Adaptive Management and Climate Change Adaptation: Two Mutually Beneficial Areas of Practice

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Research Impact Statement: Adaptive Management (a rigorous approach to learning while doing) and Climate Change Adaptation (a way to reduce risks from climate change) are mutually beneficial and supportive fields of practice.

Abstract: Adaptive management (AM) is a rigorous approach to implementing, monitoring and evaluating actions, so as to learn and adjust those actions. Existing AM projects are at risk from climate change, and current AM guidance does not provide adequate methods to deal with this risk. Climate change adaptation (CCA) is an approach to plan and implement actions to reduce risks from climate variability and climate change, and to exploit beneficial opportunities. AM projects could be made more resilient to extreme climate events by applying the principles and procedures of CCA. To test this idea, we analyze the effects of extreme climatic events on five existing AM projects focused on ecosystem restoration and species recovery, in the Russian, Trinity, Okanagan, Platte and Missouri river basins. We examine these five case studies together to generate insights on how integrating CCA principles and practices into their design and implementation could improve their sustainability, despite significant technical and institutional challenges, particularly at larger scales. Though climate change brings substantial risks to AM projects, it may also provide opportunities, including creating new habitats, increasing the ability to quickly test flow-habitat hypotheses, stimulating improvements in watershed management and water conservation, expanding the use of real-time tools for flow management, and catalyzing creative application of CCA principles and procedures.

Key Terms: adaptive management, climate change adaptation, climate variability/change, watershed management, aquatic ecology, fish, flooding

INTRODUCTION

Adaptive Management (AM) is the guiding strategy for many projects and programs seeking to restore ecosystems and recover species at risk while dealing with uncertainty (Williams *et al.,* 2009; Williams and Brown, 2012). Bernardt *et al.*, (2005) estimated that at least $14 to $15 billion was spent on restoration of streams and rivers within the continental United States between1990 and 2003, an average of more than $1 billion a year. It's essential to ensure the sustainability and resiliency of such investments under present and future variation in climate. Over the last decade, it has become clear that the uncertainties created *by landscape and continent-scale* changes in climate can potentially have equal or greater effects on ecosystems and species than other uncertainties traditionally considered in AM projects (e.g., *local* factors that limit species' distributions, reproduction, growth and survival). Therefore, we argue that AM practitioners need to apply the methods of Climate Change Adaptation (CCA) in their projects, and expand the scale at which they define the problem they're trying to solve. If they don't, their projects are much more likely to fail or not be sustainable, risking large investments in ecosystem restoration and species recovery. To substantiate our argument, we first provide an overview of the best current practices of AM and CCA, highlight gaps in the current guidance for both practices, identify common features, describe how the tools and mind sets of CCA can improve the design and implementation of AM projects, and outline how the rigor of AM can assist practitioners of CCA. We then examine five case studies from our recent project experience to justify our proposed changes in practice, describing the effects of extreme climatic events, and decadal-scale changes in climate. In the Discussion we compare these five AM projects, describing common challenges brought by climate change, potential CCA strategies which have been or could be implemented to deal with these challenges, and the basin attributes which either enable or inhibit implementation of such strategies. We conclude with recommendations to practitioners of both AM and CCA.

AM is already difficult, and climate change makes it harder. AM is a rigorous approach to environmental management designed to reduce uncertainty regarding the most effective on-the-ground actions for achieving management objectives. While there are many definitions of AM (see Holling, 1978; Stankey *et al.*, 2005; Williams *et al.*, 2009; Williams and Brown, 2012), we define AM as "a rigorous approach for designing and implementing management actions to maximize learning about critical uncertainties that affect decisions, while simultaneously striving to meet multiple management objectives" [Murray *et al.,* 2011, pg. vi]. The "rigorous approach" of AM includes careful experimental design to test hypotheses related to critical uncertainties, the selection of appropriate monitoring protocols, and thorough data analyses to generate defensible evaluations of outcomes and applied hypotheses as input to management decisions. Collaborative AM can help to build trust among interested parties with differing views of what management approaches can best meet agreed-upon objectives; disagreements over objectives require other methods such as conflict resolution (Lee, 1991; Scarlett, 2013). There are multiple technical and institutional challenges to effective AM (Walters, 1997; Greig *et al.*, 2013; Scarlett, 2013; Murray *et al.*, 2015). As elaborated in Murray *et al.*, 2015, AM becomes increasingly challenging at larger scales, for both technical reasons (e.g., more difficult to create treatment contrasts and replicates, more confounding factors), and institutional reasons (e.g., large numbers of stakeholders and competing objectives impedes collaboration). Climate change adds other challenges to AM, including uncharted territory of hydrological variation beyond the design parameters of the project (i.e., non-stationarity, Milly *et al.*, 2008), climate-driven limitations on the range of feasible management actions, extreme climate events that can swamp the signal of AM experiments or undermine strategies for recovering species, and large social and economic impacts that can outweigh ecological considerations.

In the early 2000s, AM guidance documents did not refer to the need for a consideration of climate change (NRC, 2004; Stankey *et al.*, 2005). However, guidance manuals on AM are now beginning to recognize the importance of climate change, though neither these manuals nor other guidance have advocated our perspective – using CCA principles and procedures to rethink and improve the *design and implementation* of AM projects. Currently, the most commonly cited guidance to AM is the 74-page Technical Guide to AM developed by the U.S. Department of Interior (DOI), published in 2009 (Williams *et al.,* 2009). This document mentions the word "climate" once, in the context of largely uncontrollable and random environmental variation, and does not mention CCA. A subsequent 'Applications Guide to AM', published just three years later by DOI (Williams and Brown, 2012), mentions "climate" 102 times, and discusses applying AM principles and procedures to projects involving either climate change mitigation or adaptation. With respect to other types of AM projects, the 2012 DOI Applications Guide recommends considering climate change when setting objectives, developing models, designing monitoring, and performing assessments, noting the challenges of non-stationarity in climate-dependent functional relationships (elaborated further in Williams and Brown, 2016). However, the 2012 Applications Guide does not discuss incorporating CCA principles and practices into the *design and implementation* of AM projects. In their concluding chapter on Future Directions, Williams and Brown (2012) note that the *technical* and *collaborative* areas of AM practice have historically been operating more or less in parallel but separately, and they hope that their guide will integrate these two areas together. We believe that the same is true for AM and CCA practice areas, and we have a similar objective for this paper.

Despite the climate-sensitivity of AM projects, AM practitioners have historically tended to largely ignore climate change in the design of efforts to restore ecosystems and recover species. For example, historical plans for ecosystem restoration and species recovery generally use past data (e.g., on flows, precipitation, temperatures, salmon returns) to assess the likely range of system variability rather than fully exploring the impacts of past *and future* variability in climate (see reviews by Roni *et al.*, 2002, Marmorek *et al.*, 2004; Wiens *et al.,* 2017, NRC 2009; Fluixá-Sanmartín *et al.,* 2018). The future, under climate change, may display considerable shifts in the form and magnitude of system variability (Beechie *et al.,* 2008, Bisson *et al.,* 2009).

Climate Change Adaptation (CCA) has a variety of strategies and tools to help human communities and ecosystems achieve greater resilience to the shocks and surprises brought by climate change (WRI, 2011; Furniss *et al.*, 2013; Nelitz *et al.,* 2013; Brown *et al.*, 2012). The Intergovernmental Panel on Climate Change (IPCC, 2014) defines CCA as follows: "The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects". Implementation of specific "on the ground" measures to reduce harm or exploit benefits from climate change is a newly emerging practice (Eyzaguirre and Warren, 2014; Mimura *et al.*, 2014) and there is not yet sufficient evidence regarding the effectiveness of CCA polices and measures (Klostermann *et al.*, 2018). Embedding CCA approaches within rigorously-designed

AM projects can improve the evidentiary foundation for assessing the effectiveness of actions to restore ecosystems, recovery species *and* adapt to climate change.

Scientists applying the principles of CCA to studies of watersheds, forest ecosystems and human communities recommend an adaptive approach or formal AM (Pahl-Wostl, 2007; Carter *et al.*, 2007; Glick *et al.*, 2011; Nichols *et al.*, 2011; Furniss *et al.*, 2013; Lawrence *et al.*, 2013; Stein *et al.*, 2014; Seidl *et al.*, 2016; Addington *et al.*, 2018). Therefore, the opportunity exists for CCA practitioners to benefit from the rigor embodied in AM in the design, implementation, monitoring, and evaluation of CCA plans, as discussed by Williams and Brown (2012). Although our primary focus in this paper is on the benefits of CCA for the design and implementation of AM projects, we briefly touch on the reverse: how CCA studies could benefit from the rigor in AM. We recognize that climate change brings many types of uncertainties outside of management control (discussed by Williams, 2011, and Rist *et al.*, 2013). We suggest, however, that CCA actions are amenable to the principles of applied experimental design and AM; examples are provided in Williams and Brown (2012); Conroy *et al.* (2011); McDonald-Madden *et al.* (2011).

BEST PRACTICES OF AM AND CCA

To operationalize the above-described definitions of AM and CCA, and clarify their similarities and differences, we now describe the principles (Table 1) and procedures (Table 2) of each practice area, citing key references in the table captions. AM is more strongly rooted in systems analysis and the scientific method (Holling, 1978), focusing on the critical uncertainties that affect how to best achieve management objectives, and the rigorous design of management interventions that reduce these uncertainties (Murray *et al.,* 2015). AM emphasizes hypothesis testing, experimental design, and explicit learning (i.e., closing the loop to periodically adjust management decisions; Sit and Taylor, 1998), more so than the practice of CCA currently does (e.g., the IPCC AR5 reference for the chapter on Adaptation Planning and Implementation (Mimura *et al.,* 2014) has no mention of the words 'hypothesis' or 'experiment').

CCA is more strongly rooted in participatory processes that involve populations facing climate risk, and using information on the root causes of vulnerability to inform policy formulation and decision making (Fűssel and Klein, 2006). In the planning stage, CCA emphasizes analyses of historic vulnerability and anticipation of future impacts (Stein *et al.,* 2014; CCME, 2015) more so than AM does (Williams *et al.,* 2009, Williams and Brown, 2012). The selection of adaptation interventions relies on a range of context-specific criteria but an overarching goal is to address known vulnerabilities and mitigate against uncertain future impacts/risks (Stein *et al.*, 2014; CCME, 2015). Implementation of CCA actions is followed by monitoring and review (Stein *et al.,* 2014; CCME, 2015; Mimura *et al.*, 2014), though as mentioned above there has not been much time to evaluate the effectiveness of CCA actions, and existing CCA guidance (e.g., Mimura *et al.,* 2014) does not emphasize the need for rigorous experimental designs to test the effectiveness of implemented CCA actions. At this time, there is no standard guidebook for CCA principles and practices. The International Organization for Standardization is currently working on two guidance documents for CCA, to be released in 2019 (Principles, requirements and guidelines - https://www.iso.org/standard/68507.html; Vulnerability, impacts and risk assessment - https://www.iso.org/standard/68508.html).

Table 1. A comparison of the principles of AM and CCA. Sources for Principles of AM: Holling, 1978; Walters and Holling, 1990; Taylor et al., 1997; MacDonald et al., 1997; Marmorek et al., 2006; Williams et al., 2009; Scarlett, 2013; Murray et al., 2015. Sources for Principles of CCA: Eriksen et al., 2011; NCCARF, 2011; Interagency Climate Change Adaptation Task Force, no date; Craig, 2010; Prutsch et al., 2010.

Principles of Adaptive Management	Principles of Climate Change Adaptation
Be clear about objectives and desired outcomes.	Clarify the context for climate change vulnerability, including multiple stressors.
Isolate complex issues and use 'systems thinking' to analyze them.	Recognize that different values and interests shape adaptation choices and outcomes.
Focus on uncertainties that have the most influence on decisions.	Work with uncertainties, including adopting risk management practices.
Use collaborative processes for building consensus on critical uncertainties, and rigorous ways of reducing them.	Build strong partnerships to set values-based priorities and coordinate implementation.
Commit to rigorous monitoring, evaluation, and adjustment of management actions – backed by an organizational culture that's focused on learning by doing.	Plan for the long term but promote flexibility and adaptiveness.
Implement contrasting interventions to test hypotheses and hasten learning.	Adopt integrated approaches by modifying existing policies, structures and processes.
Take advantage of unexpected events that provide an opportunity to test hypotheses.	Consider potential feedbacks across scales, avoiding maladaptation.
	Monitor and evaluate climate change impacts and adaptation performance systematically.

Table 2. A comparison of the steps used in AM and CCA. Sources for steps in AM: Taylor et al., 1997; Nyberg, 1998; Murray and Marmorek, 2003; Marmorek et al., 2006; Williams et al., 2009; Williams and Brown, 2012; Noble, 2015; Murray et al., 2015 . Sources for steps in CCA: CCME, 2015

Steps in Developing AM Plans	Steps in Developing Plans for CCA
Assess and define the problem. Work with stakeholders, managers and scientists to collaboratively define management goals and objectives, critical uncertainties, conceptual models, testable hypotheses, alternative management actions (experimental ‘treatments’), measurable indicators, spatial and temporal bounds, key assumptions, and anticipated learning.	**Initiate adaptation process**. Work with the lead organization developing an adaptation plan to examine and set the context for the plan, build awareness around climate impacts, identify a champion of the exercise, define and build teams to complete and implement the process, engage experts, stakeholders, other partners, and document the planning process.
	Increase knowledge and collect data. Invest in additional efforts to increase climate change knowledge by gathering historical baseline data, future climate projections, and evidence around climate change impacts.
	Assess current vulnerability and future risks. Once some baseline information has been compiled, it is important to assess the sensitivity of, exposure to, and adaptive capacity of the system to respond to climate impact. This information is used to assess overall vulnerability of the current situation and to assess future risks due to climate change.
Design the management experiment. Based on input from statisticians, stakeholders and analyses of existing data, develop an experimental design to address critical uncertainties (ideally with contrasts, replications, and controls), describing expected outcomes and next steps under each outcome. Develop a data management plan, a monitoring plan, and a formal AM plan for all of the remaining steps. Peer-review the design and plans.	**Generate adaptation solutions**. Adaptation solutions are identified that can address the vulnerabilities and risks identified in the assessment stages with the ultimate intent of reducing climate risks.
Implement the management experiment, as designed, using contrasting treatments, monitoring the implementation and documenting unavoidable changes.	**Implement adaptation solutions**. An implementation plan is prepared and adaptation solutions are implemented as designed.
Monitor. Implement the monitoring plan, including baseline monitoring, effectiveness monitoring and validation monitoring.	**Monitor and review.** This step involves developing a monitoring and evaluation plan to determine the effectiveness of adaptation solutions. Insights should be communicated and fed back into the adaptation plan at regular intervals.
Evaluate results, promptly comparing monitoring results against objectives, assumptions, critical uncertainties, hypotheses, and model predictions, with input from statisticians and peer reviewers. Boil down bottom lines for decision makers.	
Adjust hypotheses, conceptual models, & management, documenting what learning occurred and communicating this to decision makers, scientists and stakeholders.	

The similarities in how AM and CCA are done exceed the number of differences, and this parallelism makes these two practice areas well suited to be mutually supportive. Both approaches emphasize collaboration, planning, doing and learning (Williams *et al.***,** 2009, Stein *et al.*, 2014; CCME, 2015; Mimura *et al*. 2014).

However, there are important differences between AM and CCA. AM is generally applied to problems of managing ecosystems and species, in situations where management uncertainties can be reduced by deliberately creating contrasting actions over space and time, while accounting for other forms of uncertainty (e.g., natural environmental variation, uncertainty about the structure of the system, implementation uncertainty or partial controllability, observation error or partial observability; Williams *et al.***,** 2009, Williams and Brown, 2012). CCA develops proactive responses to threats and opportunities from climate change, in its effects on both people and the ecosystems on which they depend (Mimura *et al.*, 2014). In both AM and CCA, the driving uncertainties in climate are not manageable (except over the long term through reductions of greenhouse gas emissions), but it may be possible in both areas of practice to reduce uncertainties regarding what types of actions are most effective in achieving intended objectives (e.g., alternative patterns of flow release from a dam (Alexander *et al.*, 2006, Hyatt *et al.*, 2015); designing infrastructure projects to withstand rising global sea levels under climate change (USACE, 2014)). Some practitioners of CCA have argued that it's better to "tame uncertainty" with risk-based approaches than to confront it with formal AM experiments exploring alternative policies (e.g., Kuklicke and Demiritt, 2016) in their assessment of flood risks in England). While this might be true for situations where project designs can fully accommodate the potential range of future climate uncertainty; AM is not required in situations with low uncertainty (Murray *et al.*, 2015). However, we believe that such situations are relatively rare, and concur with other authors who have advocated for applying AM approaches to CCA (Glick *et al.*, 2011; Stein *et al.*, 2014).

As noted in the Introduction, existing guidance on AM (e.g., Williams *et al.*, 2009, Williams and Brown, 2012) does not emphasize the need to apply CCA principles and procedures to the *design* and *implementation* steps of AM projects, so as to increase their resilience to extreme climatic events. Table 3 lists some of the challenges for AM projects due to climate change, and opportunities for using CCA approaches to improve the outcomes of AM projects. These challenges are elaborated in the case studies that we present in the following section. Table 4 lists some of the challenges and needs in CCA that could benefit from the principles and approaches of AM, drawn from our experience with CCA over the last decade, and our much longer experience with AM projects.

Table 3. Challenges of climate change for AM projects, and opportunities for using the principles of CCA to improve AM projects.

Challenges of climate change for AM projects	Opportunities for using CCA in AM projects
Flows of very high magnitude or duration can destroy property and habitat restoration sites, launching court cases and decreasing support for AM projects.	Floods can create new habitats, and offer opportunities to test flow-habitat hypotheses. Floods *may* lead to long overdue improvements in collaborative floodplain management and planning.
Long, severe droughts limit the range of feasible management actions in AM projects to recover species and restore ecosystems.	Droughts force long overdue efforts at water conservation and management, which over the long term may increase available water for ecosystems.
It is difficult to know what flows to use when designing AM projects to restore habitats: the historical flow record is likely inapplicable to the future; and Global Circulation Models (GCMs) have too coarse a spatial and temporal resolution.	During the Assess and Design step of an AM project, combine bottom-up and top-down approaches to climate risk assessment (Brown *et al.,* 2012) to develop more robust and resilient AM Plans, which capitalize on some of the benefits of climate variability while adapting to its detrimental effects.
Stochastic events can suddenly turn normal years into extreme years, with adverse consequences for ecosystems and people.	Use real-time tools for flow management to mitigate risks and impacts, and protect habitats, species and property.
Long term climate change and unexpected extreme events make already difficult problems even harder.	During the Assess step of an AM project, explore a wide range of climate scenarios across long planning horizons, leading to the design of more resilient adaptive management plans, and ecosystem restoration strategies.

Table 4. Challenges in CCA projects, and opportunities for improving integration of CCA with AM.

Challenges in CCA projects	Opportunities for using AM in CCA projects
The discipline and state of practice of CCA is relatively nascent; recent work emphasizes assessing vulnerability, identifying adaptation measures, and implementing no regrets adaptation measures (Tamburello *et al.*, 2017). Monitoring and evaluation are used to track implementation, but rarely integrated into the planning stage (Christiansen *et al.*, 2018, Leiter and Pringle, 2018)	AM is a relatively mature discipline having been applied over the last 40 years. Monitoring and evaluation of management actions or decisions is encouraged in the early stages of planning and linked to hypothesis testing and evaluation of alternative actions / decisions (i.e., assess and design steps).
Concepts of resilience and vulnerability reduction are often cited as broad goals underlying CCA; general metrics to evaluate the effectiveness of adaptation across different contexts remain elusive which contributes to a lack of understanding about whether actions are working (Stadelmann *et al.*, 2015).	AM encourages a clear line of sight between measurable management goals or objectives, management uncertainties, and the ability of management actions or decisions to influence those goals. Goals are made measurable through objective hierarchies and uncertainties are prioritized based on those that have the most influence on a decision maker's ability to achieve their objectives.
Mismatches in the scale of the climate change problems and scale of adaptation solutions create challenges in identifying and implementing appropriate and effective adaptation measures (Wilbanks and Kates, 1999, Cash *et al.*, 2006, Tamburello *et al.*, 2017).	Systems analysis of coupled social-ecological systems and explicit hypothesis testing in AM encourage alignment between the scale of the problems that need to be addressed and the scale of the management actions or decisions that are needed to address the problems.
CCA focuses on implementation of adaptation measures as pilot projects to build capacity, test and learn about whether actions are working as intended and designed (Gogoi *et al.*, 2014; Webber, 2015).	Principles of experimental design during the implementation of adaptation measures and effectiveness monitoring can hasten learning about and testing the effectiveness of alternative adaptation actions (Sit and Taylor, 1998).
CCA requires strong and effective governance arrangements to support decision making. Improvements in governance imply integration of adaptation thinking into existing processes and structures (mainstreaming) (Mimura *et al.*, 2014). It's difficult to reshape governance to tackle a wide range of CCA issues, over long time scales, involving a wider range of stakeholders (Cooley and Gleick, 2011).	AM requires strong and effective governance arrangements to support decision making. Adaptive governance in AM can provide insights about how to develop structures that can effectively execute decisions and efficiently learn as new information and knowledge emerge about the effectiveness of actions or decisions over time (Gunderson and Light, 2006, Duit and Galaz, 2008).

CASE STUDIES

All five case studies involve habitat restoration and other actions to recover fish or wildlife species at risk, using AM as a guiding strategy (Table 5). The authors have worked in each of these five river basins as experts in adaptive management, and observed how recent extreme climatic events present both challenges and opportunities for successfully implementing adaptive management, restoring ecosystems, recovering species at risk, and meeting human needs. For each case study we provide an overview of the project, and the impacts of recent climatic events. Our purpose is to focus on the particular attributes of each project that highlight the intersection of AM, extreme climate events, and CCA; the cited references provide much more detail on each project for interested readers. Table 5 summarizes the attributes of the five case studies. In the Discussion, we draw insights on the common climate challenges affecting these five AM projects, and the degree to which various CCA strategies could potentially help to address these challenges, noting among-basin differences in the technical and institutional feasibility of implementing each strategy.

As noted in the Introduction, scale is a key variable affecting the technical and institutional feasibility of AM. The six basin areas (Table 5) span 3.4 orders of magnitude. Scale issues can also affect CCA plans. The spatial and temporal scale of the adaptation interventions to reduce climate change impacts need to match the spatial / temporal scale of the problem. Problems arise when these spatial / temporal scales don't match (e.g., small scale actions and policies don't significantly reduce large scale problems).

Table 5. Attributes of the river basins described in the case studies. Maps of each river basin follow below. Abbreviations: BC=British Columbia; CA=California; CO=Colorado; IO=Iowa; KA=Kansas; MT=Montana; MO=Missouri; ND=North Dakota; NE=Nebraska; WA=Washington; WY=Wyoming.

River	Basin Area (km^2)	States / Provinces in River Basin	Focus of AM Projects
Dry Creek	565	CA	Habitat enhancement in Dry Creek (Russian River basin) to improve juvenile survival of endangered coho salmon and threatened steelhead.
Trinity	7,500	CA	Restore habitat forming processes through flow management, fine and coarse sediment management, and channel rehabilitation, to recover anadromous fish populations.
Okanagan	21,000	BC, WA	Habitat restoration, flow management, and range expansion to recover sockeye salmon
Platte	220,000	CO, WY, NE	Increase nesting and roosting habitats, add water and sand to recover piping plovers, least terns and whooping cranes.
Missouri	1,370,000	MT, WY, CO, ND, SD, NE, KA, MO, IO	Build habitat and *possibly* change flows to recover piping plovers, least terns and pallid sturgeon.

Dry Creek, CA

Overview. This project involves the creation of side channels, alcoves and other habitat features over 6 miles of Dry Creek, a 14-mile tributary of the Russian River, just north of Santa Rosa CA (Figure 1). These features provide spawning and rearing habitats for coho salmon and steelhead, as well as refugia from winter storms. The project is implemented by the Sonoma County Water Agency (SCWA) within a rigorous AM framework (for full AM Plan, see Porter *et al.*, 2014). Enhanced habitats are carved out of remnant channels and, in some cases, land adjacent to Dry Creek (mostly vineyards), in collaboration with adjacent landowners. The Warm Springs Dam and Lake Sonoma reservoir at the upper end of Dry Creek (Figure 1) blocks fish access to the upper watershed. Lake Somoma has a surface area of 11 km^2 and can store 0.47Gm^3 of water. The reservoir is managed to generally keep flows below 120 cfs (3.4 m^3/s), supplying water to communities in Sonoma and north Marin counties, and maintaining a steady supply of cold, high quality water for rearing juvenile salmonids. Much higher flows occurred prior to the completion of Warm Springs Dam in 1983, and the post-dam stabilization of flows has drastically changed the morphology of the channel (NMFS 2008, pp. 122-124). The habitat enhancement sites closer to Warm Springs Dam are fixed in place, whereas those further downstream were designed to evolve with the range flows observed in the historical record. Critical management uncertainties include the suitability and sustainability of constructed habitats, the extent to which salmonids will use these habitats, the level of juvenile salmon production, and salmonid survival rates in both freshwater and marine environments. Adjustments to project designs may be required based on the outcome of monitoring and evaluation studies (Porter *et al.*, 2014).

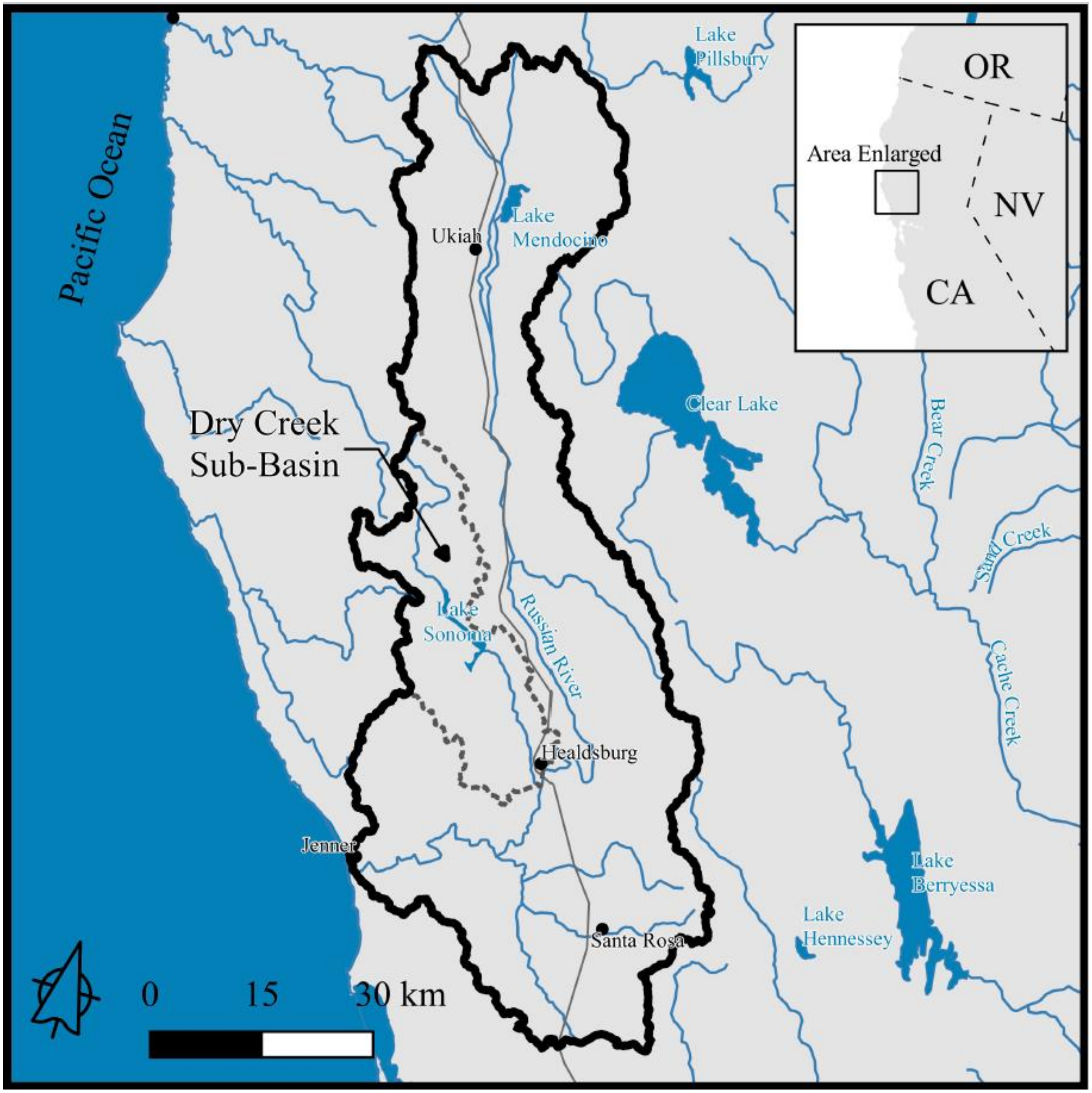

Figure 1. Map of the Russian River watershed (solid line), and the Dry Creek sub-basin (dashed line).

Effects of Recent Climate Events. Up until the fall of 2016, the constructed habitats were being well utilized by both juvenile and adult salmon, as well as steelhead. However, the winter flows in December 2016 were about 40-50 times higher than normal (Figure 2), flooding the creek, constructed habitats, adjacent vineyards and infrastructure along the banks of the creek (Figure 3).

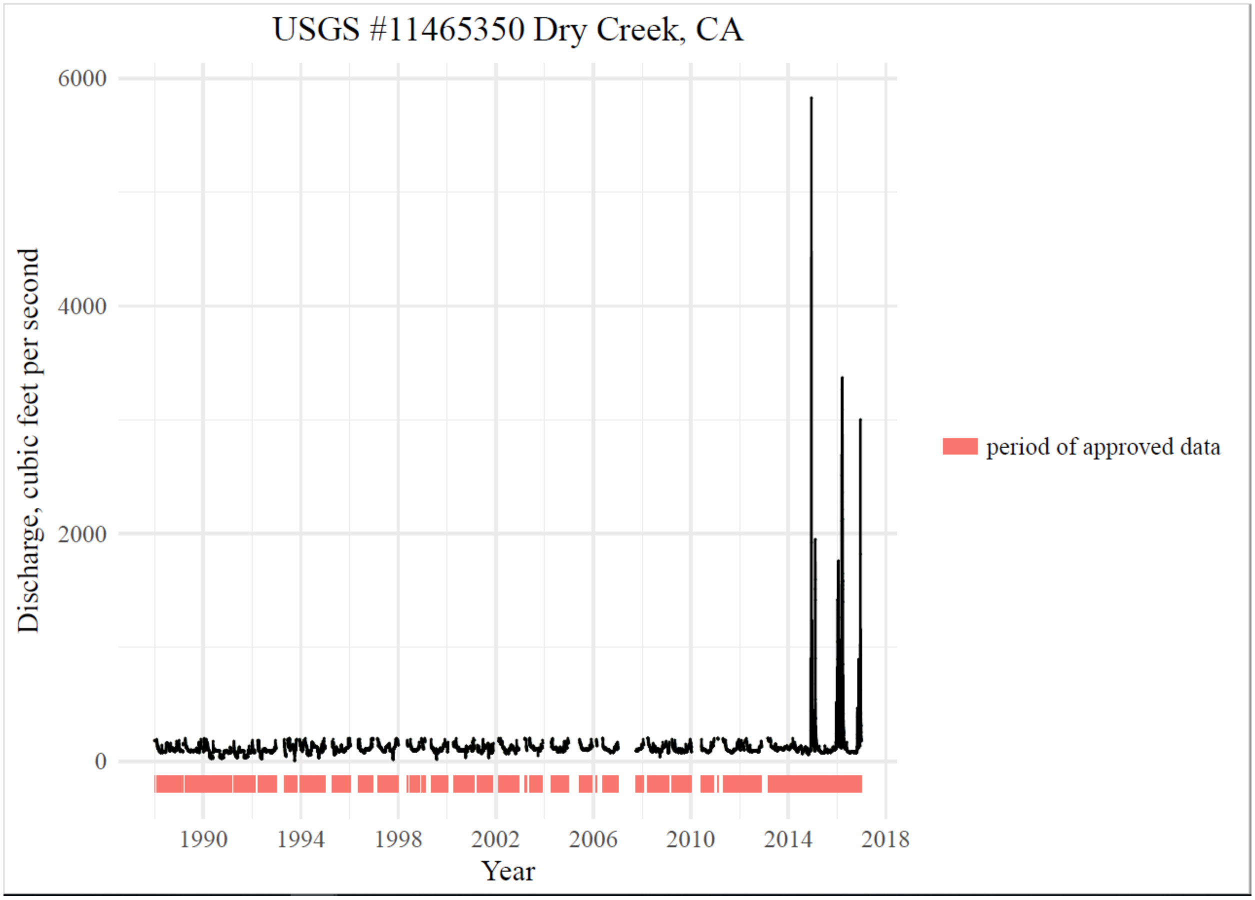

Figure 2. Discharge in Dry Creek CA from 1988 to 2016 at Healdsburg CA. Source: USGS https://waterdata.usgs.gov/nwis/dvstat/?referred_module=sw

Figure 3. Pictures of a path for pedestrians and cyclists along Dry Creek during normal conditions (left) and during the December 2016 flood (right).

Alcoves and backwater ponds, which are only connected to Dry Creek at their downstream end, generally withstood the December 2016 high flows (Gregg Horton, SCWA, pers. comm. 2017; see pictures of restoration sites under flood and typical flows in Manning, D. 2017. Dry Creek

Habitat Enhancement Project Update. http://www.scwa.ca.gov/files/images/projects/dry-creek/Dry%20Creek%20Community%20Meeting%202017_2.15.17%20for%20Web.pdf). However, some side channels connected to Dry Creek at both their upstream and downstream ends, received over a meter of sediment as the storm eroded banks and moved material downstream, completely filling and blocking the side channels at their upper end (Gregg Horton, SCWA, pers. comm., 2017).

Trinity River, CA

Overview. Dams on the Trinity River (Figure 4) were completed in 1964, diverting up to 90% of its flow into the Sacramento River Basin for power generation and irrigation of agricultural land in the Central Valley of California. This led to an 80% decline in Chinook salmon abundance, and similar declines in other species (USFWS and HVT, 1999). After 20 years of research and 11 lawsuits, a Record of Decision (ROD) was signed in 2000 to restore the Trinity River, increasing instream releases from as low as 10% of the original inflows during 1964 to 2000, to approximately 50% of the original inflows (USDI, 2000). The five pillars of the Trinity River Restoration Program (TRRP; USFWS and HVT, 1999, TRRP and ESSA, 2009) are channel rehabilitation, flow manipulation, coarse sediment management, watershed rehabilitation to reduce fine sediment inputs, and AEAM (Adaptive Environmental Assessment and Management, the form of AM first described by Holling, 1978). The channel, flow and coarse sediment actions are intended to restore the fluvial geomorphic processes that create and maintain fish habitats, but on a smaller scale than what existed prior to the construction of upstream dams and reservoirs.

Trinity Lake is a large reservoir, about 1800 km^2 in surface area, and able to store up to 2.45 million acre-feet of water ($3.02 Gm^3$). In the 2000 ROD, each of five different types of water years (critically dry, dry, average, wet, extremely wet) was allocated a different volume of water, a pre-specified peak release, and a distinct flow schedule to meet varying objectives (see Table 6). The ROD flow releases are intended to recreate a natural spring snowmelt, while relying on lower elevation, rainfall dominated tributaries downstream of Lewiston Dam to provide winter flow variability. Although the ROD did not discuss climate change, it did consider year to year variability in water years and flows, and built flexibility into the TRRP on how to use water within each water year type for various objectives (Table 6). Analyses completed for the ROD (USFWS and HVT, 1999) concluded that Trinity Lake would provide sufficient volumes of water to maintain salmon and their habitats in the Trinity River, given the historical record of water years.

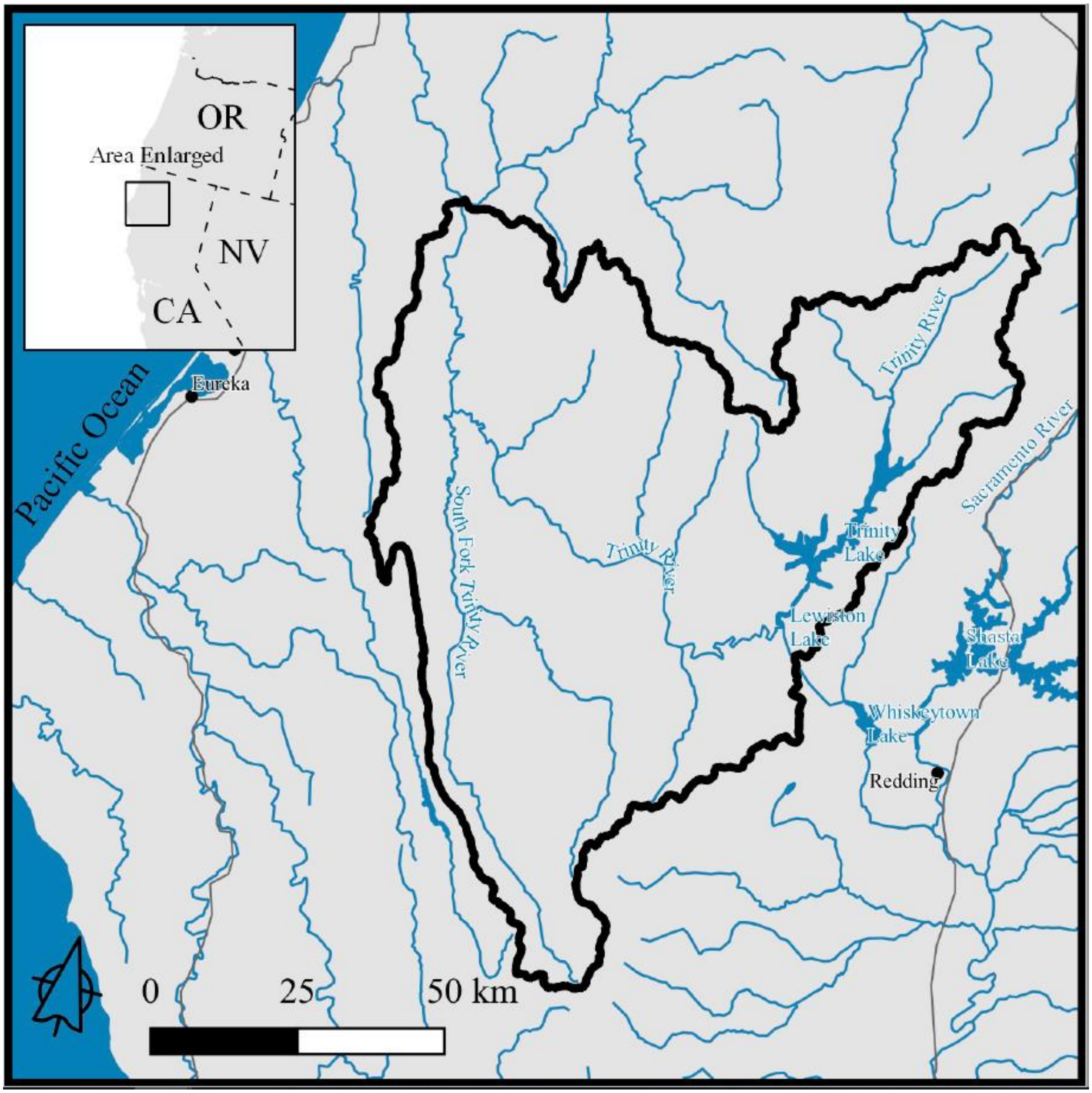

Figure 4. Map of the Trinity River watershed. Water is diverted southwest from Lewiston Lake through a tunnel under the easternmost boundary of the Trinity watershed to Whiskeytown Lake, just to the northwest of Redding CA, and from there proceeds through two paths to the Sacramento River.

Table 6. Volumes of water, peak flows and primary objectives for each type of water year within the ROD for the Trinity River (USDI 2000). Frequencies of occurrence of water years were based on analyses of flow data for 1912 to 1995 (USFWS and HVT, 1999). Abbreviations for Objectives: MT=Marginal Temperatures for fish; OT = Optimal Temperatures for fish; SR = Spawning and Rearing habitats; RS = Riparian scour along the low flow channel; R=Riparian recruitment on upper bars and floodplains; FG=Fluvial Geomorphic Processes. For elaboration on objectives within each water year, see Chapter 8 in USFWS and HVT (1999).

Water year type	Frequency of occurrence	Volume (AF; Gm^3)	Peak Release (cfs; m^3/s)	Primary Objectives
Critically dry	(12%)	369,000; 0.45	1,500; 42	MT, SR
Dry	(28%)	453,000; 0.56	4,500; 127	MT, SR
Normal	(20%)	647,000; 0.80	6,000; 170	OT, SR, RS, R, FG
Wet	(28%)	701,000; 0.86	8,500; 241	OT, SR, RS, R, FG
Extremely wet	(12%)	815,000; 1.01	11,000; 311	OT, SR, RS, R, FG

Effects of Recent Climate Events. It takes many years of observations to statistically demonstrate a change in the variability of flows. Over the last 16 years (a short time series), there appear to be fewer normal water years, more dry years, and more wet years (relative to the long-term historical record). The sequence of water years is important for maintaining temperatures below critical thresholds for fish survival in the Trinity River. Droughts during 2006-2009 and 2013-2015, while not unprecedented, drained Trinity Lake down to its lowest level since 1977 (Figure 5). Salmon would likely have been exposed to potentially lethal water temperatures if 2016 had also been a dry year, as it would no longer have been possible to maintain a cold-water pool in Trinity Lake and release cold water for salmon (John Bair, McBain Associates, pers. comm., 2017). Fortunately, 2016 was a wet year, and the storage in Trinity Lake was replenished.

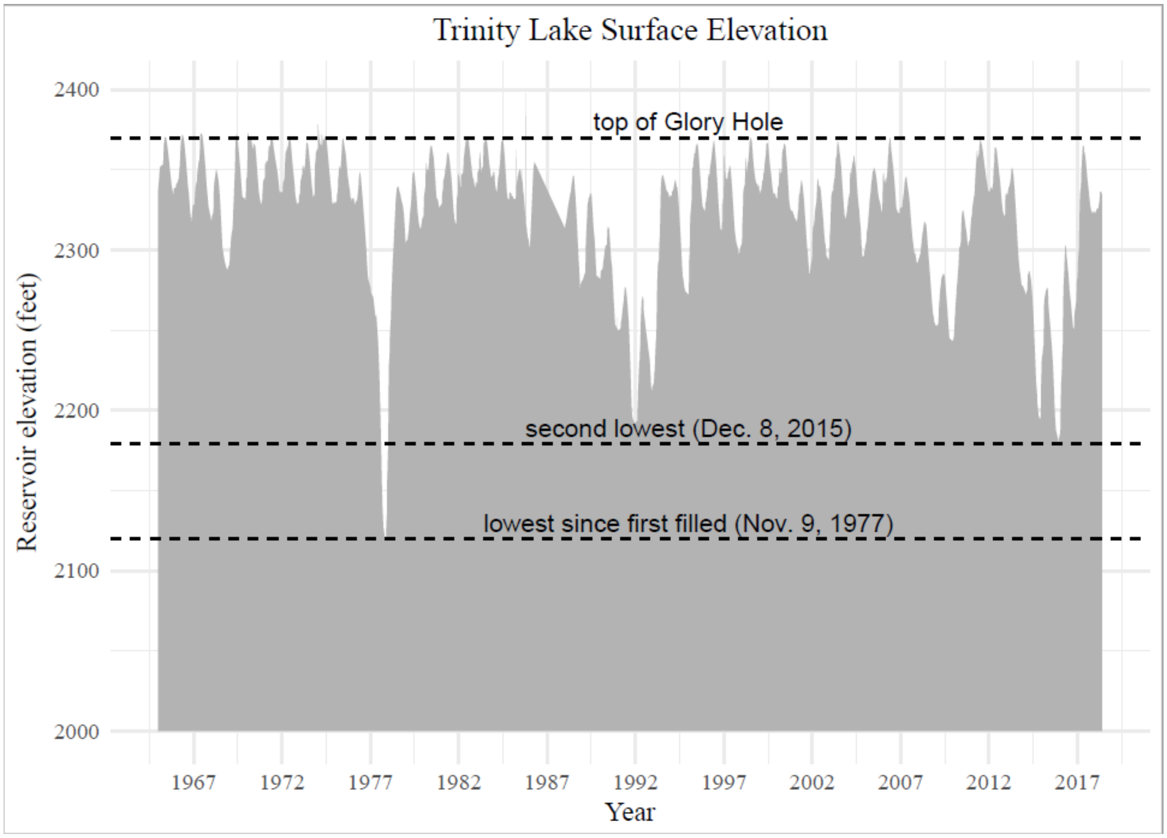

Figure 5. Elevation of the Trinity Reservoir (in feet) during the period from 1965 to 2017. The reservoir elevation on Dec. 8, 2015 was the lowest since Nov. 9, 1977. Source: http://www.trrp.net/restoration/flows/lake-conditions/

Okanagan River, BC

Overview. The Okanagan River flows south from Okanagan Lake in south-central British Columbia, across into Washington State, where it joins the Columbia River (Figure 6). Most of the storage for the Okanagan River is provided by the 120km long Okanagan Lake, with an area of 342 km^2, a total volume of 24.6Gm^3, and an effective storage volume of about 0.62 Gm^3 (allowing for about 2m of fluctuation in lake surface elevation, Figure 7; see https://www.obwb.ca/wsd/about/project-reports). Minor additional storage exists in tributary headwater reservoirs and in smaller downstream lakes. About 30 km downstream from Okanagan Lake is the terminal spawning area for Okanagan River sockeye salmon, which then rear in Osoyoos Lake, before migrating about 1000 km through the Columbia River and 9 major hydroelectric projects to the Pacific Ocean. This population is one of only two remaining naturally reproducing sockeye stocks on the Columbia River, the other being in Lake Wenatchee (WA); Quinn *et al.*, 1997.

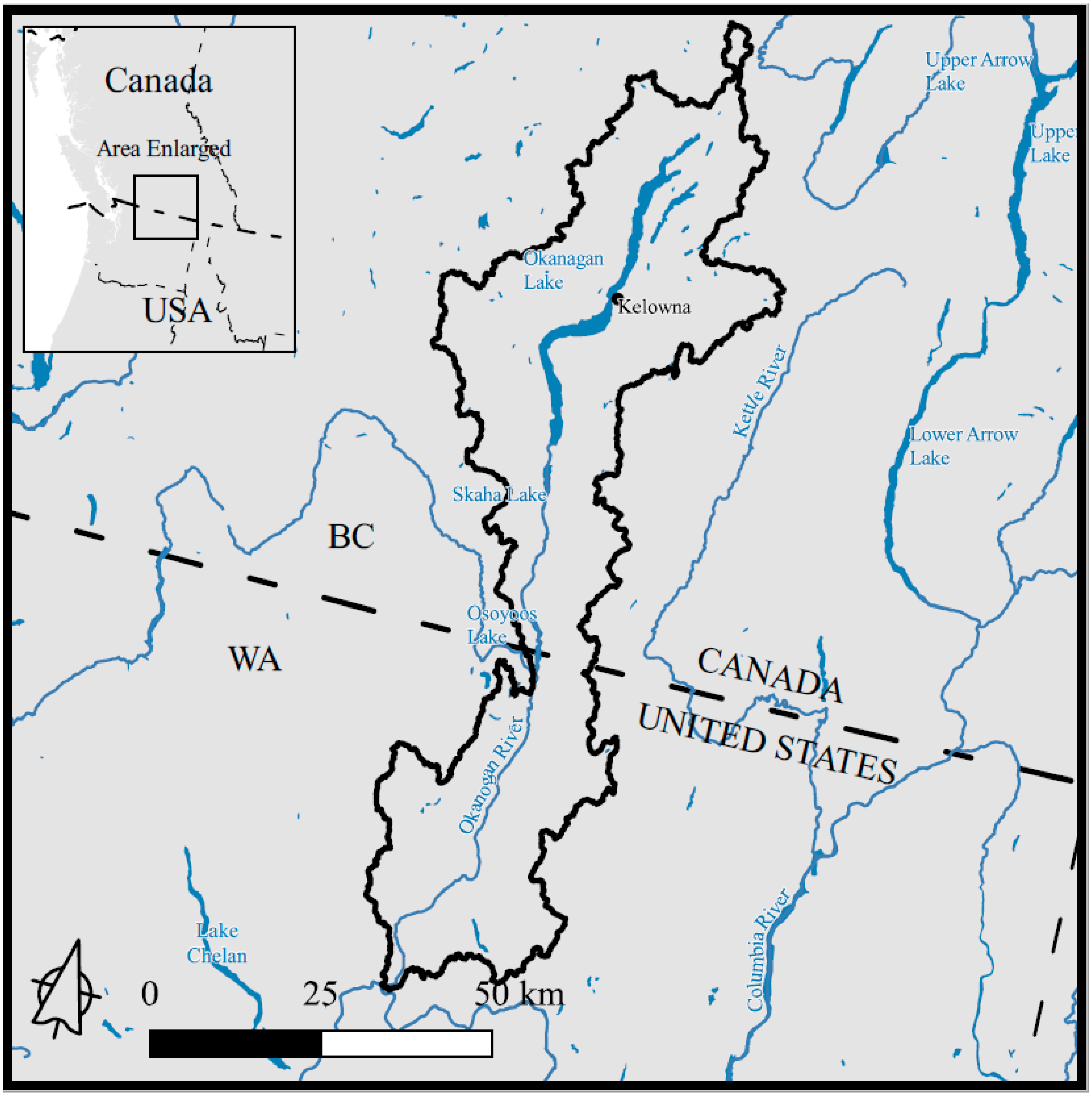

Figure 6. Map of the Okanagan River watershed.

Starting in 2002, a collaborative working group developed a real-time decision tool for managing water flows out of Okanagan Lake, called the Fish Water Management Tool or FWMT (Hyatt *et al.*, 2015). FWMT uses real-time, web-accessible information on snowpack, lake levels, stream temperatures and stream flows to help managers make the best possible decisions on how much water to release each week from Okanagan Lake. Water web services have been in place in British Columbia since 2001, with new sensors and enabling technologies added regularly, consistent with the principles and trends described by Bales (2016) for the Open Water Data Initiative, created in 2014. By allowing multiple users to test a variety of alternative water release strategies within a 'no regrets' modeling environment, the tool helps managers to find flow releases which best meet multiple objectives: sockeye, flood control, water supply, navigation, irrigation and kokanee fish in Okanagan Lake. Also in 2002 (unrelated to FWMT), the Okanagan Nation Alliance began an effort to re-establish sockeye in Skaha Lake, capturing eggs from returning spawners, raising them in a hatchery, and stocking them into Skaha Lake. Like some of the other intelligent water systems summarized by Bales (2016), FWMT began long before the creation of the Open Water Data Initiative in 2014; FWMT has been used since 2002.

We performed blind retrospective modeling with FWMT, providing users with the same information that water managers see each week, based on historical data but with the year changed to a pretend year in the future (e.g., 1991 became 2034). These modeling exercises predicted an average 55% increase in sockeye smolt production as a result of operating Okanagan Lake using the forecasting routines and multi-objective rule-sets in FWMT with historical hydrology (Hyatt and Alexander, 2005). To our surprise, these predictions have been greatly exceeded: there has been a 600% increase in the abundance of Okanagan sockeye (measured as spawners) over the last 15 years (Kim Hyatt, Fisheries and Oceans Canada, pers. comm., 2018), reflecting multiple causes (higher ocean survival, improved freshwater habitat, improved freshwater survival through the use of FWMT, range expansion).
However, when we used downscaled projections of climate conditions in 2050 (based on Merritt *et al.*, 2006), we found that chronically shorter and accelerated freshet periods and drier conditions led to a 44% decrease in smolt production (Clint Alexander, unpublished, Effects of climate change on production of Okanagan sockeye). Based on this work we expect that over the next few decades drier water years will become more and more common and additional water management strategies to promote access to cold water refugia ever more essential. In addition to our work showing the threat to Okanagan sockeye from climate change, many other studies have highlighted threats to water supply for human uses in the Okanagan Basin (e.g., Cohen *et al.*, 2006; Brandes and Kriwoken, 2006; Shepherd *et al.,* 2006; Harma *et al.,* 2012).

Effects of Recent Climate Events. The 2017 water year contradicted our expectations of drier conditions. What appeared to be an average snowpack in the Okanagan Basin on March 1st (86% of normal) reached 147% of normal by May 1st. The first six days of May brought a “Pineapple Express” storm from the Hawaii area of the mid-Pacific, dropping 40 mm of rain and melting much of the surrounding snowpack. Then in late May temperatures reached unseasonably warm levels (20-23°C), which caused further rapid snowmelt. By June 3rd, the elevation of Okanagan Lake was at its highest level in 200 years, causing severe flooding (Figure 7).

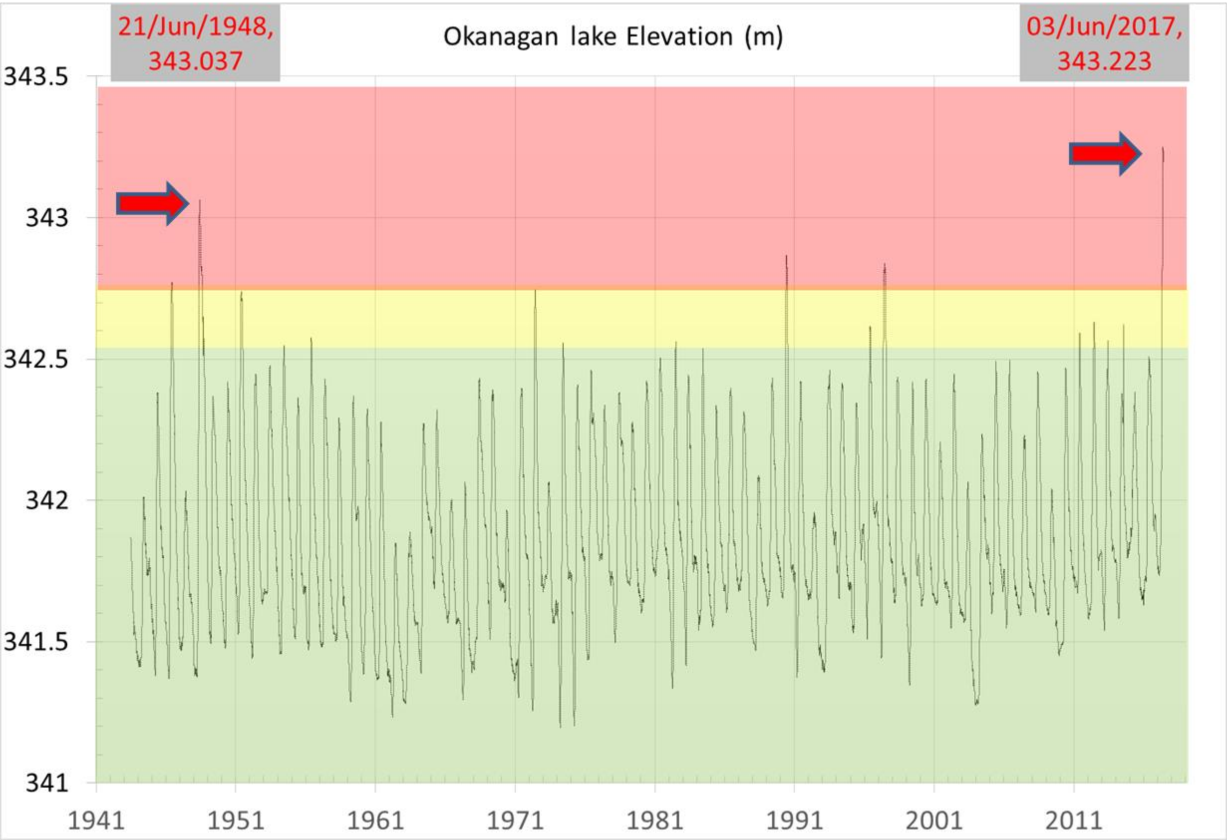

Figure 7. Elevations in Okanagan Lake, southeastern British Columbia, from 1941 to 2017. Colors represent various levels of estimated damage from flooding associated with lake elevations: green (<$1.5M CAN), yellow ($1.5M to $17M), red (> $17M).

Platte River (NE, WY, CO)

Background. The Platte River begins in Colorado as the North and South Platte Rivers, 1500 km from its terminus at the confluence with the Missouri River (Figure 8). The focus of this AM effort (the Platte River Recovery Implementation Program PRRIP)) is to restore habitat for endangered interior least terns, Northern Great Plains Piping plovers, and whooping cranes in a 150-mile Program area near Kearney, Nebraska (Figure 8), while protecting uses of the Platte River by pallid sturgeon (Smith, 2010). Flows in the Program area are affected by management decisions at an upstream reservoir (Lake McConaughy), which has an area of 144 km^2, and can store 2.15 Gm^3 of water. Two alternative approaches have been tested to create and maintain nesting habitat for least terns and piping plovers: 1) using flow and sediment augmentation to have the river naturally build sandbars; and 2) using off-channel sandpits adjacent to the river as nesting habitat. The first approach has been unsuccessful. Extended periods of high flow in recent years have eroded both natural and constructed sandbars. Nearly all of the bird nesting is occurring on off-channel sandpits (Farrell *et al.*, 2018, PRRIP, 2015), with increasing numbers of nests over time, confirming the effectiveness of the second approach.

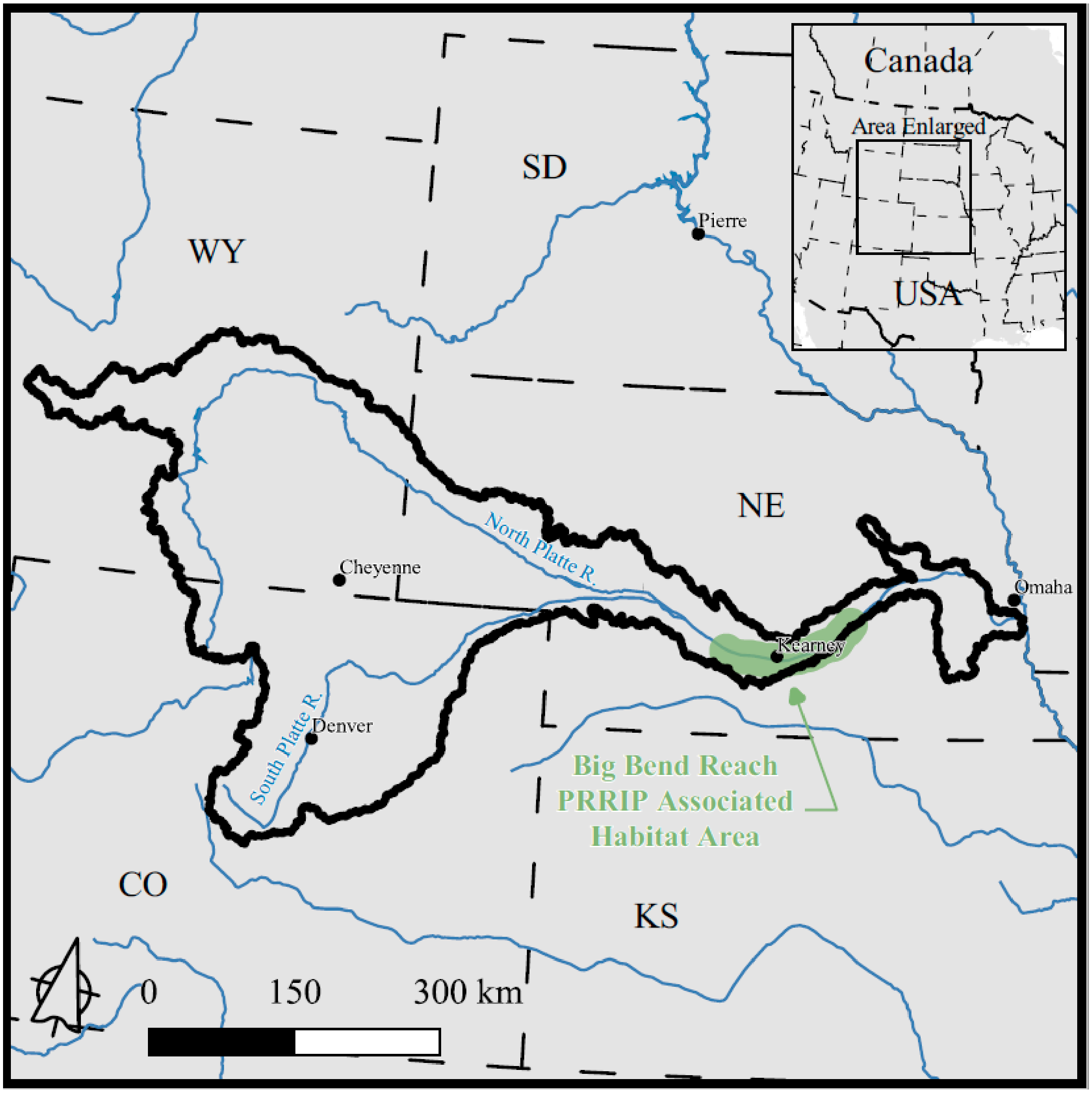

Figure 8. Platte River watershed. Shaded area near Kearney NE (Big Bend Reach) is the focus of habitat restoration efforts by the Platte River Recovery Implementation Program.

Effects of Recent Climate Events. Natural high flows during the last decade (Figure 9) have provided a powerful natural experiment to test AM hypotheses. One of the flow hypotheses being tested in the Platte was that 3 days of flow at 5,000 to 8,000 cfs (142 to 227 m^3/s; "Short Duration High Flows", SDHF), the range shown by the horizontal lines on Figure 9) would build sandbars suitable for bird nesting. Though it isn't feasible to release exactly that amount of flow, seven natural flow events occurred over the last decade (Figure 9), which were of equal or greater magnitude and duration, and allowed scientists to test (and reject) the SDHF flow hypothesis for this part of the Platte River. More details on the evaluation of this hypothesis can be found in the State of the Platte Report for 2014 (PRRIP, 2015) and in Farnsworth *et al.* (2018).

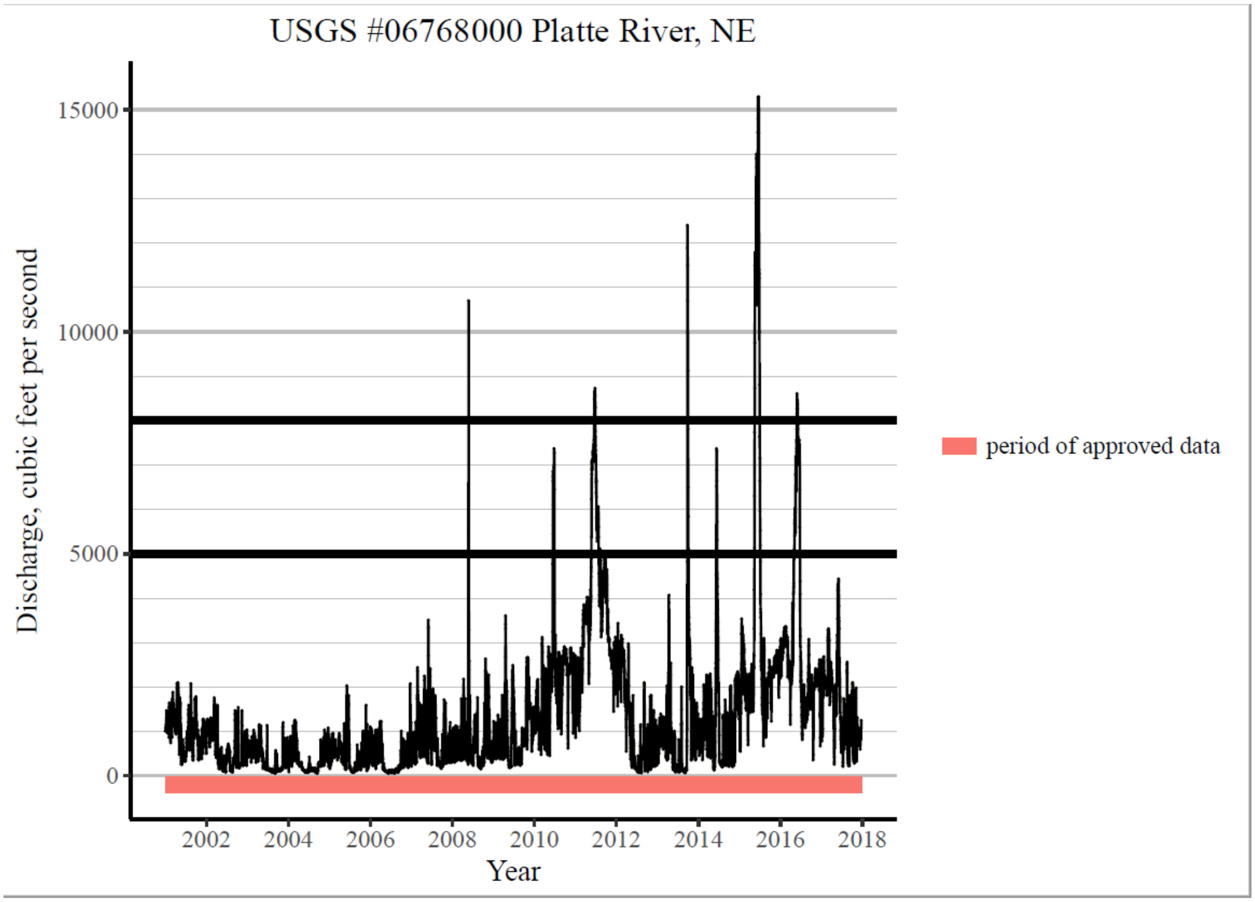

Figure 9. Flows in the Platte River over the period from 2001 to 2017. The thick horizontal lines indicate the flow range from 5,000 to 8,000 cfs hypothesized to create sandbars in the river (142 to 227 m^3/s; note the log scale),. Since 2008 there have been seven flow events either within or above that range of flows. Source: USGS https://waterdata.usgs.gov/nwis/dvstat/?referred_module=sw

Missouri River (MT, WY, CO, ND, SD, NE, KA, MO, IO)

Background. At 1,370,000 km^2, the Missouri River is the second largest basin in the continental U.S. (next to the Mississippi Basin, of which it forms a significant part); Figure 10. The Missouri is a highly engineered system, with six large dams and reservoirs (Figure 10), bank stabilization structures, and channelization to support various authorized purposes (flood control, navigation, fish and wildlife, irrigation, power, recreation, water supply, water quality) as well as the many other human uses and ecological services provided by the river. The Missouri River Recovery Program (MRRP) is focused on not jeopardizing the continued existence of piping plovers, least terns and pallid sturgeon (3 of the 4 species addressed in the Platte Program), while at the same time minimizing negative impacts to human uses of the river. Actions such as habitat construction for both birds and fish, passage for pallid sturgeon on the Yellowstone River, and flows to encourage sturgeon spawning are analyzed and implemented within a rigorous, stepwise AM framework (Fischenich *et al.*, 2018). Critical management uncertainties include the *amount of habitat* required to support species persistence and recovery, the *best form of habitat* (e.g., spawning vs. rearing habitat for pallid sturgeon; river-created vs. constructed sandbars for birds), and the *best use of flows* to support habitat creation and persistence, as well as reproduction and survival (of both birds and fish). The AM Framework (Fischenich *et al.*, 2018) describes a systematic approach to project implementation, monitoring and evaluation (as well as research) to increase learning and reduce critical management uncertainties, while meeting objectives for species at risk and supporting human uses of the river. The final Environmental Impact Statement for the Missouri River Recovery Program (USACOE, 2018) explored two different strategies for building sandbars on which terns and plovers could nest: 1) direct construction; and 2) using flows (either in spring or fall). Using flows to construct habitat is considerably cheaper than using bulldozers, but raises concerns among stakeholders, particularly for flooding.

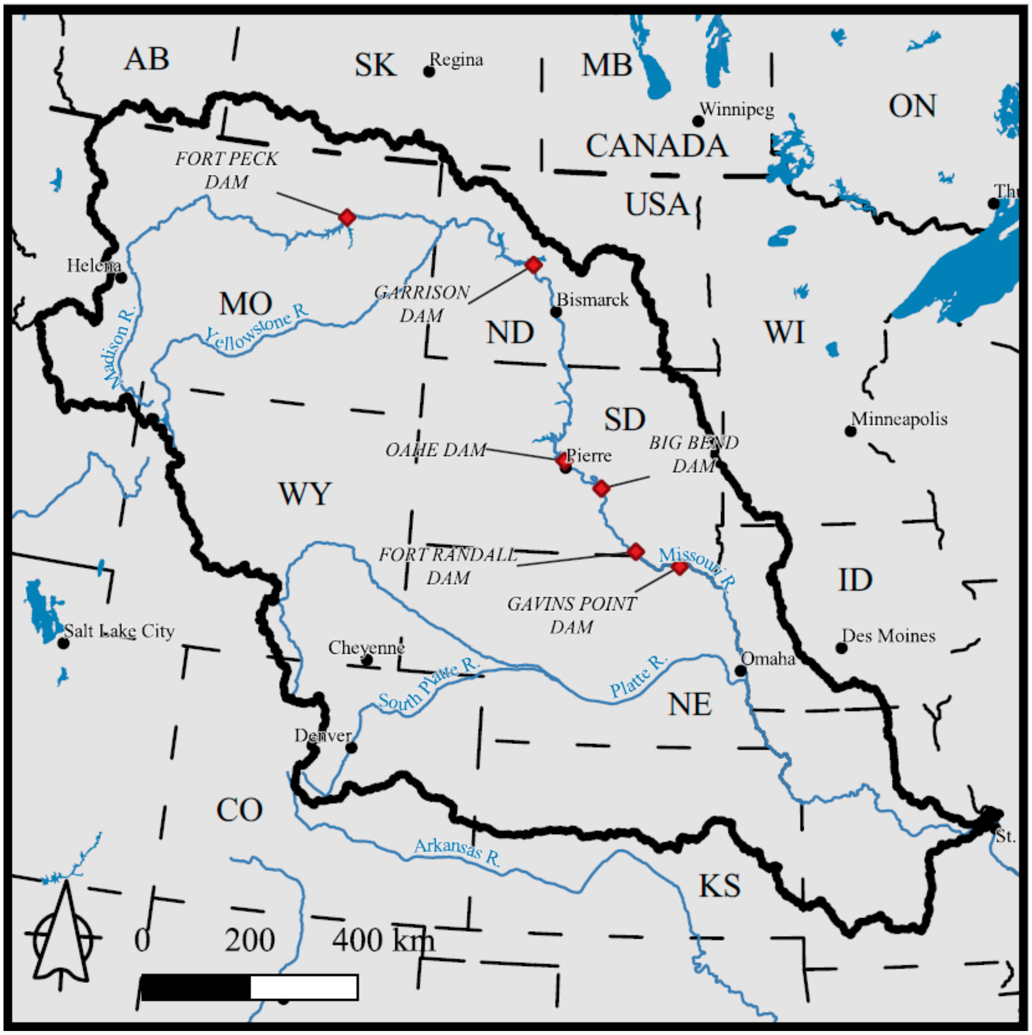

Figure 10. Missouri River basin. Major dams on the Missouri River are shown with diamonds.

Effects of Recent Climate Events. In 2011, higher-than-average snowmelt runoff combined with heavy spring rains caused a very large flood in the Missouri River (Figure 11). Several locations in the Missouri River subbasin received one-third to one-half of their normal annual rainfall during the second half of May 2011 (Vining *et al.*, 2013). The flood caused considerable damage to property (Figure 12), and also eroded and deposited enough sand to produce approximately a 15-fold increase in the amount of sandbar habitat available for nesting terns and plovers in the Lower Missouri River (Figure 33 on page 218 in Fischenich *et al.*, 2018). Analyses included in the EIS have shown that moderate flow releases can create sandbar habitat without significant impacts on human uses, but the 2011 flood (as well as other floods) have left stakeholders deeply concerned about variation in flows beyond those in the Master Manual historically used by the U.S. Army Corps of Engineers (USACOE) to manage dam releases. Floods in 2007, 2008, 2010, 2011, 2013, and 2014 led to a lawsuit by farmers, landowners and business owners against the USACOE (Firestone, 2018), and more flooding has occurred in 2019.

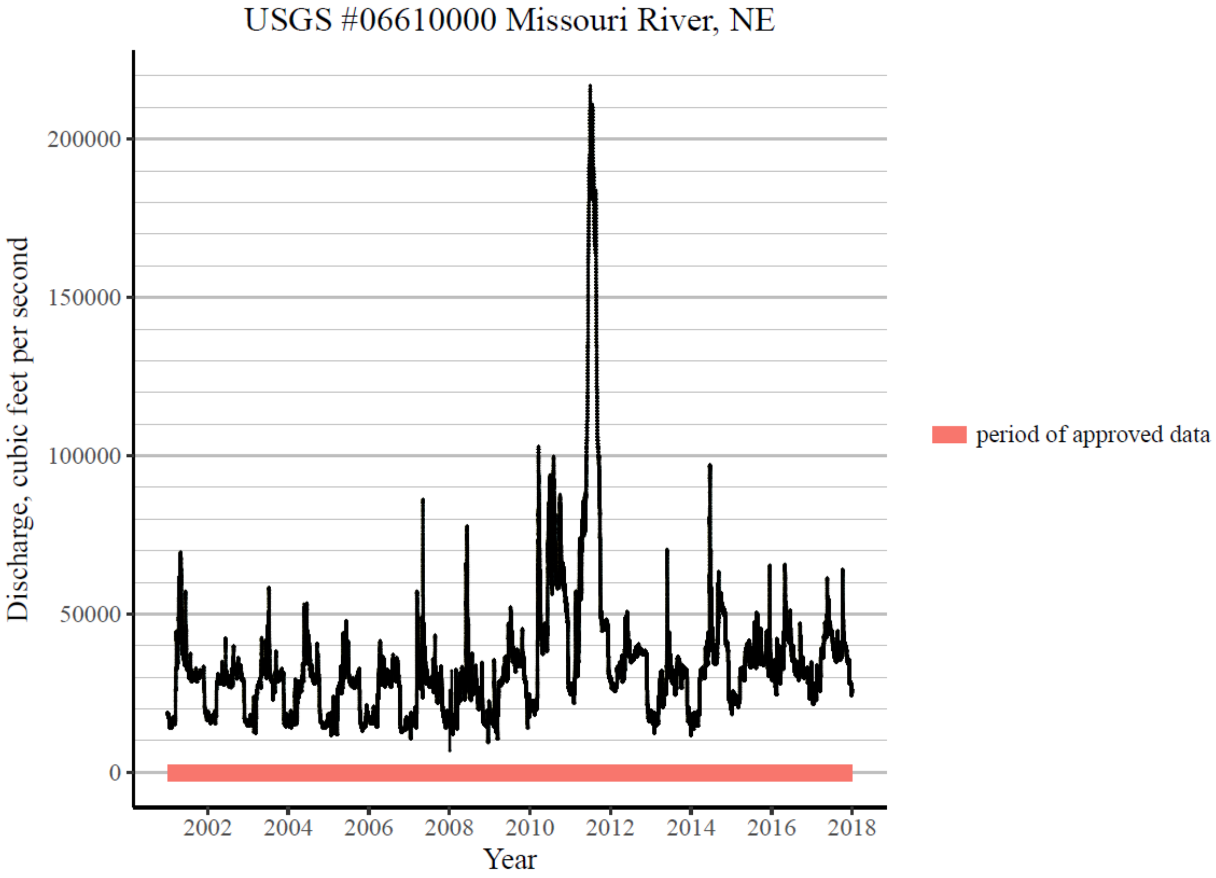

Figure 11. Flows on the Missouri River at Omaha, NE.

Figure 12. The 2011 flood in the Missouri River. Corps of Engineers photo of June 16, 2011, showing the Fort Calhoun nuclear power plant (Nebraska) surrounded by flood water. Source (public domain): https://upload.wikimedia.org/wikipedia/commons/3/35/Corp_of_Eng._6-16-11A_267.JPG

DISCUSSION

In Table 7 we summarize some of the challenges created by climate change that have been observed in the five case studies, and various strategies which may be helpful in dealing with these climate challenges. Some of these strategies have already been implemented within the five river basins, or are under consideration. After briefly discussing the challenges in Table 7, we review each of these strategies, highlighting those case studies which either exemplify their application, or demonstrate technical / institutional challenges in their implementation.

Table 7. Synthesis of the challenges created by climate change in the five case studies, and the possible CCA strategies to deal with these changes. X=Climate challenges observed within a case study. Abbreviations in cells related to strategies that have either been implemented (I) or are under consideration (UC).

Attributes of each case	**Case Studies of AM Projects**				
	Dry Creek	**Trinity River**	**Okanagan River**	**Platte River**	**Missouri River**
Challenges created by climate change:					
1. Extreme runoff and flow events have destroyed habitat and property.	X		X	X	X
2. Decreasing precipitation leading to longer periods of drought have negative impacts on biota.	X	X	X		
3. Scale of climatic impacts and required intervention >> scale of AM program control	X	X	X	X	X
CCA strategies to deal with these challenges:					
a. Use variability in flow to test flow-habitat hypotheses	I	UC	I	I	I
b. Use real time decision support systems to manage flows	I		I	UC	I
c. Develop advanced systems for anomaly detection and flood forecasting from weather	UC		UC		
d. Increase storage (dams, groundwater, wetlands, ponds) to reduce impacts of drought.				UC	
e. Rethink and re-design habitat restoration for greater resilience during droughts and floods.	I	UC	I	I	I
f. Implement actions to reduce water demand	I		I		
g. Revise basin-wide water management strategies to meet species' needs and accommodate increased variability in flows.	I	UC	I	UC	UC

Four of the five basins have recently experienced extreme runoff and flow events (challenge 1 in Table 7) which destroyed (as well as created) habitat for species at risk, and affected property in the Russian, Okanagan, Platte and Missouri basins. The Trinity is an exception, as the large volume of storage in Trinity Lake mitigated recent storm events. The three westerly basins (Russian, Trinity, Okanagan) have experienced longer periods of drought (challenge 2), with consequent effects on salmon populations, also partly mitigated by upstream reservoirs. All five basins are experiencing impacts of climate change at a scale much greater than the scale at which managers have authority (challenge 3). For the three salmon-bearing basins (Russian, Trinity, Okanagan), recent coast-wide declines in both Chinook and sockeye salmon production appear to be most strongly related to large scale changes in ocean conditions driven by climate change, rather than by local habitat factors (Marmorek *et al.*, 2011; Peterman and Dorner, 2012; Dorner *et al.*, 2017) . In the Trinity Basin, further revisions to water allocations (e.g., increasing the amount of water allocated to the Trinity River in Table 6) would require negotiations outside of the Trinity Basin and the authority of the TRRP (e.g., with water users in the Central Valley, who use water diverted from the Trinity Basin into the Sacramento Basin); this is very unlikely to occur. While the Platte River has recently experienced relatively high flows, there is limited upstream storage to either create managed flows of similar magnitude for fluvial geomorphic processes, or to mitigate the impacts of the next major drought cycle. The scope of the Missouri River Recovery Program includes the mainstem Missouri and Yellowstone Rivers, but not the rest of the Missouri River basin, where actions may be required to establish sufficient upstream storage to mitigate both floods and droughts. We now discuss each of the strategies listed in Table 7.

Use variability in flow to test flow-habitat hypotheses.

The Platte program has, in particular, embodied the AM principle of taking advantage of unexpected events that provide an opportunity to test flow-habitat hypotheses (Figure 9), and has been able to reject a key hypothesis concerning the purported benefits of short duration high flows for in-river habitat (PRRIP, 2015; Farnsworth *et al.*, 2018). Scientists working in three of the other four basins have also used contrasts in flows to improve their understanding of the optimal flow ranges for creating and maintaining habitats (Dry Creek (Martini-Lamb and Manning, 2015), Trinity (Curtis *et al.*, 2015), Missouri (Fischenich *et al.*, 2014).

A recent study by Alexander *et al.* (2018) demonstrated that adopting a dynamic water allocation approach, which shifts flow priorities from year to year, can improve the ability to meet multiple competing objectives across multiple species. The approach, termed “Turn Taking Optimization” (TTO), is based on the principle of taking turns, taking advantage of year to year variability in flows to meet the particular flow needs of each species or habitat complex. Rather than attempting to optimize conditions for all species’ objectives and indicators every year, which is impossible, TTO creates flexibility and opportunities for different indicators to be successful in different years, informed by the frequency with which each species’ ecological needs should be met. Once a species or habitat objective is met in a particular year, its priority in one or more subsequent years is reduced (Alexander *et al.*, 2018).

Use real time decision support systems to manage flows.

The application of real time decision support systems has been a notable success in adapting water management to climatic variability in the Okanagan Basin, and contributing to a remarkable recovery of Okanagan sockeye populations. The Okanagan case study is also a good illustration of the impacts of non-stationarity and climate extremes. The FWMT decision support system used in the Okanagan relies on weighting historical water years alongside estimates of total inflow from the British Columbia River Forecast Centre (RFC) within a statistical matching algorithm to predict daily net inflow to Okanagan Lake (Ma *et al.*, 2018). The model predictions for spring 2017 represented the 'best guess' estimate based on combining historical information, River Forecast Centre (RFC) estimates and real-time data. Although FWMT net inflow predictions are bookended with lower and upper limits, these are constrained by what has previously been observed, and by the quality of the RFC forecast of bulk inflow. RFC forecasts are based on four factors (upper elevation snowpack, rainfall during the previous fall, low elevation precipitation during the winter, and current river flows), but do not incorporate forecasts of future weather conditions (Associated Environmental Consultants, 2017). Since 2017 went far beyond what was previously observed (Figure 7), the RFC and FWMT inflow forecasting models greatly underestimated the actual inflow to Okanagan Lake (Associated Environmental Consultants, 2017).

The events of 2017 are forcing a re-examination of existing tools to forecast inflows, consistent with the principles and practices of bottom-up CCA. Two critical improvements are required to prepare managers for more extreme flow scenarios: a higher resolution of watershed snow and precipitation sensors, and improved self-adjusting inflow forecasting algorithms. In response to the 2017 experience, there are three approaches that have been considered and developed for FWMT. First, we have ensured the existing inflow forecast model has 'self-learning' capabilities in the forecast algorithm, so that if a similar hydrologic year occurs in the future (like 2017), the algorithm will place a high weighting on 2017 when predicting daily net inflow (Ma *et al.*, 2018). Second, we have added 'early warning indicators' (e.g., snowpack, groundwater, total rainfall, total precipitation, total snow) that are more sensitive in real-time to sudden extreme events providing additional information to managers to help them adjust risk tolerances. Third, FWMT operators can use physically-based models to predict bulk inflows that operate on finer temporal and spatial scales instead of coarser statistical methods currently employed by RFC.

Bales (2016) summarizes a number of advanced techniques for flood forecasting, some of which may potentially be applicable to the Okanagan and other regions, depending on their responsiveness, reliability and information requirements. Perez *et al.*, (2016) discuss the value of pre-calculating many weather-driven flood scenarios in a physical model, and then using a statistical algorithm (similar to FWMT) to match the current and rapidly evolving situation. High resolution local information is a foundational requirement for all inflow and flood forecasting tools. In the Russian River basin, a collaborative effort has led to the implementation of a real time decision support system called FIRO (Forecast Informed Reservoir Operations; http://cw3e.ucsd.edu/firo/) for releases from Lake Mendocino, though such as system does not yet exist for Lake Sonoma above Dry Creek. Real-time decision support systems offer the potential to piggy back dam releases on top of storm events, thereby achieving much greater downstream geomorphic and riparian benefits; this could be particularly beneficial for salmon in the Trinity River, whooping cranes in the Platte River and both piping plovers and pallid sturgeon in the Missouri River, provided that such releases do not cause unacceptable property damage. The stream channels in Dry Creek and Okanagan River are, however, narrow and heavily engineered, with high flows posing a significant risk to property.

Increase storage (dams, groundwater, wetlands, ponds) to reduce impacts of drought.

The Trinity River basin (Figure 4) exemplifies the value of large storage reservoirs to maintain cool temperatures for salmon. While high flows occasionally exceed this storage, the restoration strategy for the Trinity (USFWS and HVT, 1999) depends on higher flows to restore geomorphic processes. However, salmon in the Trinity are now subjected to a double whammy, with periodic, severe droughts in their freshwater phase due to lower precipitation, and low survival during their ocean phase (Mantua, 2015). Ironically, the dams and reservoirs which first caused the decline of salmon and steelhead in the Trinity River during the latter half of the twentieth century may now be necessary for their preservation during drought periods and episodic heavy rains in the twenty-first century. Dam removal has been implemented to recover salmon in the Elwha watershed in northwestern Washington state (Shaffer *et al.*, 2017), and is under consideration in the Klamath basin (USDI, 2012), which includes the Trinity River. While removal of run-of-river dams is likely to have more benefits than detriments for salmon, this may not always be true for watersheds where storage reservoirs provide large cold water pools to buffer the effects of a series of drought years under climate change. Large AM projects considering dam removal need to be coupled with a careful analysis of their implications for fish populations under different climate change scenarios, using the principles and practices of CCA. Other effects of climate change in the Trinity Basin, including major forest fires, have led to the development of a Forest and Water Resources Climate Adaptation Plan (Medley-Daniel *et al.*, 2011).

In the Dry Creek sub-basin, larger amounts of storage in Lake Sonoma Reservoir might have reduced the extent of damage to fish habitat from the high flows of December 2016 (Figure 2), but increasing the size of this reservoir isn't feasible. In fact, the Dry Creek sub-basin currently has more upstream storage (relative to sub-basin area) than the Trinity basin (both have far more total upstream storage relative to basin area than the Okanagan, Platte and Missouri). A more practical approach is to revise the designs of habitat restoration efforts to make them less vulnerable to high flows, as discussed in the next section.

In salmon bearing watersheds that are vulnerable to drought, but without storage reservoirs to buffer its effects on stream flows and temperatures, it may be worth exploring other forms of water storage, including storage in groundwater aquifers, wetlands and multiple small ponds. Nelitz *et al.* (2007a, 2007b, 2009) uses a CCA lens to explore various strategies for reducing the vulnerability of salmon populations to climate change. Conjunctive water management, the coordinated use of ground and surface water supplies, is being implemented in Colorado (including in the S. Platte basin) and Arizona, but in California there has historically been a greater number of legal, organizational, financial and institutional constraints to this form of storage (Blomquist *et al.*, 2001).

Rethink and re-design habitat restoration for greater resilience during droughts and floods.

The current philosophy of stream habitat restoration is to rely on (or recreate) watershed inputs of flow, sediment and wood, and fluvial geomorphic processes, so as to create and sustain fish habitat (Trush *et al.*, 2000, Roni and Beechie, 2012). In Dry Creek, the extreme flood of December 2016 seriously damaged some constructed habitat (i.e., side channels), while other habitats were protected from extreme flows (alcoves, backwater ponds). Dry Creek is not a unique example. In 1995 and 1996, floods destroyed 250 of 500 habitat structures in Fish Creek (Clackamas drainage), in north-central Oregon (Reeves *et al.*, 1997). George *et al.*, (2015) documented the effects of a 1 in a 100-year flood on trout and other fish species in Esopus Creek (Catskill Mountains, SE NY), and summarize the effects of other flood events in the northeastern U.S. These examples suggest that restoration ecologists and engineers need to fully explore the consequences of extreme flow events during the Design and/or Adjust stages of the AM cycle for habitat restoration projects. High flow events were much more common prior to the construction of dams and storage reservoirs, but designers have become acclimated to post-dam hydrologic conditions, and now need to reconsider the potential future range of flows (Figure 13 A and B). Figure 13 illustrates that basins with large upstream storage have already experienced a substantial reduction in the natural variability of flows (i.e., Figure 13B vs. Figure 13A). Climate change could have the benefit of restoring some of this lost variability, while upstream storage mitigates the most extreme events (Figure 13B). Holling and Meffe (1996) noted that variability is essential for maintaining habitat and species diversity.

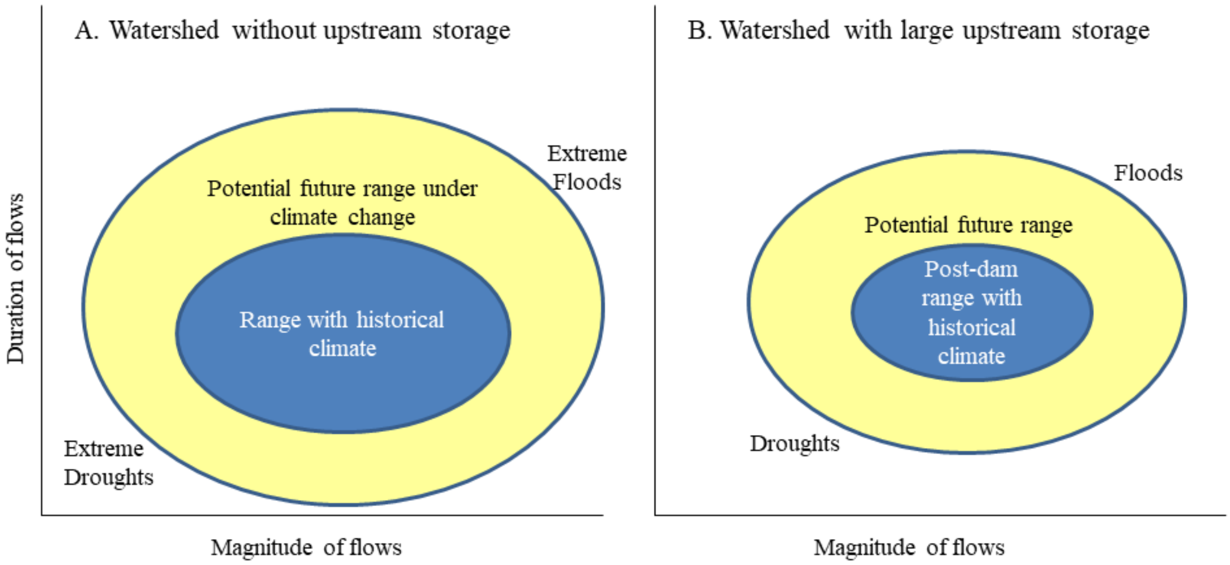

Figure 13. A challenge for restoration ecologists and engineers is to move from designing for the historical range of flows to the potential future range of flows. Graph A (no reservoir storage) shows a larger range of flow magnitude and duration under both historical and future climate conditions than graph B (large storage reservoir). In highly regulated watersheds (B), climate change could restore some flow variability required for fluvial geomorphic processes.

A *spread-the-risk* restoration strategy would be to provide a diverse portfolio of habitats: in-river habitats maintained through fluvial geomorphic processes but vulnerable to the effects of floods (i.e., anticipating periodic destruction and creation of habitat elements), coupled with off-channel habitats which require continued monitoring and maintenance but are protected from flood forces. The Platte program embodies the CCA principle of climate resilience, in that off-channel bird nesting habitats are completely unaffected by high flow events. In-river sandbars were washed away by high flow events, but the piping plovers and least terns continued to nest productively on constructed, off-channel sand pits. A disadvantage of off-channel sand pits is that they are not self-sustaining, and require a long term investment in maintenance. However, such investments may be what are required in the era of climate change and increased flow variability. Restoration practitioners could benefit from applying the principles and practices of "bottom-up" CCA (Brown *et al.*, 2012) to engineer greater resilience under a wider range of potential future flow conditions (Figure 13), while still creating and maintaining habitat through natural processes. More research is required to determine what forms of channel restoration are likely to persist and be used by fish populations under a wider range of climatic conditions, ideally through empirical observations of the physical and biological effects of extreme events, similar to the work of George *et al.,* (2015). Restoration ecologists and engineers will need to manage the expectations of decision makers, as significant fractions of the habitat portfolio may be enhanced, damaged or destroyed with each swing of the climate pendulum.

Implement actions to reduce water demand

The Russian, Trinity and Okanagan River basins are increasingly vulnerable to severe droughts. In the Russian River basin, the Sonoma County Water Agency (SCWA) implemented a successful program of water conservation by residences and businesses, though one ironic consequence was that reductions in regional water use led to increased costs per gallon, as infrastructure costs remained roughly constant (Dave Manning, SCWA, pers. comm., 2014). The Okanagan Basin Water Board is making substantial efforts at demand management and water conservation (https://www.obwb.ca/tag/water-conservation/), implementing a CCA approach to the strong likelihood of increasingly severe drought. Applying the rigor of AM can reveal which CCA practices are most effective in reducing water demand. For example, Shepherd *et al*., (2006) found that water metering in the Okanagan Basin in British Columbia was much more effective in reducing residential water use than in affecting agricultural water use.

Revise basin-wide water management strategies

Basin-wide water management can help to mitigate or take advantage of extreme climatic events such as droughts and floods. Substantial revisions to water management have been implemented in the Russian River basin through the NMFS Biological Opinion (NMFS, 2008), in the Trinity Basin through the ROD in 2000, and in the Okanagan Basin through revisions to the Okanagan Basin Implementation (Hyatt and Stockwell, in press). These are all relatively small basins. The Trinity program has managed water in response to climatic variation since its inception in the year 2000, using high flows in wetter years to achieve geomorphic objectives, and maintaining river temperatures for salmon in drier years with low flows. But the 2013-2015 droughts almost exhausted the pool of cold water in Trinity Lake. As noted above in the summary of challenges, it's very unlikely there would be any revision to the water volumes allocated in the 2000 ROD (Table 6). From the perspective of CCA, the Trinity challenges appear to represent a scale mismatch, a problem common in resource management, particularly under climate change

(Wilbanks and Kates, 1999, Cash *et al.*, 2006). The Trinity River Restoration Program makes decisions in the Trinity basin (7,500 km^2), but the climate adaptation solutions to droughts in the 21st century may require difficult policy decisions on the scale of the combined Trinity and Sacramento River basins (76,000 km^2, an order of magnitude larger), so as to arbitrate between water to support salmon harvests in the Trinity River (particularly by the Hoopa Valley and Yurok tribes) and water for power generation and agriculture in the Central Valley.

Achieving consensus on how to revise water management is particularly difficult in the Missouri Basin. For example, development of the final EIS (USACOE and USFWS, 2018) and the Science and AM Plan (Fischenich *et al.*, 2018) involved collaboration with a 75-person Missouri River Recovery Implementation Committee (MRRIC, a consultative body to advise the U.S. Army Corp of Engineers and the U.S. Fish and Wildlife Service), and input from several hundred members of the public. MRRIC includes representatives for 16 different interests (2 people per interest), 29 tribes, 8 states, and 9 federal government agencies. By contrast, development of the AM Plan for Dry Creek in the Russian River basin (Porter *et al.*, 2014) involved collaboration with about 15 people.

The Missouri is a highly engineered river, and has been for more than 80 years. Human uses of the river channel and adjacent lands have depended on that level of engineering, which creates institutional inertia. Inertia is compounded by the scale of the basin and the diverse interests of its many stakeholders, which constrains the ability to creatively implement the principles of AM and CCA. While tremendous progress has been made in applying AM to the Missouri River, as documented in Fischenich *et al.* (2018), future extreme climate events in the Missouri are likely to require even more proactive planning, scientific collaboration and managerial agility, and a greater use of the practices of CCA. This is likely to be very challenging in a huge basin with many competing objectives and an adversarial environment (many lawsuits), as has been found in the Columbia River (Marmorek and Peters, 2001).

Applying AM to CCA studies

While our proposal to apply AM to CCA studies makes intuitive sense, we expect that there will be exceptions. Just as there are many situations where AM is not an appropriate tool for resource management (e.g., too risky or infeasible to conduct management experiments, insufficient uncertainty to require AM; Murray *et al.*, 2015), we expect that AM will not always be appropriate in CCA efforts. AM experiments require a sufficient duration of treatment comparisons and sufficient replication to convincingly evaluate management actions and improve decision making (e.g., Walters and Green, 1997; Alexander *et al.*, 2006), which may not be feasible for longer term, large scale CCA actions.

CONCLUSION

Climate change and extreme climatic events pose significant risks for AM projects that are attempting to restore ecosystems and recover species. Billions of dollars have been spent on such projects (Bernhardt *et al.*, 2005), and there is a high cost to having them fail. Climate risks could be substantially reduced (and some opportunities realized) by applying the principles and procedures of CCA during the assessment, design and implementation steps of new AM projects, and the adjustment step of existing AM projects (Table 3). On the flip side, CCA practitioners could obtain multiple benefits by applying the rigor of AM (Table 4), improving the rate of learning regarding which actions are most effective in adjusting to climate change. While CCA and AM are well aligned in their principles and procedures (Tables 1 and 2), and have a great potential to be mutually beneficial, existing guidance documents in both fields have failed to truly integrate these two practices, which remain largely separate endeavors. We hope that this paper will begin to harness the complementary strengths of AM and CCA. Doing so is akin to shifting from monocular to binocular vision. Or, in haiku form:

Using CCA
In AM project design
Builds resilience!

Applying AM
To climate adaptation
Will improve learning!

Bringing these fields together will require adjustments in the way practitioners in both fields understand and do their work. We have the following recommendations for practitioners involved in planning or implementing AM projects to restore aquatic ecosystems and/or recover species: 1) learn about the field of CCA (e.g., Stein *et al.*, 2014; CCME, 2015); 2) do (or redo) the *assessment* step of the AM cycle for your project in a manner that blends the two columns of Table 2, rigorously considering the potential effects of future climatic variation (e.g., Figure 13); 3) rethink the *design* and *implementation* steps of your AM project in light of your climate-aware assessment, considering the seven strategies outlined in Table 7 (and the following discussion) to reduce climate risks, increase project resilience, realize opportunities to benefit from increased climate variability (e.g., testing hypotheses, creating habitat), and consider collaborative strategies for CCA at much larger spatial scales than the scale of your AM project; 4) review the *monitoring* and *evaluation* activities currently in place (or planned) for your project, revising them to enable greater elucidation of climate effects on project objectives; and 5) share your climate insights with other AM professionals.

For practitioners of CCA, we recommend the following: 1) learn about AM (e.g., Williams *et al.*, 2009, Williams and Brown, 2012; other references in Tables 1 and 2); 2) take advantage of the four decades of AM practice to make a quantum leap in the level of rigor applied to the design, implementation, monitoring and evaluation of CCA actions; 3) institutionalize learning into the paradigms applied by managers of CCA programs; and 4) share your AM insights with other professionals in the field of CCA.

We are excited by the potential for finding opportunities to bring together components of these two mutually complimentary, but historically separate, areas of practice, and to determine over time where this synthesis does or doesn't make sense. We hope that this paper helps to expand the toolbox and mindsets of water managers who are seeking robust actions in an era of increasing climate uncertainty, stimulates AM practitioners to consider how the practices of CCA can help their projects, and encourages CCA practitioners to explore how the rigor of AM could improve their ability to learn over time which methods of adaptation to climate change are most effective. It would be worth doing further research to qualitatively and quantitatively assess when and where AM would improve CCA decisions, and in which situations an application of AM is either unnecessary or infeasible.

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