na	Aquatic ecosystems	Local/ Regional	na	Synthesizes/Conducts comparative analysis of studies measuring change
Chessman 2013	Australia	Fish	Local/ Global	annual	Quantifies/describes traits indicating vulnerability
Christensen and Lettenmaier 2007	Colorado	Water resources	Local	2010-2039, 2040-2069, 2070- 2099	Quantifies and compares degree of impact
Chu et al., 2005	Canada	Fish	Regional	2020, 2050	Quantifies and compares degree of impact
Coe et al., 2012	Arizona- Sky Islands	Terrestrial animal species	Local	30-50 year future window	Quantifies traits indicating vulnerability
Decker and Fink 2014	Colorado	Aquatic ecosystems	State	2050	Quantities vulnerability and estimates impact

Authority	Location	Focal system	Application Scale	Time frame	Approach
Decker and Rondeau 2014	San Juan/Tres Rios in SW CO	Aquatic Ecosystems	Local	2050	Quantities vulnerability and estimates impact
Enquist and Gori 2008	New Mexico	Comprehensive	State	2030, 2060	Quantifies and compares degree of impact/vulnerability
Enquist et al., 2008	New Mexico	Water resources	State	na	Quantifies and compares degree of impact
EPA 2011	U.S.	Water resources/ Aquatic ecosystems	National	na	Quantifies/Describes traits indicating vulnerability
Foden et al., 2008	Global	Terrestrial animal species	Global	na	Quantifies traits indicating vulnerability
Friggens et al., 2013	New Mexico	Terrestrial animal species	State/ Local	30-50 year future window	Quantifies traits indicating vulnerability
Friggens et al., 2014	New Mexico	Terrestrial animal species	State	2030, 2060, 2090	Quantities vulnerability and estimates impact
Furniss et al., 2012	U.S.	Watershed	Regional	varies	Develops and demonstrates method for estimating vulnerability
Gleick 1990	U.S.	Water resource Region	National	na	Quantifies/describes traits indicating vulnerability
Gordon and Ojima 2015	Colorado	Comprehensive	State	2050	Synthesizes/Conducts comparative analysis of studies measuring change
Howe 2012	Colorado	Watershed	Regional	2050	Develops and demonstrates method for estimating vulnerability
Hurd and Coonrod 2008	Southwestern U.S.	Water resources	Regional	2000, 2030 and 2080	Quantifies and compares degree of impact
Hurd et al., 1999	U.S.	Water resources	National	na	Quantifies/describes traits indicating vulnerability

Authority	Location	Focal system	Application Scale	Time frame	Approach
Johnson et al., 2005	Prairie pothole region	Terrestrial animal species	Regional	general projections for the future; no specific time periods	Quantifies and compares degree of impact
Julius et al., 2006	Southwestern U.S.	Aquatic ecosystems	Regional	na	Synthesizes/Conducts comparative analysis of studies measuring change
Lane 1999	U.S.	Water resource region	National	2100	Quantifies/describes traits indicating vulnerability
Lawler et al., 2009	North America	Terrestrial animal species	West Hemisphere	2071-2100	Quantifies and compares degree of impact
Lawler et al., 2010	North America	Terrestrial animal species (amphibians)	West Hemisphere	2071-2100	Quantifies and compares degree of impact
Louie 2012	Montana- Gallatin National Forest	Watershed	Regional	na	Develops and demonstrates method for estimating vulnerability
Lukas et al., 2014	Colorado	Water resources	State	na	Synthesizes/Conducts comparative analysis of studies measuring change
Meyer et al., 1999	U.S.	Aquatic ecosystems	National	na	Quantifies traits indicating vulnerability
Moyle et al., 2013	California	Fish	Local	na	Quantifies and compares degree of impact
Neeley et al., 2011	Gunnison Basin	Comprehensive	Regional	2040-2069	Synthesizes/Conducts comparative analysis of studies measuring change
Nelson et al., 2009	Western U.S.	Water resources	Regional	na	Synthesizes/Conducts comparative analysis of studies measuring change

Authority	Location	Focal system	Application Scale	Time frame	Approach
Ojima and Lackett 2000	U.S.	Comprehensive	National	na	Synthesizes/Conducts comparative analysis of studies measuring change
Ojima and Lackett 2002	Western U.S.	Comprehensive	Regional	Historical and GCM data for 2025-2034 and 2090-2099.	Quantifies and compares degree of impact
Perry et al., 2013	laboratory (glasshouse)	Vegetation	Regional	na	Quantifies and compares degree of impact
Quiñones and Moyle 2014	California- San Francisco Bay Area	Fish	Local	na	Quantifies and compares degree of impact
Steinke 2012	Arizona- Coconino National Forest	Watershed	Regional	2020, 2050, 2080	Develops and demonstrates method for estimating vulnerability
Theobald et al., 2010	Western U.S.	Aquatic ecosystems	Regional	2030	Quantifies vulnerabilities for riparian ecosystem
Weinhold 2012	Colorado- White River National Forest	Watershed	Regional	mid and late century	Develops and demonstrates method for estimating vulnerability
Winter 2000	U.S.	Wetlands	National	na	Quantifies and compares degree of impact
Woodbury et al., 2012	Colorado	Streamflow	Regional	2040, 2070	Quantifies and compares degree of impact

TERRESTRIAL ANIMAL SPECIES

Eight assessments focused solely on the vulnerability of animal or plant species associated with aquatic habitats within the western U.S. Most of these assessments covered a diverse set of terrestrial species including species associated with wetlands, riparian areas, ponds or other water bodies. One assessment regards water fowl (Johnson et al., 2005), six discuss amphibians (Foden et al., 2008; Lawler et al., 2009,2010; Bagne and Finch 2012, Coe et al., 2012, Friggens et al., 2013b, 2014),three include riparian obligate birds (Bagne and Finch 2012, Coe et al., 2012, Friggens et al., 2013b, 2014), two riparian associated mammals (Friggens et al., 2013b, 2014), and two consider aquatic reptiles (Friggens et al., 2013b, 2014).

- Johnson et al. (2005) used WETSIM, an applied simulation model, to predict wetland status under warming and identified potential outcomes for breeding waterfowl in the prairie pothole region of the U.S. They used a scenario based approach based on three climate futures: 1) 3°C temperature increase with no change in precipitation; 2) a 3°C temperature increase with a 20% increase in precipitation, and 3) 3°C temperature increase with a 20% decrease in precipitation. Across all scenarios, the most productive habitats for waterfowl shift to the northeast. Additionally, wetlands in dryer areas of the region were found to be highly vulnerable to drought induced habitat degradation and loss with warming temperatures. Johnson et al. (2005) conclude that substantial increases in rainfall would be necessary to head off habitat loss for waterfowl.

- Foden et al. (2008) quantified species traits to measure vulnerability of three animal groups: birds, amphibians, and corals across the world. Foden et al. (2008) generated a list of species traits indicative of species response to climate change that inspired later assessment tools (e.g. NatureServe's climate change vulnerability index, CCVI, Young et al., 2010, and the SAVS system, Bagne et al., 2011). Specialized habitat or microhabitat climates and limited dispersal capacities were considered most problematic issues for species under changing climates. Approximately 52% of amphibian species were considered vulnerable to future climate changes. The Bufonidae family (toads and true toads) had more than 50% of its species considered susceptible to climate change. Traits associated with amphibian vulnerability, including specialized habitat requirements, exclusive occurrence or reliance on threatened or unbuffered aquatic habitats, and dispersal issues related to barriers created by unsuitable habitats.

- Lawler et al. (2009) used a consensus based bioclimate envelope model (see Friggens et al., 2013a for discussion of vulnerability assessment measures) to assess the effects of climate change as simulated by 10 Global Climate Models (GCMs) under 3 emission scenarios (B1, A1B, and A2) on the range of 1,818 birds, 723 mammals, and 413 amphibians across the western hemisphere. They compared estimated distributions under both no dispersal versus unlimited dispersal scenarios. To measure change in species composition, Lawler et al. (2009) calculated species turnover rates under each of the climate scenarios. For the majority of climate scenarios (80%), their analysis showed a loss of 11 and 17% of species under B1 and A1 scenarios, respectively. Lawler et al. (2009) estimated that the greatest turnover for all taxa will occur in mountainous regions and that amphibians are most likely to experience range contractions and loss.

- In a more specific analysis, Lawler et al. (2010) focuses on amphibians and integrates bioclimate model projections with data on the presence of range restricted species and future conditions. They identified vulnerability according to an index generated by the number of times certain conditions exist within an area. Areas with high species turnover, high number of range restricted species, and reduced precipitation were considered most vulnerable to negative impacts arising from climate change. Species turnover (due to displacement by non-suitable climates and shifts in distributions) was moderately high (40% turnover) across the western United States under lower emission scenarios and approached 60% or more under higher emission scenarios. Northern areas, including the Northwest and California, had a higher percentage of range restricted species, which are considered more vulnerable to climate induced habitat changes. Within the United States, the Southwest had the highest vulnerability to climate change under lower emission scenarios but the entire west show high vulnerability under more extreme climate conditions.

- Three assessments (Bagne and Finch 2012; Coe et al., 2012; Friggens et al., 2013b) focused on vertebrate animal species using a System for Assessing Vulnerability of Species (SAVS, Bagne et al., 2012).

    - Coe et al. (2012) focused on 30 species in the Sky Island region of southern Arizona. Riparian associated birds (elegant trogon, *Trogon elegans*, Western yellow-billed cuckoo, *Coccyzus americanus*) and amphibians (Tarahumara frog, *Lithobates tarahumarae,* Chiricahua leopard frog *Lithobates chiricahuensis*) were among the highest scoring species. Of these, the Western yellow-billed cuckoo resides within the SRLCC boundary. Though Coe et al. (2012) assessed the southern variant of the Chiricahua leopard frog (see http://www.azgfd.gov/w_c/edits/documents/Ranachir.fi_000.pdf), their findings could have relevance to northern populations that fall within SRLCC boundaries. The primary issues contributing to species' vulnerability included: drier environments which reduce over wintering survival and reduced activity periods, mortality from increased spring flooding, and multi-year droughts that reduce the success and number of breeding events. The riparian associated Western red bat (*Lasirurs blossevillii*) also received a score indicating high vulnerability primarily due to expected impacts to its habitat and changes in the timing of critical resources. The introduced American bullfrog (*L. catesbeianus*) received a lower score but was still considered vulnerable to negative habitat impacts.

    - Bagne and Finch (2012) examined species inhabiting Ft. Huachuca in Southwestern Arizona. This study was focused on Threatened, Endangered and At-risk species including 21 animals and 2 plants (Bagne and Finch 2012). Their findings suggest that many already threatened species are at risk of additional issues due to climate change. Among aquatic species, they found the Sonoran tiger salamander (*Ambystoma tigrinum*) and Chiricahua leopard frog (*L. chiricahuensis*) both vulnerable to further habitat loss due to increase temperatures, reductions in aquatic or moist habitat, and reduced quality of remaining habitat (e.g. UV, pollution, invasive species).The Huachuca water umbel, received scores indicating increased vulnerability under climate change which was related to its restriction to wet sites. This assessment did not include any other species with relevance to the SR LCC landscape or riparian habitats.

- Friggens et al. (2013b) scored 117 species inhabiting the Middle Rio Grande Valley of New Mexico. Riparian obligate species tended to be more vulnerable than species with broader habitat associations. Aquatic amphibian species including the Northern leopard frog (*Lithobates pipiens*), Western chorus frog (*Pseudacris triseriata*), were more vulnerable than more terrestrial species such as the spade foot toads (*Spea* spp.). Reduced pond duration, reduced availability of appropriate breeding habitat, increased water temperatures, and increased crowding and invasive species were the primary drivers of increased vulnerability for amphibians. The Great Plains skink (*Plestiodon (Eumeces) obsoletus*), two gartersnakes (*Thamnophis cyrtopsis and T. marcianus*), the western painted turtle (*Chrysemy picta*), big bend slider (*Trachemys gaigeae)*, and Spiney soft-shelled turtle (*Apalone spinifera*) were most vulnerable within the reptile group. For these animals, loss of riparian associated vegetation and water as might occur with increasing drought was a primary source of vulnerability. Riparian obligate birds including the southwestern willow flycatcher, the Western yellow-billed cuckoo and the common yellowthroat (*Geothylypis trichas*) were found highly vulnerable to future climate impacts. For these species, habitat loss and high habitat specificity contributed most to their high scores. For mammals, the New Mexican meadow jumping mouse (*Zapus luteus*) and hoary bat (*Lasiurus cinereus*) received the highest scores due to their dependence on moist habitats and large trees, respectively. The beaver (*Castor canadensis*) and muskrat (*Ondatra zibethicus*) scored somewhat lower due to more generalized habitat needs within the riparian corridor and ability to withstand short periods of resource variation.

- A recent report (Friggens et al., 2014) assessed the vulnerability of 12 riparian obligate species inhabiting the riparian corridor in New Mexico. Climate change impact was measured through species distribution models that estimate change in suitable habitat under three climate scenarios for three time periods, 2030, 2060, and 2090. Vulnerability of species resulting from non-modeled impacts (e.g. species interactions, tolerances to extreme events) was calculated using a modified version of the SAVS index. Niche model results often corresponded with vulnerability scores, where species with high scores (high vulnerability) also tended to lose the most habitats under future scenarios. All three birds, the Yellow-billed cuckoo, Southwestern willow flycatcher, and Lucy's warbler (*Oreothlypis luciae*), both reptiles, the Western painted turtle (*Chrysemys pita belli*) and the black-necked gartersnake (*Thamnophis crytopsis*), two bats, the Yuma bat (*Myotis yumanensis*) and the occult bat (*Myotis occultus*), and the New Mexico meadow jumping mouse appear to be at high risk of population declines in the near future. Among amphibians, the American bullfrog appeared to have more resilience to climate impacts but experiences significant habitat loss under all three future scenarios. In contrast, the leopard frog (*Lithobates pipiens*), appeared more vulnerable to climate change impacts (from this and Friggens et al., 2013b assessments), but might experience increased availability of suitable habitat. Increased availability of suitable habitat was also estimated by models for the cotton rat, *Sigmodon hispidus*, though those predictions assumed no change in the presence and persistence of streams.

AQUATIC ECOSYSTEMS

Several studies present a more inclusive assessment of multiple components of aquatic ecosystems. Eight assessments considered impacts to aquatic ecosystems that include plants, habitats, and animal species.

- In a study of comparative impacts among riparian plant species, Perry et al. (2013) identify specific outcomes under a set of assumptions about future stream flow. Specifically, changes in streamflow are expected to reduce the abundance of native early successional species but favor greater herbaceous species and late successional and drought-tolerant woody species. Climate changes will also reduce nutrient cycling and litter decomposition and, in general, decrease habitat quality for many species.

- Meyer et al. (1999) conducts a review of climate assessments for freshwater systems across the United States with a focus on how climate impacts the provision of goods and services. This review does not constitute an assessment of vulnerability for any particular system but rather provides insight into the relative vulnerabilities of various regions and systems to climate change. Meyer et al. (1999) provide qualitative descriptions of the vulnerability of each region according to the extent of the expected effect and the context of the systems with respect to anthropogenic influences. Notably, these authors suggested that altered patterns of land use, water withdrawal, and species invasions may dwarf or at the very least exacerbate climate change impacts. Their review highlights several specific predictions:

    - Shifts in distributions of aquatic insects (Sweeney et al., 1992).
    - Altered plant assemblages and changes in nutrient cycles (Meyer and Pulliam 1992).
    - Changes in sediment load and channel morphology (Ward et al., 1992).
    - Loss of some fish species (particularly from east-west oriented streams [Carpenter et al., 1992]).
    - Changes in hydrologic variability (e.g., the frequency or magnitude and seasonality of storm or flood events) may have a greater impact on aquatic systems than long-term changes in means.
    - Vulnerability has different sources depending upon the system. For wetlands, changes in water balance increase vulnerability to fire and changes to greenhouse gas exchanges are the largest consequence. Streams will be more heavily influenced by impacts on the riparian zone, species-specific thermal tolerances, and changes in flow regime.
    - Systems that are isolated are at an increased risk of endemic species extinction as a result of climate change.

- Increases in salinity due to increase evaporation and reduced precipitation may exacerbate the rate of species invasions and lead to widespread changes in riparian structure and food webs (Meyer et al., 1999).
- Finally, changes to the periodicity of flow (from episodic to perennial or vice versa) are much more likely to result in irreversible changes and reduce ecosystem function in the short term.

The Arctic, Great Lakes, and Great Plains (particularly the prairie potholes) are identified as vulnerable to climate change effects. For the Rocky Mountains, warmer temperatures will lead to fragmentation of cold water fish habitat and change aquatic insect distributions though it is pointed out that this is a region overtly affected by human activities, which may ultimately be more important than climate impacts (Meyer et al., 1999). The Great Plains and Prairie regions of the United States and California are considered particularly vulnerable to climate change due to changes in precipitation and flood regimes. Increased salinity as a result of increases in evaporation rates, especially in the western Great Plains, is a leading factor predicted to lead to loss of endemic fish species, many of which are already near their thermal tolerance limit. The arid SW is also vulnerable to climate effects but Meyer et al. (1999) felt that there is too much uncertainty in potential impacts to accurately assess this region.

- A risk assessment approach was applied to the San Pedro National Conservation area in Southern Arizona as well as the Sacramento River Watershed in California (Julius et al., 2006). For the San Pedro case study, Julius et al. (2006) evaluated the influence of five climate scenarios on species, vegetation, and habitat suitability. They linked vegetation data to ground water and surface water models to characterize evaporation processes. Results were generated by linking climate, hydrology, and ecosystems models to simulate future change and then incorporating land use stressors. They used historic weather data to create transient climate scenarios for the period 2003-2102 and created multiple possible future scenarios that were based on projections provided by SRAG (2000). Julius et al. (2006) found clear evidence that climate change leads to greater fragmentation of riparian habitats and a transition to more xeric plant communities. Variations were seen for predictions of future recruitment of native species because winter precipitation timing and amount could lead to lower or higher than currently observed recruitment rates. In general, late successional habitats dominated by mesquite, ash patch types and sacaton grassland were expected to become more dominant over the next 100 years. Results of comparing habitat suitability indexes showed a varied response for avian biodiversity: 26% of the most abundant species were expected to decline, 25% remain unaffected and 43% are likely to benefit from future conditions. Species that are likely to decline were those most dependent on cottonwood/willow gallery forests. The yellow-billed cuckoo is expected to see a decline in habitat and the Botteri's sparrow (*Peucaea botterii)* an increase regardless of climate impacts.

- Enquist and Gori (2008) ranked vulnerability of watersheds in New Mexico according to two measures: magnitude of exposure and biological diversity. Exposure was estimated using climate data generated from the Climate Wizard site, which provides long-term trends in climate data, information on snowpack trends and water runoff patterns to generate an estimate of moisture stress. Biodiversity and, in particular, diversity of sensitive species was used to indicate the importance of each watershed. Enquist and Gori (2008) also identified species as sensitive if they were reported as a Species of Greatest Conservation Need (SGCN) by the New Mexico Department of Game and Fish's State Wildlife Action Plan (SWAP). In general, lower elevation watersheds have experienced greater drying than high elevation watersheds though about 93% of watersheds overall showed some decrease in moisture availability over the 1970-2006 study periods. There tended to be more drying at drier watersheds though some watersheds, primarily in the southeast quadrant of the state, appeared to experience less drying for summer and fall seasons. Enquist and Gori (2008) report that though there were no significant trends overall, they did find a strong and significant relationship between increasing moisture stress and species richness when considering only the most species-rich watersheds. The Jemez, Cloverdale, and Playas Lake watersheds were identified as the most vulnerable due to the magnitude of observed moisture stress. The Pecos Headwaters, Upper Rio Grande, Upper Gila, and San Francisco watersheds have less moisture stress but are species rich. Enquist and Gori (2008) conclude that changes in climate and hydrology affect species in numerous ways and, within the SW, may be especially important where species face critical thresholds relating to metabolic and reproductive success (noted first in Burkett et al., 2005 and Ryan et al., 2008). The authors also identified two types of watersheds of concern: those found to be most vulnerable and those identified as most ecologically important due to high levels of biodiversity.

- Theobald et al. (2010) reviewed and analyzed threats to riparian ecosystems in the Western United States using a risk assessment approach. This analysis is comparable to that conducted by the EPA 2006 (Appendix 1). By creating "riparian threats score" based on indicators, Theobold et al. (2010) integrated information from three sources. They developed three scenarios that classified three system components—longitudinal, upland, and riparian zone— within which were multiple variables. Using geospatial data, models of runoff and sediment yield were generated and past and future scenarios of climate and land-use change were integrated to characterize landscape-scale processes influencing riverine and riparian areas. Theobold et al. (2010) include two key stressors, urbanization and changes in climate (primarily precipitation), in their assessment. The most modified watersheds occurred in the lower Colorado River and Great Basin regions. Decreased precipitation and increased temperatures are expected to increase erosion and decrease riparian vegetation cover leading to increased sedimentation. This effect is more pronounced in steeper and more arid part of the west, in particular, within the Southern Rocky mountains, Basin and Range and the Sierra Nevada. Overall the highest combined threat score was found for western Washington, the Great Basin, southern Idaho and northern Utah, and southern Arizona and New Mexico. The least threatened riparian systems were the Cascade and Sierra ranges, western Colorado and southeastern Utah. Theobald et al. (2010) found decreased flows in the Rio Grande region due to increased discharge but predicted increased flow for Colorado and Great Basin Regions. Southern Arizona and New Mexico received very high riparian threats scores. Flow fragmentation was among the worst for watersheds in Arizona and New Mexico though these same watersheds were not among those with the highest degree of modified riparian area.

- Capon et al. (2013) takes a different approach and describes the ways in which riparian ecosystems may be vulnerable as it pertains to exposure, sensitivity and adaptive capacity. Though not a vulnerability assessment that ranks vulnerability of different watersheds or species, Capon et al. (2013) demonstrate relative vulnerability among aquatic ecosystem components through a review of major areas of exposure, sensitive and adaptive capacity for riparian ecosystems. They discuss ecosystem services and likely impacts. This is a comprehensive yet succinct review of the major issues and underlying causes for climate change impacts. They use this review as a backdrop for presenting adaptation options.

- Decker and Fink (2014) present the results of a climate change vulnerability assessment for terrestrial ecosystems in Colorado which include playas, riparian woodlands and shrublands, and non-riparian wetlands. They consider the current range of climate conditions for each ecosystem within its distribution and estimate exposure and sensitivity based on the degree of departure from those conditions by 2050. Adaptive capacity was estimated through a scoring process based on a modified version of the system used by the Manomet Centure for Conservation Science (MCCS 2010). Playas were considered highly vulnerable to climate change. Within areas containing playa habitat, seasonal precipitation and drought days remain largely unchanged but spring and summer temperatures increase outside the known tolerance of these systems. Further, playas are susceptible to loss due to their isolated nature and human activities like agriculture. Riparian woodlands and shrublands scored differently based on their location. Ecosystems in western Colorado were considered moderately vulnerable to climate change, whereas riparian woodlands and shrublands in eastern or mountainous portions of the state had low vulnerability. Future spring precipitation, drought days and mean summer temperature fell outside the current range of conditions for these habitats. Drought and invasive species were identified as likely issues. Wetlands included marshes, seeps, springs, and wet meadow habitats. Again differences were detected for wetlands depending on their geographic locations with eastern ecosystems appearing more vulnerable to climate impacts. Though wetlands appear to be equally able to deal with biological stressors, extreme events, landscape condition and other elements used to predict adaptive capacity, eastern areas are expected to experience a greater divergence of future climate conditions, especially drought days.

- In a similar assessment, Decker and Rondeau (2014) apply the process outlined in Decker and Fink (2014) to terrestrial habitats within the San Juan and Tres Rios areas of southwestern Colorado. Three wetland types were included in the analysis: riparian, wetland and fen habitats. Low elevation riparian/wetland habitats scored as highly vulnerable and high elevation riparian/wetland habitats as moderately vulnerable. Lower elevation habitats were typically under greater stress due to streamflow modifications and were more vulnerable to droughts than habitats at higher elevations.

WATER RESOURCES

This section includes studies and assessments that cover a broad array of approaches for determining functional or ecological impacts due to changing hydrological conditions. Ten assessments consider vulnerability from the perspective of how climate change might reduce the capacity of aquatic systems to provide ecosystem services.

- Gleick et al. (1990) is the earliest assessment reviewed in this section. Gleick et al. (1990) identified five measures of vulnerability and used them to rank 18 U.S. water resource regions. The indicators, hydropower dependence, storage ration, demand ratio, streamflow variability, and ground-water overdraft, represent risk to both human and ecological systems. Gleick et al. (1990) assigned critical threshold values for each indicator based on studies and expert opinion. Resource regions were then ranked according to how many thresholds were exceeded. Within the West, Gleick et al. (1990) found the Great Basin region and California as highly and moderate vulnerability, respectively.

- Lane et al. (1999) built upon on Gleick et al. (1990) and incorporated additional indicators that represented both socio-economic and ecological factors for water resource regions in the U.S. Their final list includes five socio-economic indicators: Consumptive use, storage vulnerability, relative poverty, hydropower, import demand ratio, and five environmental indicators, withdrawal ratio, water quality, coefficient of variation, runoff ratio, and dependence ratio. They determined warning thresholds for each variable based on previous research or expert opinion and assess each region. Future conditions were estimated using future temperature and precipitation estimates (year 2100), future water demands, population growth projections, and changes to hydropower production (assumed to be proportional to estimated change in streamflow). Indicators for regions in the arid west (13-16 and 18) exceeded warning thresholds for consumption, storage vulnerability, relative poverty, withdrawal, coefficient of variation and runoff ratio indicators. Lane et al. (1999) also provides methods for displaying complicated outputs generated from multiple indicators as well as review the use of indicators for assessing the vulnerability of aquatic systems.

- In a similar effort, Hurd et al. (1999) developed a set of measures and criteria to assess vulnerability of regional water resources and water dependent resources to climate change. Hurd et al. (1999) also built upon the work of Gleick et al. (1990) with the goal to develop a more refined set of indicators to assess vulnerability at more local scales. The indicators of Hurd et al. (1999) fall into two categories: those pertaining to water supply, distribution, and consumptive use and those that pertain to instream use, water quality and ecosystems support. The first set of indicators includes total groundwater and surface withdrawal, withdrawal to baseflow ratio, amount of water consumed a dryness ratio, streamflow variation, and institutional flexibility. These measures consider the flexibility of the system to deal with changing water supplies where high withdrawals and consumption combined with little option to trade water leads to high vulnerability. In the second class, ecosystem thermal sensitivity, dissolved oxygen, mean baseflow, and number of species at risk are used to assess ecological vulnerability. An increase in the number of very hot days or loss of cold weather periods is likely to stress aquatic systems. Temperature increases also reduce dissolve O^2, stressing wildlife. Streams and rivers with low flows are more vulnerable to drought. Quantifying species at risk provides a measure of impact for the study system where greater numbers indicate greater potential impact. For each of the twelve indicators, value ranges were divided into low, medium, and high vulnerability categories. They used these criteria to develop a database to compare regional vulnerability of U.S. water resources. Overall, southern watersheds tend to be more vulnerable to changes in water quality, flooding and in stream water uses, whereas consumptive water use was among the most vulnerable resources in the West, especially in the southwestern United States.

Individually, the indicators developed by Hurd et al. (1999) were used to provide a relative measure of vulnerability among watersheds. Western watersheds, specifically east of the Rocky Mountains, Central and Southern California, had the most intensive use of available water and were found highly vulnerable to climate related reductions in stream flow. Increased natural variability was also considered an indicator of greater vulnerability and was generally high across the West and in California, the Great Basin, and the northern and southern Great Plains. Western U.S. watersheds also scored high in dryness ratio and consumptive use. Vulnerability associated with groundwater depletion was greatest for the Southwest, California and southern and central Great Plains. The interior west was among the least vulnerable to flood risk due, in part, to low population numbers. Scores for the second category showed the desert southwest, southern Great Plains and cold-water fisheries of the Rocky Mountain States to be most likely to experience thermal stress. Ecosystems with the lowest stream flow and greatest ecosystem vulnerability were found in the Great Plains and the Southwest. Used collectively, Hurd et al.'s (1999) indicators can identify sources of vulnerability within watersheds. The cumulative vulnerability scores for instream use, water quality and ecosystem support were highest for southern California, central Arizona and lowest for watersheds in the Pacific Northwest and Nevada. The western United States and particularly California, Utah, Nevada, Arizona, New Mexico, eastern Colorado and Wyoming, Nebraska, Kansas and Western Texas were considered highly vulnerable when scores were aggregated for water supply, distribution and consumptive use.

- Austin et al. (2000) report on an assessment of climate vulnerability in the Middle San Pedro River. http://www.climas.arizona.edu/files/climas/pubs/CL3-00.pdf. Their research finds that under current conditions, residential/commercial water providers seem to be least sensitive while irrigation providers, depending on the availability of surface water in the San Pedro River, could be considered most affected by climatic variations. Electricity providers appear best equipped to respond to meteorological and short-term climatic changes.

- Winter (2000) used the characteristics of hydrological landscapes to determine climate change vulnerability. Vulnerability was related to the inherent capacity of the system to compensate (through reliance on other water sources) for variation in precipitation variables. These characteristics serve as a measure of how and why a hydrological system is vulnerable to climate change, which then can be applied to classify systems. Winter (2000) classified six types of hydrological landscapes. Among these, wetlands in mountainous landscapes, wetlands associated with glacial landscapes and broad interior basins (playas) are predicted to be the most vulnerable. Vulnerability of wetlands in plateaus and high plains and riverine landscapes vary according the degree to which upper and lower regions depend upon precipitation and according to the size of the hydrological systems. Those that rely on precipitation (typical of upland areas) and are small are most vulnerable.

- Christensen and Lettenmaier (2007) conducted a quantitative analysis to estimate the implications of future climate change on runoff for the Colorado River Basin. Though not a climate change vulnerability assessment as technically defined (Friggens et al., 2012a), this publication provides a comprehensive modeling effort for the Colorado River Basin and is the first to identify specific outcomes as a result of climate change. Christensen and Lettenmaier (2007) considered output from 11 GCMs under 2 emission scenarios for 3 time periods. Their primary findings predict increased winter precipitation and decreased summer precipitation and all showed substantial declines in runoff. The authors found evapotranspiration had greatest influence on runoff estimates and runoff declines were reflected in reservoir performance, which led to lost reservoir storage and declines in hydropower.

- Hurd and Coonrod (2008) conducted an analysis focused within the SW using models of streamflow and runoff. They also include assessments for how land use and future agricultural and urban water demands might interact with climate impacts. Hurd and Coonrod (2008) show that peak flow and total stream flow declines across both wetter and drier scenarios. Further, they indicate that increased monsoons will not offset effects of reduced snowpack in headwaters. Finally, over time, there will be a pronounced shift to an early peak flow and significant shift in late winter runoff. This leads to greater reliance on reservoirs and aquifers. The southern reaches of the Rio Grande are likely to be most vulnerable to these effects.

- Adrian et al. (2010) developed a set of indicators to identify vulnerability of lakes to climate change. They propose that lakes may be good sentinels of global climate change because they are sensitive to environmental changes and reflect changes to the surrounding terrain. They selected indicators that reflect key properties of lakes and are likely to change with changing climate. Variables were also selected for their applicability across multiple lake types, ease of measurement, and relevance to ecosystem function. Adrian et al. (2010) assessed the suitability of a response variable based on its relationship to primary climate drivers, possible confounding effects, and the basic utility (ease of measurement, advantages, and disadvantages) of that indicator. Indicators were categorized according to lake types and climate region. Good indicators for all lake types and climate region were water temperature, dissolved organic carbon (DOC) and plankton composition. Distinct climate drivers were apparent in different climate zones. For lakes in temperate arid or tropical zones, air temperature alone drove increases in stratification period and stability, but decreases total Phosphorous and Nitrogen, which decreases productivity. They also predict decreased bottom O_2 and increased H_2S, NH_4 and PO_4 which decreases habitat and nutrient storage.

- The Environmental Protection Agency has developed a large set of indicators to identify vulnerability of aquatic systems within the U.S. (EPA 2011; Appendix 2). Their approach is based on the idea that vulnerability to climate or global change will manifest through changing the innate resilience or sensitivity of the system. Therefore, measures that relate to impacts of multiple stressors are relevant to the pursuit of a climate change vulnerability assessment. The vulnerability indicators are comprised of biophysical measures that relate to the exposure and sensitivity of the system to environmental change (Appendix 2). Adaptive capacity is measured by the degree to which those indicators resist change when exposed to stress. Indicators reflect a range of properties from ecosystem services like drinking water quality to indicators that reflect more inherent vulnerabilities of aquatic systems. These efforts resulted in the identification of 53 vulnerability indicators that reflected a relative measure or value judgments. These were further whittled down to 25 mappable indicators which were used to rank watersheds across the Nation (Appendix 2). An additional 28 indicators were also identify as good vulnerability indicators but did not have the appropriate geospatial information or coverage to make the final list. High scores are an indication of high sensitivity or low resilience.

  The EPA indicator dataset presents a standard package of measures to compare vulnerabilities of watersheds or aquatic systems across the nation that have been thoroughly vetted by the selection and review process employed by the EPA. However, since the goals of the EPA effort was to produce national maps, indicators were selected or excluded based on the availability of data across the Nation and were mappable. Therefore, additional indicators may exist that are important to specific aquatic ecosystems. The EPA report also identifies how indicators can be modified to reflect local conditions and concerns. In addition to the development of a set of vulnerability indicators, the EPA report discusses several important concepts with respect to assessments within aquatic systems and describes in detail how each indicator measures or represents vulnerability to climate change. Ultimately, these indicators can be used in additional assessments that project future conditions to assess changes in vulnerability over time and in response to specific climate scenarios.

- Woodbury et al. (2012) analyzed the sensitivity of streamflow to climate changes within three Colorado watersheds. They used comparison of observed changes and extrapolated responses to future conditions. Their objective was to develop a method and dataset that would allow users to gauge the impacts of climate change as estimated under multiple scenarios on water availability. Woodbury et al. (2012) compare changes in runoff estimates across a wide range of climate scenarios and two hydrological models. They find streamflow estimates vary across scenarios in unique ways. They do not find evidence for elevation based differences in response in contrast to predictions made by others (e.g., Meyer et al., 1999; Weinhold 2012).

- The USDA Forest Service Climate Change Resource Center in collaboration with National Forest conducted a pilot watershed assessment of 11 National Forests (Furniss et al., 2012). The primary goal of this assessment was to link and integrate the relatively well known hydrological impacts of climate change with existing programs and policies currently applied to western National Forests. Each participating Forest independently assessed watershed vulnerability under a proposed National Watershed Vulnerability Assessment (WVA) framework that considered aquatic species, water uses, and infrastructure. Of particular interest to this report are the assessments conducted by Steinke (2012), Louie (2012), Howe (2012), and Weinhold (2012).

    - Using a step-wise approach based on USDA Watershed Analysis (USDA 1994), Steinke (2012) compared vulnerability among five watersheds in the Coconino National Forest, Arizona. In addition to the three variables of the WVA, Steinke (2012) included values relating to riparian and spring and stream habitats. Each watershed was given a resource value based on the number of sensitive fish and amphibian species, degree of anthropogenic disturbance (roads), and miles of riparian habitat. Exposure estimates of future temperature, precipitation, runoff and snowpack for years 2030 and 2080 were generated using predictions from climate and the Variable Infiltration Capacity models provided by the Climate Impacts Group (CIG). Sensitivity was determined by considering current condition as well as natural sensitivities of watershed to changes in climate and flow parameter. Each element, water value, sensitivity, and exposure was then assessed by the pilot working team and scored as either low, moderate, or high. Composite scores and maps were then generated to describe each area by their score values. The greatest perceived issue arising from changes in climate dealt with decreased snowpack, to which watersheds above 6400 ft. are most likely to be susceptible. In addition, high elevation sites tended to have high resource values and sensitivity scores and were generally found most vulnerable in this assessment.

    - Louie (2012) presents results for the Gallatin National Forest, Montana. Watersheds were characterized and assessed for relative sensitivity to disturbance as described for Steinke (2012). Louie's (2012) objective was to develop a broad-scale GIS model to predict the effects of climate change on stream thermal regime that, in turn, can provide the bias for estimating impacts on fishery resources. A second vulnerability analysis was applied to further prioritized watersheds using geophysical/sensitivity characterization, the WCF, resources of value (fish aquatic habitat), and exposure (climate projections). Results are presented in figures in the report. Results of their assessment describe the general consequences of warmer temperatures for water resources including reductions in flows exacerbated by current water uses/diversions and potential shifts in fish populations to favor invasive fish and fish that favor warmer water. They also display a relative vulnerability outcome based on the combined sensitivity factors, risk for change, and presence of high value resource.

- Howe (2012) combined climate projections, current status assessments, VIC models and value resource layers to identify most vulnerable watersheds within the Gunnison National Forest, CO. Howe (2012) includes a number of measures: runoff variables, erosion/sedimentation, exposure to precipitation/temp changes, stressors (roads, recreation, water draw) and values (presence of cold water fish, water bodies). Watersheds within the Uncompahgre National Forest are expected to experience the greatest exposure, followed by Grand Mesa, then San Juan and West Elk. Watersheds within the Upper Taylor and Cochetopa National Forests experience less extreme changes. Results represented the culmination of water use values with sensitivities and stressors. Ultimately, the San Juans had the highest overall vulnerability followed by Upper Taylor, Grand Mesa, Uncompahgre, West Elk and Cochetopa.

- Weinhold (2012) identified important attributes associated with watersheds in the White River National Forest in Colorado using weighted values to indicate importance for predicting resiliency. Weinhold (2012) identified net effects relative to climate change. Overall, lower elevation subwatersheds had highest vulnerability to changing climate because they are the most dependent snowpack and snowmelt characteristics. It is important to note that all the watersheds within this study are at fairly high elevations, however. Natural and anthropogenic factors do not radically change. Weinhold (2012) notes that a focus on a few resource values and a relatively simple framework is an effective approach for assessing climate change vulnerability at the watershed level. Weinhold (2012) did not use VIC models in this case study and argues that to do so does would not add commensurate information to the study given the inherent broad brush characteristics for this approach. For example, measuring one resource with a known sensitivity to low water sources will sufficiently represent other similarly impacted resources.

COMPREHENSIVE ASSESSMENTS

Here we include assessments that consider climate change impacts for all ecosystems across the entire United States. Other global assessments, notably the IPCC reports (Kundzewicz et al., 2007), provide similar data though at a more regional scale. Because these assessments provide information at a broad scale they have limited applications for informing management needs at more local scales. Still, the following assessments present information and demonstrate process relevant to the SR LCC.

- Ojima and Lackette (2000) compiled climate change impact data for the entire United States into an assessment as part of the National Assessment Synthesis Team for the Global Change Research Program Report. This assessment reviewed knowledge and extrapolated information to identify areas of greatest concern. Though general in its applicability, this report succinctly summarized ongoing issues with respect to climate change in the United States.

- Ojima and Lackett (2002) assessed future impacts of climate change on both natural and social systems. Their report covers several elements relating to measures of vulnerability. Ojima and Lackett (2002) employed a stakeholder driven assessment that draws on participants from multiple economic sectors directed analysis of future vulnerability. Output from climate models were used to inform workshops that were conducted to identify additional issues (socioeconomic), potential vulnerabilities, and coping strategies. From these efforts, Ojima and Lackett (2002) identified areas of greatest change. The greatest increases in winter temperature were expected along the western parts of the Great Plains, especially along the Front Range. They identified several specific elements that will be heavily impacted including shallow aquifer recharge and streamflow timing. Summer temperature increases are likely to impact hail, the spread of invasive tree species, and fire. From the social perspective, farm/ranch families will experience modified vulnerability as a result of climate impacts to ecological and market systems. Water use competition will change and will affect human residence as well as natural resource management. A major product of this effort was to provide coping strategies for future expected changes- a theme relevant to the management of aquatic ecosystems.

- The Gunnison Basin Climate Change Vulnerability Assessment (Neely et al. 2011) measures the relative impact of climate changes on habitats (including seven freshwater) and species. They use a mid-century mark (2040-2069) and assessed habitats and species based on whether they would be sensitive to climate related stressors like temperature increases, extreme events, reduced baseflows, and snowmelt changes. They also considered indirect or non-climate stressors relating to disease, human disturbances and current status.

  Among the freshwater habitats assessed, montane groundwater-dependent wetlands were given a “highly vulnerable” score. Mid-size streams, rivers and reservoirs and associated wetlands received “moderately to highly vulnerable” scores and small high-elevation streams, high-elevation, groundwater-dependent wetlands and high-elevation lakes were given “low to moderate vulnerability”. The current condition of wetland habitat was an important predictor of vulnerability because many changes resulting from warming conditions are likely to exacerbate ongoing challenges. Higher elevation sites were expected to remain cold enough to avoid drastic impacts.

  Species assessments were based on NatureServe’s Climate Change Vulnerability Index (CCVI, Young et al., 2011). Fifty plant species were assessed. The majority of plant species (43 of 50) were score as extremely vulnerable to climate change. Of those 50, 18 were associated with ground water dependent wetlands, one species, *Carex stenoptila*, with subalpine riparian habitats and one, *Sullivantia hapemanii var purpusii,* was associated with montane riparian habitats. *Carex stenoptila* was considered highly vulnerable, whereas three *Carex* species (*C. diandra, C. microglochin, and C. scirpoides*) from groundwater dependent wetlands were moderately vulnerable. *Sullivantia h. v.purpusii* was also considered extremely vulnerable. Among the remaining wetland species, *Luzula subcapitatat, Eriophorum altaicum var. neogaeum* and *Dosera rotundifolia* were considered extremely vulnerable. C*ladina arbuscula, Hirculus prorepens, Kobresia simpliciuscula,Lomatogonium rotatum* were highly vulnerable. The remaining species, including *C. rangiferina, E. chamissonis, E.*

Gracile, Hippochaete variegata, Sphagnum angustifolium, S. girgensohnii, Triglochin palustris, and *Utricularia minor* were considered moderately vulnerable. The primary drivers of plant species vulnerability were poor dispersal capability, restriction or reliance on cool microhabitats, narrow or restricted range and dependence on ice and snow.

Among animals, amphibians (two species), fish (one species) and insects (one species) obtained the highest vulnerability scores. Amphibian and fish scores were driven in large part by their restricted habitats and limited capacity to disperse to new habitats. The insect was associated with alpine zones, which are likely to recede in the future. Among the birds assessed, the black swift (*Cypseloides niger*), Bald eagle, (*Haliaeeatus leucocephalus*), and Lewis's woodpecker (*Melanerpes lewis*) were associated with water or riparian areas. The black swift and bald eagle were listed as presumed stable and the woodpecker was given an "increase likely" score. Of the mammals assessed, none had a strong affinity to riparian areas and are not reviewed here.

- The Third National Climate Assessment (Melillo et al., 2014) reviews analyses of climate data and trends for the United States. Though not a vulnerability analysis of climate change impacts, several chapters address vulnerabilities pertaining to the Western United States. Of particular interest here are chapters that deal with water topics including: Water Resources; Ecosystems, Biodiversity, and Ecosystem Services; Energy, Water and Land Use; and The Southwest. Each chapter reviews current conditions and management issues and discusses future expected climate changes and impacts. Climate is expected to have direct impacts on water cycles as well as water demand leading to increased water shortages in the southern and Midwestern United States. Water quality will suffer as lower flows and less flooding encourages increased sediment, nutrient, and contaminant loads. Warming can also change plant growth and decomposition rates altering feedbacks into the environment. The Southwest, Great Plains and Southeast are expected to be most vulnerable to changes in water supply and demand. These regions are expected to experience more intense and longer-term droughts. Garfin et al. (2015, Southwest chapter) note substantial declines in snow water equivalent values for the lower Colorado and Rio Grande River Basins. Combined with expectation for a 10-50% increase in ground water withdrawals by 2060, water shortages are likely to increase within the Southwest. Watersheds in the Southwest showed widespread water stress due to municipal, energy, and agriculture water demands, using a water stress index. In addition, Native Nations, border cities, identifies agricultural industries are likely to be vulnerable to projected changes in climate conditions.

- Gordon and Ojima (2015) present a review of the key vulnerabilities of Colorado's economy and resources under climate change. They measure the capacity of Colorado's economy, resources, and populations to cope with negative impacts of climate change. Within the ecosystems sector they identify vulnerabilities for forests, alpine ecosystems, grasslands, and aquatic wildlife species. Within the Water (utility) sector, entities with inadequate storage such as small municipal utilities, those with junior rights, with aging water supply infrastructure, and municipalities that supplement surface waters with groundwater withdrawal are likely to be most vulnerable to hydrological consequences of climate change. In addition, water treatment facilities in fire prone areas or with older technology are at risk, and endangered fish programs and recreation activities might be negatively affected.

SUMMARY

This synthesis identified 43 vulnerability assessments covering a wide range of aquatic resources and implemented across diverse spatial scales. Climate vulnerability assessments for fish, aquatic invertebrates, and riparian plant communities within the SR LCC boundary were underrepresented in the vulnerability assessment literature. Though these components are often considered in context of ranking watershed or riverine values, their use is commonly limited to a measure of biological diversity. There is value in quantifying the direct effects of climate change on aquatic species and populations because the resulting assessments can inform monitoring, specific habitat needs, and adaptive management plans. Most of the assessments for the Interior West focused on watersheds or ecoregions across the entire nation (e.g., EPA 2011; Hurd et al., 1999). Within these assessments, the southern Great Plains (Meyer 1999; Hurd et al., 1999) and southwestern (Theobald et al., 2010) regions were indicated as highly vulnerable. At more local scales, vulnerability was often associated with lower elevation or more xeric sites (e.g., Furniss et al., 1999). These areas are generally not well represented in the literature of climate impacts (Appendix 1). Streamflow was the most common focus of concern and the over allocation of natural water flows is among the greatest issues facing all western water resources (EPA 2011).

Studies regarding climate change impacts on aquatic ecosystems and water resources continue to grow, providing a wealth of information by which to measure diverse components and processes within the U.S. (Appendix 1). Climate change vulnerability assessments use this information to identify the relative impacts of change across systems, populations, species or processes. The majority of aquatic climate change vulnerability assessments tend to incorporate indicators of current condition and resource values and estimate how these are impacted by changing conditions. Vulnerability assessments in this review either assessed the ability of the system to cope with disturbance or measured the degree to which a disturbance or change impacted functionality or provision of critical resources.

Climate change is but one of the issues facing our water resources. Riparian systems in the west face many threats including: Grazing, dams, land use change, invasive species, timber harvesting, climate change, recreation, water quality, water diversion, groundwater depletion, fire, and mining (Poff et al., 2011). Commonly, multiple threats are affecting a system at the same time. The presence of multiple threats especially where they create a negative synergy are difficult to assess because they can rarely be explained by examining any one threat. It is clear from the climate change vulnerability assessments reviewed here that there exists a wide range of potential impacts and inherent sensitivities within western aquatic systems. Increases in temperature alone drive many observed changes with precipitation acting to mediator or exacerbate aquatic system functionality. For many focal ecosystems assessed here, the impact of climate change was largely determined by the extent to which climate exacerbates current stressors, which directly relate to human use issues. Within the western U.S., the combined stress of human water use and climate induced changes to the hydrological regimes will present a major challenge for resource managers. Vulnerability assessments are a first step toward identifying research and management needs.

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Appendix 1.

List of climate change impact studies, reviews, or methods for aquatic systems in the Southern Rockies Landscape Conservation Cooperative. Studies that present relevant material but are from outside the focus area are also included. The citations organized alphabetically by focal topic. This data is maintained in an excel file that is available upon request. In addition, requests can be made for customized lists of relevant topics or locations (e.g. all studies within Colorado) by sending an email to: Megan Friggens at, meganfriggens[at]fs.fed.us.

Table A1. Key to focal topics.

Focal Topic	Number of Sources
Aquatic Animals	30
Studies and reviews of climate impacts on aquatic animal species.	
Aquatic Ecosystems, Habitats, Features	39
Studies of climate impacts for riparian ecosystems. These documents tend to focus on habitat characteristics (plant species or communities) or features (e.g. specific river system). May include animal species.	
Aquatic Ecosystems/Hydrology/Biogeochemistry	1
Studies and reviews of climate impacts on aquatic species.	
Assessment, Planning, Analysis Guidance	15
Various methods and guidance documents for climate change vulnerability assessments, studies and planning.	
Carbon	1
Studies and reviews of climate impacts on carbon cycles in aquatic systems.	
Debris flows, Erosion, Fire Effects	4
Studies and reviews of climate impacts on disturbance processes or effects.	
Ecosystems	4
Studies of terrestrial ecosystems that include aquatic types. Tend to be generalized (e.g. Riparian Habitats).	
Hydrology	62
Studies and reviews that focus on climate effects on hydrological processes (as opposed to ecosystem response).	
Invasive species	5
Studies and reviews of the implications of climate change for invasive species.	
Public Utilities and Water Resource Management	7
Studies and reviews of the impact of climate impacts on water utility and resource management.	
Reservoirs	1
Review of the implications of climate change on reservoir storage.	
Restoration	2
Studies specifically addressing restoration under climate change	
Studies and Reviews of Climate Impacts and Predictions	9
Studies and reviews of likely climate futures and relative impact across the landscape. Often provide data.	
Studies and Reviews of Water Resources	33
Studies f climate impacts on aquatic systems that includes consideration of socioeconomical resources.	
Terrestrial Animals	10
Studies of climate impacts on terrestrial animal species that rely on or are associated with aquatic habitats.	
Water Quality	2
Studies and reviews with a primary focus on climate impacts on water quality.	

Table 2. List of Impact studies by focal group.

Aquatic Animals

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APPENDIX 2.

Appendix 2. List of vulnerability indicators, excluding those pertaining to coastal ecosystems that can be used to assess condition and vulnerability of watersheds to climate change (EPA 2011). These represent both indicators of condition and indicators of potential negative impacts. Table adapted from EPA (2011) report.

Indicator	**Literature Source**
Acid Neutralizing Capacity (ANC)	U.S. EPA, 2006
Altered Freshwater Ecosystems (percent miles changed)	Heinz Center, 2008
At-Risk Freshwater Plant Communities	Heinz Center, 2008
At-Risk Native Freshwater Species	Heinz Center, 2008
Commercially important fish stocks (size)	Heinz Center, 2008
Fish and Bottom-Dwelling Animals (comparison to baseline)	Heinz Center, 2008
Flood events (frequency)	Lettenmaier et al., 2008
Freshwater Rivers and Streams with Low Index of Biological Integrity (ecosystem condition)	Heinz Center, 2008
Groundwater Depletion - Ratio of Withdrawals/ Baseflow	Hurd et al., 1998
Groundwater reliance	Hurd et al., 1998
Harmful algal blooms (occurrence)	Heinz Center, 2008
Invasive species - Coasts affected (area, ecosystem condition)	Heinz Center, 2008
Invasive species in estuaries (percent influenced)	Heinz Center, 2008
Low flow sensitivity (mean baseflow)	Hurd et al., 1998
Meteorological drought indices	Jacobs et al., 2000
Number of Dry Periods in Grassland/Shrubland Streams and Rivers (Percent of streams with dry periods over time)	Heinz Center, 2008
Ratio of Snow to Precipitation (S/P)	Lettenmaier et al., 2008
Ratio of water withdrawals to annual streamflow (level of development)	Hurd et al., 1998
Riparian Condition (Riparian Condition Index)	Heinz Center, 2008
Status of Animal Communities in Urban and Suburban Streams (Percent of urban/suburban sites with undisturbed and disturbed species)	Heinz Center, 2008
Streamflow variability (annual)	Hurd et al., 1998
Stream habitat quality	Heinz Center, 2008
Water Clarity Index (real vs. reference)	NEP, 2006
Water Quality Index (5 components)	NEP, 2006
Waterborne human disease outbreaks (events)	Heinz Center, 2008
Wetland loss)	MEA, 2005
Wetland and freshwater species at risk (number of species)	Hurd et al., 1998

Ratio of water use to safe yield	Schmitt et al, 2008
Erosion rate	Murdoch et al., 2000
Instream use/total streamflow	Meyer et al., 1999
Total use/total streamflow	Meyer et al., 1999
Snowmelt reliance	IPCC, 2007
Pesticide toxicity index	USGS, 2006
Population Susceptible to Flood Risk	Hurd et al., 1998
Herbicide concentrations in streams	USGS, 1999
Insecticide concentrations in streams	USGS, 1999
Organochlorines in Bed Sediment	USGS, 1999
Herbicides in Groundwater	USGS, 1999
Insecticides in Groundwater	USGS, 1999
Salinity intrusion (coastal wetlands)	Poff et al., 2002
Heat-Related Illnesses Incidence	Pew Center, 2007
Precipitation Elasticity of Streamflow	Sankarasubramanian et al., 2001
Ratio of reservoir storage to mean annual runoff	Lettenmaier et al., 2008
Runoff Variability	Lettenmaier et al., 2008
Macroinvertebrate Index of Biotic Condition	U.S. EPA, 2006
Macroinvertebrate Observed/Expected (O/E) Ratio of Taxa Loss	U.S. EPA, 2006
Threatened & Endangered Plant Species	U.S. EPA, 2008
Vegetation Indices of Biotic Integrity (IBI)	U.S. EPA, 2008
Instream Connectivity	Heinz Center, 2008
Water Availability: Net Streamflow per capita	Hurd et al., 1998

APPENDIX 3.

Examples of software and tools applied to aquatic systems to assess and plan for climate change impacts.

Name	Abstract/Description	Link or citation
Spatial Prioritization Software		
Zonation framework and software	Produces a hierarchical priority ranking across all grid cells in a landscape based on occurrence levels and connectivity for species in cells while simultaneously balancing the solution for all species in analysis.	www.helsinki.fi/biosciene/consplan/
Marxan	Using Marxan, planners can identify an efficient system of reserve sites, or other types of zoning patterns, that include a suite of biodiversity or human use targets at a minimal cost. Marxan provides a unique method for designing site networks that is systematic and repeatable, and is the most used conservation planning tool worldwide.	http://www.uq.edu.au/marxan/marxan-software
Bayesian Network Model for Bull Trout	Assists with the spatial prioritization of management actions and resources among populations, and comparing the benefits of removing/installing a fish barrier in a stream.	http://www.fs.fed.us/rm/boise/AWAE/workshops/CADS/Peterson/BayesianNetworkModelBullT
North American Freezing Level Tracker	Uses climate trends/data on streams and elevation data to describe isopleths.	(www.wrcc.dri.edu/cwd/products)

Name	Abstract/Description	Link or citation
Decision Support Tools		
Water Supply Stress Index (WaSSI) Ecosystem Services Model	WaSSI is an integrated, process-based model that can be used to project the effects of forest land cover change, climate change, and water withdrawals on river flows, water supply stress, and ecosystem productivity (i.e. carbon dynamics). WaSSI operates on a monthly time step at the HUC-4 (8-digit HUC) watershed scale (see more on HUCs) and across Mexico at the 0.5 degree scale. For the conterminous U.S., the model can also be run at the HUC12 scale for water and carbon balances from 1960 to 2012. As water yield and carbon sequestration are tightly coupled, WaSSI can be used to evaluate trade-offs among management strategies for these ecosystem services.	http://www.forestthreats.org/tools/WaSSI
River Bathymetry Toolkit (RBT)	Our goal is to characterize in-stream and floodplain geomorphology to support aquatic habitat analyses and numerical models of flow and sediment transport. The (RBT) is available for free and is under active development. Tools exist for cutting cross sections and longitudinal profiles into high resolution DEMs to extract hydrologic parameters such as wetted area, bankfull width, hydraulic radius, gradient and sinuosity. These methods will allow a user to describe the "off-channel" habitat under different flow conditions.	River Bathymetry Toolkit (RBT),
ST-Sim. State-and-Transition Simulation Models	SyncroSim is a generalized framework for running and managing scenario-based stochastic simulations over space and time. Different kinds of simulation models can "plug-in" to SyncroSim as modules and take advantage of general features common to many kinds of	http://www.apexrms.com/projects/stsm

Name	Abstract/Description	Link or citation
	simulation models, such as defining scenarios of model inputs, running Monte Carlo simulations, and viewing charts and maps of outputs.	
Water Erosion Prediction Project (FS WEPP)	The erosion rates and sediment delivery are predicted by the Water Erosion Prediction Project (WEPP) model, using input values for forest conditions developed by scientists at the Rocky Mountain Research Station.	http://www.fs.fed.us/rm/boise/AWAE/projects/water_erosion_prediction_project.shtml
Terrain Works (Net Map)	NetMap was created to provide off the shelf analysis capabilities in resource management, risk mitigation and conservation that are unavailable elsewhere. Our goal at TerrainWorks is to make user-friendly GIS watershed databases and tools readily available to agencies, NGOs, and private sector. NetMap also provides support in the form of online technical help, online mapping tools and a community based approach to tool development and dissemination. NetMap applications include fish habitat mapping, floodplain delineation, road analyses, slope stability, riparian management and wildfire.	http://www.terrainworks.com/
FarmAdap and StreamTemp	The climate adaptation includes working models (FarmAdap and StreamTemp) available for download from this webpage. The test-bed is comprised of a suite of decision models designed to simulate climate impacts in agriculture and infrastructure and allow testing of various responses using principles of decision analysis such as maximum expected utility, decision scaling and sensitivity analysis, game theory, and options analysis.	http://wwa.colorado.edu/resources/tools/decision_models/index.html

Name	Abstract/Description	Link or citation
U.S. Forest Service's Watershed Condition Framework	Provides a framework for treating whole watersheds with an integrated set of watershed-scale restoration treatments. This six-step process begins with a classification of watershed condition, and progresses through the steps of prioritizing watershed for restoration, developing watershed action plans, implementing integrated projects, tracking restoration accomplishments, and monitoring and verifying restoration outcomes.	http://www.fs.fed.us/publications/watershed/watershed_classification_guide.pdf
Decision Support Planning Methods (DSPMs)	Reviews Decision support planning methods. DSPMs include variety of methods for dealing with uncertainty as applied to utilities. Common examples include: 1. Classic decision analysis; 2. Traditional scenario planning; 3. Robust decision making; 4. Real options; and, 5. Portfolio planning. Each method presents unique systems for handling uncertainty. Classic decision analysis assigns probabilities to uncertainties, traditional scenario planning develops equally likely scenarios based on the uncertainties, and the others combine different variations of these two approaches.	http://www.wucaonline.org/assets/pdf/pubs_whitepaper_012110.pdf
The Mesohabitat Simulation Model (MesoHABSIM)	The Mesohabitat Simulation Model (MesoHABSIM) is an effective approach to modeling instream habitats at the river and site specific scale. It uses a computer model, Sim-Stream, that predicts the quantity of habitat for aquatic communities in rivers and streams for watershed management scenarios. It is used in water management for instream flow assessments as well as in river conservation and restoration planning.	http://www.mesohabsim.org/

Name	Abstract/Description	Link or citation
U.S. EPA. BASINS and WEPP Climate Assessment Tools (CAT)	There is growing concern about the potential effects of climate change on water resources. U.S. EPA and partners have developed two assessment tools, the BASINS and WEPPCAT climate assessment tools that facilitate application of existing simulation models for conducting scenario-based assessments of potential climate change effects on streamflow and water quality.	U.S. EPA. BASINS and WEPP Climate Assessment Tools (CAT): Case Study Guide to Potential Applications (Final Report). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-11/123F, 2012.
VisTrails	VisTrails is an open-source scientific workflow and provenance management system that provides support for simulations, data exploration and visualization. As an engineer or scientist generates and evaluates hypotheses about data under study, a series of different, albeit related, workflows are created while a workflow is adjusted in an interactive process. VisTrails was designed to manage rapidly-evolving workflows. A key distinguishing feature of VisTrails is a comprehensive provenance infrastructure that maintains detailed history information about the steps followed and data derived in the course of an exploratory task: VisTrails maintains provenance of data products, of the workflows that derive these products and their executions. It also enables a series operations and user interfaces that simplify workflow design and use, including the ability to create and refine workflows by analogy and to query workflows by example. VisTrails supports the creation and execution of workflows. It allows the combination of loosely-coupled resources, specialized libraries, grid and Web services.	Morisette, J.T., C.S. Jarnevich, T.R. Holcombe, C.B. Talbert, D. Ignizio, M.K. Talbert, C. Silva, D. Koop, A. Swanson, and N.E. Young. 2013. VisTrails SAHM: visualization and workflow management for species habitat modeling. Ecography 36: 129-135 (ver. 1.2.0). Available at https://my.usgs.gov/catalog/RAM/SAHM/

Name	Abstract/Description	Link or citation
SSN & STARS: Tools for Spatial Statistical Modeling on Stream Networks	The purpose of the Spatial Tools for the Analysis of River Systems (STARS) toolset is to generate and format the data needed to fit spatial statistical models in R software. The STARS toolset makes use of the Landscape Network, a data structure used to efficiently navigate throughout a stream network. The Spatial Stream Network (SSN) package was developed for R statistical software. Once the streams data have been properly formatted using the STARS toolset, the SSN package allows users to: 1) import and store their spatial data in R, 2) calculate pair-wise distances and spatial weights based on the network topology, 3) fit spatial statistical models to streams data where autocorrelation is based on three spatial relationships (Euclidean, flow-connected, and flow-unconnected), 4) estimate relationships between stream variables (spatial regression), 5) make predictions at unobserved locations (prediction sites), 6) export spatial data for use in other software programs, and 7) visualize the spatial data.	http://www.fs.fed.us/rm/boise/AWAE/projects/SpatialStreamNetworks.shtml
Information Sources and Databases		
The Database for Inventory, Monitoring and Assessment (DIMA)	The Database for Inventory, Monitoring and Assessment (DIMA) is a highly customizable software tool for data collection, management, and interpretation. DIMA is a free Microsoft Access database that can easily be used without extensive knowledge of Access. Data can be entered for common, nationally accepted vegetation and soil monitoring methods in either English or metric units.	http://jornada.nmsu.edu/monit-assess/dima

Name	Abstract/Description	Link or citation
National Riparian Vegetation Monitoring Technical Guide: Conterminous United States	The purpose of this document is to provide guidance on measuring riparian vegetation and channel characteristics along wadeable stream channels, floodplains, and valley bottoms. This protocol is designed to guide the user in gathering data to assess riparian plant species composition and channel conditions at the reach scale, to compare species composition and conditions to other reaches at a point in time or the same reach through time, and to provide a basic framework for riparian vegetation monitoring that can be built upon to address specific management objectives.	http://www.fs.fed.us/biology/watershed/riparian.html and other tools listed on http://pacinst.org/resources/tools-for-water-managers/
Stream Monitoring Network	Google Map tool that displays the locations of many of the existing 1,375 full year temperature monitoring sites. So far focused on NW U.S.	(http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temperature.shtml)
Native Communities and Climate Change	The Native Communities and Climate Change project seeks to provide resources for climate change adaptation and natural resource planning by American Indian tribes as well as to provide useful information to organizations and agencies working with Indian tribes on these issues.	http://www.tribesandclimatechange.org/
Stakeholder Identified Needs	Part of the Western Water Assessment, this links to a list of workshop and presentations that identify stakeholder driven meetings to identify needs for climate information and research.	http://wwa.colorado.edu/resources/adaptation/stakeholder_climate_needs_docs.html

Name	Abstract/Description	Link or citation
Water Data Exchange (WaDE)	The Western States Water Council (WSWC), in cooperation with the Western Governors' Association (WGA), the U.S. Department of Energy (DOE), the DOE National Labs (led by the Sandia National Lab), and the Western Federal Agency Support Team (WestFAST) are undertaking a data exchange project to provide better access to water allocation, supply, and demand data that are maintained by the states. Through collaboration with WestFAST, the WSWC will also work with the various Federal Agencies that comprise WestFAST to develop standard methods for accessing Federal data that support state-federal planning efforts and are important components to water supply estimates.	http://www.westernstateswater.org/wade/

ADAPTIVE MANAGEMENT OPTIONS FOR AQUATIC SYSTEMS: A REVIEW

Note: this document is meant to be a supplement to the document “Final Report: Synthesis of aquatic Climate Change Vulnerability Assessments for the Interior West” by Megan M. Friggens and Carly Woodlief

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INTRODUCTION

There is no one way to create an adaptation plan for climate change. As with vulnerability assessments, the planning process needs to reflect the scope and scale of the management need. The first step in developing an adaptive management plan is to identify the issue or conservation target. Next, the potential impacts of climate change needs to be assessed through vulnerability assessments and studies. Specific intervention points are identified through this process and then prioritized according to their capacity to reduce climate impacts, their cost effectiveness, and whether they achieve benefits under multiple futures (Snover et al., 2007). Uncertainties exist in projections of future climate, and in particular precipitation. Uncertainties also arise from the variations and biases in climate models, downscaling methods, hydrological processes and models, and a general lack of information about key processes. Still, information and methods are available to initiate planning processes as demonstrated by the array of management plans that have been developed with the primary objective to sustain aquatic ecosystems and species under climate change (Tables 1 and 2).

Here we review recent publications within the adaptation literature and summarize strategies and actions for managing aquatic systems under climate change. This review is framed according to the primary steps for developing adaptation plans: Assessment, Planning, Implementation and Monitoring and Adjustment (Feenstra et al., 1998). The actions listed here do not represent a prescription or recommendation. Adaptive management strategies can only be determined in context of the specific needs and goals of resource users and managers. Rather, we provide a comprehensive list of what others have done or suggested as a stepping point for developing personalized plans. Outside of the scope of this document are the planning and coordination activities necessary to link climate impact to effective action. For those who are interested, multiple frameworks (e.g. ACT) and decision support mechanisms (reviewed in Freas et al., 2008; Brekke et al., 2009) exist to guide the planning process and develop management actions. As an example, the Grantham et al., (2010) present a framework for streamflow management that considers the temporal and spatial dynamics of water supply and the needs of both human and natural systems. For a discussion of Decision Support Planning Methods (DSPMs) see http://pubs.usgs.gov/circ/1331/Circ1331.pdf

This review is meant to give the reader a perspective on the range of topics and actions discussed within the adaptation literature. We focus on reports, syntheses and literature regarding aquatic systems within the Interior Rockies. In addition, we reference documents from outside the geographic area where they provide new insight. The management strategies and actions listed within this document focus for the most part on ecological communities and systems. Many of the resources that discuss adaptation management planning contain generalized recommendations for the implementation of actions under climate change. We have not made a comprehensive list of these types of articles where they do not introduce new information. A few resources to note: Garfin et al. (2014) provides a recent and comprehensive synthesis and discussion of climate change impacts for aquatic systems in the U.S. For considerations of socioeconomic adaptation planning see the Western Water Assessment white paper series at: http://wwa.colorado.edu/projects/current/. For a synthesis on Tribal Needs see Rose et al., (2010).

Box 1. Proactive Versus Reactive Strategies

Adaptive management for climate change is often discussed in terms of proactive versus reactive actions. Proactive strategies are meant to reduce the overall impact to resources by improving resilience of key systems and preventing or reducing loss. Proactive actions are likely to have the greatest success where areas are expected to undergo less change (remain climatically suitable). Proactive actions can also increase resilience and slow rate of change in areas with more change.

Examples of suggested proactive management strategies include:

1. Replanting with species or ecotypes that are better suited for future climates.
2. Conserving populations with higher genetic diversity or more flexible behaviors or morphologies.
3. Managed relocation/ assisted migration.
4. Offsite conservation such as seed banking, biobanking, and captive breeding.
5. Intensive removal of invasive species.
6. Interventions including resistance breeding, novel pheromone applications, or herbicide treatments to prevent invasive spread.
7. Use horticultural techniques to propagate and establish native vegetation.

Compiled from Groffman et al., 2014; Agee and Skinner 2005, and Millar et al. 2007; Seavy et al 2009

ASSESSMENT

There is a consistent call within the adaptation management literature for better and more information regarding climate change impacts (Meyer et al., 1999; Capon et al., 2013). These calls range from suggestions for syntheses of existing literature (Rieman and Isaak, 2010), to climate change vulnerability assessments, to models that fill critical information gaps (Rieman and Isaak, 2010). Some of these are briefly reviewed below:

Durance and Ormerod (2009) cite a need for better datasets and models that link hydrologic regime, ecosystem processes (productivity, nutrient dynamics, food web interactions), interactions (predation, species invasions), and water quality. They have several specific suggestions including: maintaining and increasing existing stream gaging sites; adding ecological monitoring to established networks that already monitor physical and chemical properties of water bodies; increasing the sampling frequency of monitored sites to capture the short-term variations in flowing waters. They also recommend monitoring key sites and ecological populations that can serve as early warning systems for ecological change.

A number of reviews call for the use of risk and vulnerability assessments, syntheses and tools to identify vulnerabilities to expected climate impacts as well as current stressors (Millar et al., 2007; Rieman and Isaak 2010; Gitay et al., 2011; Garfin et al., 2014; Lukas and Gordon 2015). Such assessments provide information important to identify the current state of the ecosystem and help determine relative exposure and sensitivity of ecosystems to climate effects. From this information management teams can identify resilient refugia (Millar et al., 2007) or areas requiring immediate (proactive) management intervention (Nelson 2009). Assessments also help managers prioritize how, where and when to act. For instance, an assessment can be designed to identify trigger points that indicate a need for ratcheting up levels of intervention or beyond which current management strategies become futile (Palmer et al., 2009: Meyer et al., 1999; Capon et al., 2014).

In addition, vulnerability assessments should be comprehensive and include ecological, economic and social considerations. Brekke et al., (2014) suggest land use planning and zoning needs to be considered to account for the vulnerability of region to drought or flooding. Assessing risk of existing, long-lived infrastructure (dams, levees) to increased magnitude, duration and frequency of floods is also likely to be important for planning (Brekke et al., 2014). Davis

Box 2. How do you choose a strategy?

The answer depends upon the vulnerability of the system, which in turn is based in some part on its status or condition (Watson et al., 2013). High vulnerability can arise due to extreme levels of change or exposure, high sensitivity of resource of interest, or little coping ability. Innate characteristics of the system that indicate sensitivity often include initial conditions though this is not always the case.

Where high vulnerability is indicated through an expectation for unparalleled climate conditions and high sensitivity of resource to that change, intensive management activities are often required. In addition, realigning management objectives to future conditions might be necessary for sites that are significantly disturbed especially where restoration has been prescribed (Millar et al., 2007).

Where high vulnerability is due to high sensitivity under a range of lesser and more extreme conditions, management strategies need to incorporate options and flexibility. Resistance (mitigation) practices for short-term planning are often advised (Millar et al., 2007)

Where vulnerability is influenced more by the characteristics of the species or system (does not change much under changing conditions), efforts that mitigate current stressors are likely to be most useful.

(2007) calls for broad-scale assessments of water availability and to improve coordinated plans for monitoring, adaptation planning and implementation of management actions. Other suggestions include assessments of wetlands (Winter 2000), and assessments to determine changes in terrestrial-aquatic linkages as a result of climate change.

PLANNING

Management of water resources within the Western U.S. is complex because multiple competing interests must vie for a limited resource. We know that climate changes are likely to impact water availability through changes in precipitation, increased evaporation and greater human demand. However, uncertainties exist regarding hydrological, ecosystem and species' response to these changes. In this section, we outline strategies to guide adaptive management planning for climate change. These strategies lead to the development of management approaches that can improve the outcome of management actions even under the uncertainty of future conditions.

- A common theme within the adaptation literature is the call for improved coordination between public and private sectors and between scientists and managers during assessment and planning phases (Seavy et al., 2009; Reiman and Isaak 2010; Nelson et al., 201113; Capon et al., 2013; Georgakakos et al., 2014; Garfin et al., 2014; Lukas and Gordon 2015). A few specific examples:
  - Education and communication should be incorporated into all adaptation strategies (Capon et al., 2013);
  - Stakeholders, decision makers, scientists, and engineers should be involved early in the development and assessment of adaptation strategies and includes the costs, benefits, feasibility, and limits of a range of adaptation options (Garfin et al., 2014);

- Bring scientists and stakeholders together to identify projected changes in the climate and relevant consequences for particular regions or sectors considering existing or expected social, economic, and ecological vulnerabilities (Garfin et al., 2014);
- Bring resource managers, policymakers, and the public together to reassess the socioeconomic importance of urban streams and the adequacy of programs to protect them under future stress (Nelson et al., 2009).

- Recognized and incorporate climate change into ongoing project design (Nelson et al., 2009; Inkley 2004; Mitchell 2007; Mukheibir and Ziervogal 2006). For instance, consider drought in supply-demand analyses (Christensen and Lettenmaier 2007).
- Base planning on historic flow regimes and local hydrological templates (Meyer et al., 1999).
- Match action to the timeframe and need of resource.
    - Prepare to use immediate intervention (e.g. translocation) for high valued resources with high vulnerability (Capon et al., 2013).
    - Prepare to maintain status quo for a short time (Millar et al., 2007).
    - Favor actions that increase autonomous adaptation of natural and human systems over time (Capon et al., 2013).
    - Favor reversible planning actions that are easy to stop, remove or retrofit (Capon et al., 2013).
    - Cautiously plan for construction and intensive management actions that are difficult to reverse(Capon et al., 2013).
- Plan at the large scale.
    - Manage for the whole system rather than single species or assets (Groffman et al., 2014).
    - Emphasize ecological process, rather than structure and composition when making management decisions (Millar et al., 2007).
    - Plan within a landscape context considering catchment processes, relative vulnerability of riparian areas, and connectivity (Capon et al., 2013).
- Allow greater flexibility in management and institutional response (Millar et al., 2007; USGS 2007; Nelson et al., 2009; Garfin et al., 2014; Lukas and Gordon 2015). More flexible, risk-based, better-informed, and adaptive operating rules for reservoirs (Georgakakos et al., 2014). Other methods for increasing flexibility include:
    - Frequently reassess. Monitor and refine plan as needed.
    - Build in the capacity to change course as conditions change. For long-term strategies, plan incrementally to allow for course changes under new information.
    - Plan for new climates not stationary conditions.
    - Create a portfolio of management approaches. Design flexible strategies that include options that work under a range of possible conditions.
    - Allow risk-taking.
- Design reserves able to withstand shifts and disturbances (Fischlin et al., 2007; Inkley et al., 2004; Julius and West 2007; Palmer et al., 2009; The Heinz Center 2008; Mawdsley et al., 2009; The United Nations Environment Program). Specific consideration include:
  - Create refugia in areas not expected to experience drastic changes;
  - Protect multiple replicates of habitat, include representative habitat in refuges;
  - Manage for diverse conditions;
  - Include lands adjacent to rivers or headwaters;
  - Include representative species in refuges;
  - Maintain genetically diverse and connected communities.

- Mitigate increasing water demand by taking actions to improve flow management through management of water infrastructure, pricing policies, and demand-side management of supply (Frederick and Gleick, 1989; Meyer et al., 1999; Georgakakos et al., 2014). Specific approaches include:
    - Enhancing the capacity for market-based transfers of water among uses (Brekke et al., 2009);
    - Creating water banks, voluntary water leasing, or water markets (Frederick and Gleick 1989; Meyer et al., 1999);
    - Reducing water consumption through conservation and efficiency improvements such as individual metering, change crop selection/ irrigation methods, promoting household water saving (Brekke et al., 2009).
    - Designing policies and management systems that provide better signals to consumers regarding the cost and scarcity of resources (Nelson et al., 2009).

- Identify actions to enhance water supply through protection and conservation of ecological attributes. Examples include:
    - Protect watersheds (Garfin et al., 2014)
    - Improve storage and efficiency (Brekke et al., 2012)
    - Increase catchment storage capacity (Grantham et al., 2010)
    - Capture liquid water in the winter and store it through the summer (Ashfaq et al., 2013)
    - Protect riparian ecosystems by managing reservoir releases (Perry et al., 2012)

Box 3.No-Regret Actions

No-regret actions typically include some benefit under a range of conditions. Where they impact multiple entities they can also be cost effective. No-regret actions for climate change often focus on reducing current stressors or the restoration of critical habitats or elements within a riparian area (e.g. reintroducing beavers, establishing vegetation for bank stability, Rieman and Isaak 2010). One example of a no-regret strategy is to restore or preserve vegetated stream buffers, which provide thermal refugia and habitat for aquatic animals, improve bank stability, diversifies terrestrial habitat and encourages biodiversity. These actions improve habitat quality and the resilience of the riparian system to many disturbances including those relating to climate impacts.

IMPLEMENTATION: SPECIES

In this section, we list the major strategies identified for aquatic species management under climate change. Strategies are categorized by themes corresponding to information gaps, planning, habitat manipulations and management of populations. Some actions may relate to more than one theme and are listed more than once. This list contains actions mentioned in discussions of adaptation planning for wildlife species. Many of the strategies presented within the next section (Ecosystems) also have direct benefits for species.

Table 2. Adaptive Management Strategies for Species.

To Address Information Gaps
Sources: Bernardo and Spotila 2006; Brekke et al., 2009; Inkley et al., 2004; Mukheibir and Ziervogel 2006; Rieman and Isaak 2010; Seavy et al., 2009

- Clarify goals and values.
- Synthesize existing information to understand changes or trends in habitats or populations that have already occurred in local or nearby representative systems.
- Determine responsive actions based vulnerability.
- Model to fill gaps. Specific examples:
  - Study methods to improve recruitment of wildlife populations into restored areas;
  - Surveys species differences in the magnitude of metabolic stress;
  - Trend analysis.
- Monitor strategically to improve understanding of future impacts. Specific targets:
  - Indicator species;
  - Native species;
- Implement long-term monitoring programs.

To Develop Adaptive Management Strategies
Sources: Chu et al., 2005; Intersectretarial commission on Climate Change 2007; Mitchell et al., 2007; Mukheibir and Ziervogal 2006; Palmer et al., 2009; Rieman and Isaak 2010.

- Focus on populations as units of conservation.
- Focus on landscape-level management plans. Specific examples:
  - Incorporate medium and long-range planning;
  - Coordinate species migration management over broad regions;
  - Establish and review biological corridors to ensure the adaptive capacity of ecosystems and species ;
  - Promote species dispersal.
- Alter management given projected changes in distributions. Specific examples:
  - For species with projected distributional decreases, list on COSEWIC to trigger conservation and recovery efforts (e.g. arctic char);
  - For species with projected increases, focus management on economically important species, control or prevent invasive species, or delist of species currently listed by

Table 2. Adaptive Management Strategies for Species.

COSEWIC

- Consider relative values and balance resilience, representation and redundancy.
- Consider taking no action to conserve resources.

To Reduce Non-climate Stressors

Sources: Chessman 2013; Grantham et al., 2012; Quiñones and Moyle 2014; Millar et al., 2007; Rieman and Isaak 2010

- Reduce pollutants, especially from agriculture and urban runoff.
- Re-operate dams, reduce water diversion, and otherwise protect environmental flows to favor native species.
- Alleviate threats to vulnerable species during non-drought periods.

Habitat Manipulation: Restoration

Sources: Quiñones and Moyle 2014; Groffman et al., 2014; Rahel et al., 2008; Rieman and Isaak 2010

- Maintain or restore riparian, floodplain, and wetland conditions and connections with stream.
- Replant with species or ecotypes that are better suited for future climates.
- Maximize stream shading, bank stability, terrestrial food inputs, and recruitment of woody debris that helps form diverse habitat. Specific actions:
    - Reintroduce beaver;
    - Planting riparian vegetation.
- Increase rate of restoration.

Habitat Manipulation: Habitat Targets

Sources: Johnson et al., 2005; Quiñones and Moyle 2014; Groffman et al., 2014; Rieman and Isaak 2010; Rahel et al., 2008

- Identify and protect features that are important for biodiversity and are less likely to be altered by climate change.
- Ensure connecting seasonal or complimentary habitats or refugia do not become bottlenecks to production.
- Protect and restore off-channel habitats, spring brooks, and seeps important as early rearing environments.
- Protect and restore flood or thermal refugia and stream segments important as connections.
- Protect and restore critical or unique habitats that buffer survival during vulnerable periods seasonal or in the life history.
- Maintain water levels in amphibian breeding ponds.
- Protect spawning grounds.
- Restore wetlands along wetter fringes of current range to ameliorate potential impacts of climate change (for waterfowl populations).

Habitat manipulation: Reserve Design

Chessman 2013; Fischlin et al., 2007; Inkley et al., 2004; Intersecretarial commission on Climate Change 2007; Hansen et al., 2003; Julius and West 2007; Millar et al., 2007; Mitchell 2007; Palmer et al., 2009;

Table 2. Adaptive Management Strategies for Species.

Rahel et al., 2008; Rahel and Olden 2008; Rieman and Isaak 2010; The Heinz Center 2008;Seavy et al., 2009; The United Nations Environment Program

- Increase redundancy and buffers. Use redundancy and create diversity through practices that spread risks rather than concentrate them.
- Acquire upstream property.
- Create dynamic reserves with fluid boundaries and varying levels of management intensity.
- Design reserves able to withstand shifts and disturbances. Specific examples:
    - Include representative species in refuges;
    - Maintain genetically diverse and connected communities;
- Avoid reservoirs to reduce risk of whirling disease (*M. cerebralis*) and to reduce non-native predators' expansion.
- Increase habitat connectivity. Specific examples:
    - Conserve and expand the size of habitat and migratory connections networks- remove or modify barriers to fish movements;
    - Create corridors or stepping stones;
    - Restore riparian habitats and hydrological function to recreate or increases connectivity;
    - Identify critical drought refuges and advance planning to ensure that extent, quality and connectivity are sustained;
    - Prioritize connectivity in reserve design;
    - Aim to reduce fragmentation;
    - Plan at large landscape scales.
- Protect key ecosystem features (corridors, keystone species, etc.); promote conditions for ecosystem function. Specific examples:
    - Ensure ecosystem processes;
    - Preserve and strengthen natural buffering functions within watersheds;
    - Establish refuge areas where native fish need boost.

Habitat manipulations: Flow management

Sources: Chessman 2013; Grantham et al., 2012; Rieman and Isaak 2012

- Improve summer flow conditions by better storage practices.
- Enhance water storage for delayed summer discharge during warm, low flow period.

Population Management: Native species

Sources: Chu et al., 2005; Chessman 2013; Fischlin et al., 2007; Groffman et al., 2014; Inkley et al., 2004; Intersecretarial commission on Climate Change 2007; Hansen et al., 2003; Palmer et al., 2009; Julius and West 2007; Millar et al., 2007; Mitchell 2007; Rahel et al., 2008; Rieman and Isaak 2010; Seavy et al., 2009; The Heinz Center 2008

- Assist or promote natural adaptation or transitions to new states. Specific examples:
    - Increase species range, assist or promote transitions/range shifts;
    - Assist or promote population adjustments, supplement small populations, establish new populations;
    - Facilitate transition to new states- introduce new species;

Table 2. Adaptive Management Strategies for Species.

- Increase capacity to make timely response by include provisions for temporary removal or translocation of threatened species;
- Engage in offsite conservation such as seed banking, biobanking, and captive breeding.

- Manage for genetic diversity. Specific examples:
  - Conserve populations with higher genetic diversity or more flexible behaviors or morphologies;
  - Conserve genotypic/phenotypic diversity by conserving or restoring large networks;
  - Maintain large population sizes to minimize loss of genetic variability and adaptive potential;
  - Facilitate transition to new states by removing barriers to invasion.
- Protect keystone species through captive breeding and relocation.
- Accommodate change rather than resist it to facilitate gradual rather than rapid or catastrophic conversion.
- Use conservation hatcheries to increase abundance.
- Give conservation priority to coldwater populations in deep, dimictic lakes
- Conserve species through regulations. Specific examples:
  - Implement fisheries regulations that lower the allowable catch or harvest, enforce catch and release practices or impose size limits on catch.
  - Restrict human use in sensitive water bodies to allow systems to restore and rebuild their buffering capacity to withstand climate change.

Population management: Nonnative species

Sources: Chu et al., 2005; Quiñones and Moyle 2014; Millar et al., 2007; Rahel and Olden, 2008; Rahel et al., 2008; Seavy et al., 2009

- Suppress and eliminate nonnative species.
- Limit impacts of invading predators through regulation. Specific examples:
  - Increase the fishing effort placed on a newly established predator population
  - Live well inspections of boats and increased public awareness of the impact of species introductions
- Manage for salinity, which favors *Tamarisk* spp and some nonnative fish.
- Restore natural flow regimes to favor native species.
- Taking early defensive actions at key migration points to remove and block invasion.
- Create migration barriers (e.g. water fall, low-head dams, electric barriers) for nonnative fish.
- Anticipate surprises and threshold effects.
- Restore vegetation to enhance thermal refugia for native fish.

Box 4. Strategies for restoration actions under climate change.

Restore to improve resilience

- Restore for a natural range of variability (Grantham et al., 2010
- Restore entire watersheds, not just streams (Fischlin et al., 2007; McNeely and Schutyser 2003 (increase protected habitat); Mitchell et al., 2007; Palmer et al., 2009; The Heinz Center 2008).
- Maintain or restore riparian, floodplain, and wetland conditions and connections with stream (Seavy et al., 2009; Rieman and Isaak 2010).
- Reduce the impacts of extreme flood events by restoring wetlands, creating artificial wetlands (increase level of dykes), and enhancing water storage to delay summer discharge (Seavy et al., 2009; Rieman and Isaak 2010; Fischlin et al., 2007; McNeely and Schutyser 2003; Mitchell et al., 2007; Palmer et al., 2009; The Heinz Center 2008).
- Restore natural vegetation to maximize stream shading, bank stability, terrestrial food inputs, and to diversify habitat (Rieman and Isaak 2010)
- Maximize recruitment of woody debris to help form diverse habitat (Rieman and Isaak 2010).
- Enhance or replace lost ecosystem services (pollination and seed dispersal) (Fischlin et al., 2007; McNeely and Schutyser 2003; Mitchell et al., 2007; Palmer et al., 2009; The Heinz Center 2008).
- Replant with species or ecotypes that are better suited for future climates (Groffman et al., 2014).
- Conserve or restore a diverse representation of habitats across river basins (Rieman and Isaak 2010).
- Reintroduce beaver (Rieman and Isaak 2010).
- Realign management objectives to expected conditions where sites are significantly disturbed (Millar et al., 2007).
- Create incentive programs for funding, technical assistance, and infrastructure to help private landowners to modify land-use practices and restore native vegetation for conservation (Seavy et al., 2009)

Species level considerations

- Protect and restore critical or unique habitats that buffer survival during vulnerable periods seasonal or in the life history
- Ensure that nodes connecting seasonal or complimentary habitats or refugia do not become bottlenecks to production (Rieman and Isaak 2010)
- Restore and maintain off-channel habitats, spring brooks, and seeps important as early rearing environments (Rieman and Isaak 2010)
- Restore and maintain flood or thermal refugia and stream segments important as connections (Rieman and Isaak 2010)

IMPLEMENTATION: ECOSYSTEMS

In this section, we list the major strategies identified for aquatic ecosystem management under climate change. Strategies are categorized by themes corresponding to resilience and mitigation strategies, preservation strategies, strategies for reducing non-climate stressors, and strategies for preparing for fire in riparian systems. Some actions may relate to more than one theme and are listed more than once.

Table 3. Adaptive Management Strategies for Ecosystems.

Management Strategies to Increase Resilience
Compiled from the following sources: Brekke et al., 2009; Nelson et al., 2009; Seavy et al., 2009; Rieman and Isaak 2010; Millar et al., 2007; USGS 2007; Pettit and Naiman 2007; Meyer et al., 1999

- Restoration (see Box 4). Specific strategies:
    - Restore wetlands to reduce impact of flood events;
    - Intensive removal of invasive species;
    - Maintain or restore riparian, floodplain, and wetland conditions and connections with stream;
    - Restore to maximize stream shading;
    - Restore to maximize terrestrial food inputs;
    - Restore to maximize bank stability;
    - Restore to maximize recruitment of woody debris;
    - Restore to enhance water storage for delayed summer discharge during warm, low flow periods;
    - Conserve or restore a diverse representation of habitats across river basins.
- Interventions including resistance breeding, novel pheromone applications, or herbicide treatments.
- Seek resistance practices to improve forest defenses against direct and indirect effects of rapid environmental changes.
- Reduce undesirable or extreme effects of fires, insects, and diseases (see section on reducing non-climate stressors).
- Improve flow management. Specific suggestions:
    - Reestablish appropriate hydrological processes;
    - Maintain or restore instream flows and natural hydrologic regimes;
    - Reduce hydrological variability.
- Protect and restore critical or unique habitats that buffer survival during vulnerable periods seasonal or in the life history. Specific examples:
    - Look for and prevent bottlenecks in nodes connecting seasonal or complimentary habitats or refugia;
    - Include off-channel habitats, spring brooks, and seeps that are important early rearing environments.
- Reintroduce beaver.
- Prioritize no or low regret options (See Box 2). Specific examples:
    - Manage existing stressors;
    - Restoration;

Table 3. Adaptive Management Strategies for Ecosystems.

  - Retro-fit engineered structures to improve efficiency.
- Employ resistance practices for short-term planning and for habitats of high value and/or low sensitivity to climate (for forests).
- Realign management objectives to expected conditions where sites are significantly disturbed.

Mitigation strategies

- Sequester carbon in forest management. Specific examples:
  - Avoid deforestation, promote afforestation and reforestation;
  - Manipulate vegetation to favor rapid growth and long-term site retention;
  - Sequester carbon after harvest in wood products.
- Minimize return of Carbon to atmosphere. Specific examples:
  - Store carbon in wood products;
  - Use biomass to fuel electricity production to replace fossil fuels.
- Sequester carbon through fire management. Specific examples:
  - Increase forest resistance to fire, drought, and disease, usually by reducing the density of small trees by mechanical thinning, prescribed fires, or both;
  - In remote or rugged terrain, wildland fire use or appropriate management response suppression fire may be the only reasonable option (Collins et al., 2007).

Preservation Strategies

Sources: Nelson et al., 2009; Groffman et al., 2014; Rieman and Isaak 2010

- Preserve underdeveloped lands. Specific examples:
  - Protect headwater streams
  - Acquire lands near streams to free floodplains of infrastructure
- Maintain forest and vegetative cover to reduce rain on snow flooding.
- Conserve forest, wetland, and riparian areas that tend to store water for later summer base flows.
- Preserve areas important for biodiversity that are less likely to be altered by climate change.
- Conserve or restore a diverse representation of habitats across river basins.

Reduce non-Climate Stressors

Sources: Fischlin et al., 2007; Inkley et al., 2004; Intersecretarial Commission on Climate Change 2007; Hansen et al., 2003; Julius and West 2007; Mitchell et al., 2007; Mukheibir and Ziervogal 2006; Nelson et al., 2009; The Heinz Center 2008; The Wildlife Management Institute, 2008; Rieman and Isaak 2010; Hibbard et al., 2014; Millar et al., 2007; Seavy et al., 2009

- Improve forest defenses against direct and indirect effects of rapid environmental changes. Specific examples:
  - Reduce undesirable or extreme effects of fires, insects, and diseases;
  - Intensive removal of invasive species including interventions such as resistance breeding, novel pheromone applications, or herbicide treatments;
  - Buffer the effects of peak flow events.
- Reduce anthropogenic stresses. Specific examples:
  - Disconnect roads from the drainage network;
  - Remove roads and dikes that constrain or disconnect channels and flood plains;

Table 3. Adaptive Management Strategies for Ecosystems.

  - Reduce excess nitrogen and phosphorus from agricultural and industrial activities;
  - Avoid habitat fragmentation/conversion;
  - Increase agricultural productivity to reduce pressure on natural resources;
  - Implement seasonal bans, protected areas, and payments for environmental services.
- Reduce potential competitors, predators, diseases, and hybridization that may constrain habitat capacity, individual growth rates, and survival.
- Limit or stop introduction and expansion of nonnative species.
- Anticipate negative impacts from disease, insects, fire, and species loss. Specific examples:
  - Plan for higher-elevation insect and disease outbreaks;
  - Anticipate forest mortality events and altered fire regimes;
  - Accommodate loss of species' populations on warm range margins.
- Estimate rate at which ecological systems recover from disturbance.
- Increase stormwater management to reduce peak flows and temperature stress in developed basins.

Adaptive management approach to fire management
(summarized from the review by Pettit and Naiman 2007)

- Establish policy for managing fire in riparian zones.
- Base management decisions on a thorough understanding of ecological processes.
  - Assess role of fire in local riparian ecosystem processes.
  - Understand differences in the ecological effects of riparian fire for different stream orders and elevation, under multiple climatic regimes.
  - Consider long-term fire regimes with a focus on variability within and between habitats, and on resultant habitat quality and diversity.
  - Acknowledge elements and processes important for ecosystem resilience.
- Consider habitat quality and diversity at landscape scale.
- Maintain broadly defined ecosystem processes that include natural disturbance processes.
- Develop treatments to improve resilience
  - Simulate natural disturbance patterns
  - Maintain structures in aquatic ecosystems
  - Replicate natural fire regimes
  - Produce a mosaic of fire patches to create and maintain biodiversity and, thereby, ecosystem resilience.
- Continuously refine management prescriptions through feedback from monitoring.
- Carefully plan activities such as logging, construction of fire access routes along rivers and road construction along riparian corridors to prevent fires of greater frequency and severity in riparian areas

MONITORING AND REASSESSMENT

Monitoring trends and responses and adjusting plans as new information becomes available is central to the adaptive management paradigm. The articles summarized in this review noted the importance of establishing and maintaining strong monitoring programs. Established monitoring programs not only allow us to determine the ability of a management activity to achieve a desired outcome but also allow us to determine when conditions are no longer suitable for current conservation strategies. Through strategic monitoring, managers can assess when actions are no longer feasible and/or facilitate transition to new habitats types. Managers can establish monitoring programs based on sites, ecological populations, or processes and use these as early warning systems for ecological change. Monitoring also provides the only method for detecting climate related changes in pests and pathogens, invasive species, and fire regimes. Given the complex nature of water management, monitoring program that simultaneously evaluate impacts of climate change on related sectors (e.g. development and land use) are important for informing management actions. The success of future planning efforts and our capacity to research climate impacts depends upon the establishment of good monitoring protocols.

CONCLUSION

Climate change presents a new challenge for water resource managers. Climate projections and related modeling work provide information on potential futures but contain inherent biases and uncertainties that challenge management planning. As a result, the management plans that are most likely to succeed under climate change will be those that engage all stakeholders in assessment and planning phases, use assessments and monitoring to identify management objectives, and incorporate mechanisms that allow flexibility at both institutional and management levels not only for on the ground management actions but for the objectives themselves.

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