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Strategic planning for instream flow restoration: a case study of potential climate change impacts in the central Columbia River basin

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Abstract

We provide a case study prioritizing instream flow restoration activities by sub-basin according to the habitat needs of Endangered Species Act (ESA)-listed salmonids relative to climate change in the central Columbia River basin in Washington State (USA). The objective is to employ scenario analysis to inform and improve existing instream flow restoration projects. We assess the sensitivity of late summer (July, August, and September) flows to the following scenario simulations – singly or in combination: climate change, changes in the quantity of water used for irrigation and possible changes to existing water resource policy. Flows for four sub-basins were modeled using the Water Evaluation and Planning system (WEAP) under historical and projected conditions of 2020 and 2040 for each scenario. Results indicate that Yakima will be the most flow-limited sub-basin with average reductions in streamflow of 41% under climate conditions of 2020 and 56% under 2040 conditions; 1.3–2.5 times greater than those of other sub-basins. In addition, irrigation plays a key role in the hydrology of the Yakima sub-basin – with flow reductions ranging from 78% to 90% under severe to extreme (i.e., 20–40%) increases in agricultural water use (2.0–4.4 times the reductions in the other sub-basins). The Yakima and Okanogan sub-basins are the most responsive to simulations of flow-bolstering policy change (providing salmon with first priority water allocation and at biologically relevant flows), as demonstrated by 91–100% target flows attained. The Wenatchee and Methow sub-basins do not exhibit similar responsiveness to simulated policy changes. Considering climate change only, we conclude that flow restoration should be prioritized first in the Yakima and Wenatchee sub-basins, and second in the Okanogan and Methow. Considering both climate change and possible policy changes, we recommend that the Yakima sub-basin receive the highest priority for flow restoration activities to sustain critical instream habitat for ESA-listed salmonids.

Keywords: climate change, Columbia River basin, Endangered Species Act, instream flow, irrigation, Pacific salmon, scenario analysis, strategic planning, Water Evaluation and Planning System, water resource management

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Introduction

Substantial resources are expended worldwide to restore aquatic ecosystems. In the United States alone, at least $1 billion has been spent annually on restoration of rivers and streams since 1990 (Bernhardt *et al*., 2005). Over the last 30 years, Bonneville Power Administration (BPA) spent more than $11 billion to protect and restore fish populations in the Columbia River basin, (BPA, 2010). Mandated by the Endangered Species Act (ESA), restoration efforts such as these aim to improve aquatic ecosystem integrity and play an essential role in curtailing the rapid loss of biodiversity and associated habitat (Millennium Ecosystem Assessment [MEA], 2005).

Despite sustained federal financial support for the recovery of endangered species, many populations remain in peril. One possible explanation is that few restoration practitioners incorporate planning components critical for achieving project objectives under current conditions of rapid, landscape-scale changes in ecosystem processes (Barnas & Katz, 2010; Beechie *et al*., 2009; Holling, 1995; Northwest Power & Conservation Council (NWPCC), 2011). Examples of such planning components include the following: developing restoration plans under the basic assumption that ecosystem conditions are non-stationary, forecasting future ecosystem process conditions and rates and aligning project

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implementation efforts with emerging ecosystem conditions. Without such planning components, restoration practitioners are limited in their ability to meet ecosystem-scale challenges associated with climate change, altered hydrologic regimes, land-use change and invasive species that shift basic ecological processes. As a result of these and other ecological stressors, mounting evidence suggests that the composition and function of many ecosystems may soon bear little resemblance to any ecosystem that has existed in human history – compounding the complexity of the project planning and assessment process (Poff, 1992; Williams & Jackson, 2007; Hobbs & Cramer, 2008; Seastedt *et al.*, 2008).

This presents a dilemma, as many restoration decisions are made without knowledge of how restored ecosystems may function under future conditions. Possible solutions to this dilemma include the following planning tools: long-term strategic planning efforts and decision-support used to identify geographic regions or ecological conditions that may benefit most from restoration under uncertain future conditions (Huber-Lee *et al.*, 2006; Jackson & Hobbs, 2009).

In this article, we present a case study in which we demonstrate the use of such planning tools in the context of restoring instream flow for endangered salmonids in four contrasting sub-basins of the central Columbia River basin in Washington State (USA): Okanogan, Methow, Wenatchee, and Yakima (Fig. 1). We employ scenario-based strategic planning techniques to quantify the range of potential impacts of climate-induced and irrigation-driven changes in hydrology in the sub-basins of interest. Scenario-based strategic planning involves the consideration of possible future scenarios in an effort to improve strategic decision-making in a management context. Our case study also examines possible changes in instream flows under two simulated changes to the existing water resource governance system. The basic planning tools used in this case study represent some key techniques required to confront emerging ecological challenges and to improve decision-making for prioritizing flow restoration efforts.

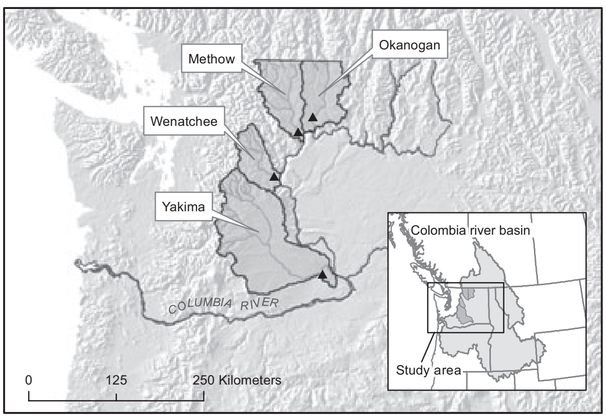

Fig. 1 Map of sub-basins of interest (Okanogan, Methow, Wenatchee, Yakima) within the Central Columbia River basin. The dots denote the location of the streamflow forecasts and the existing USGS gages used to calibrate the modeled flows.

Case study background: Columbia River basin salmonids, instream flows and water resource governance in Washington State

Columbia River basin salmonids face many challenges as a result of anthropogenic stressors (Northwest Power & Conservation Council [NWPCC], 2011). However, this case study focuses on instream flow quantities respective to the habitat needs of ESA-listed salmonids (Table 1) during the dry summer months – July, August, and September. Several regions of the Columbia River basin are already flow limited during summer when salmonid populations are threatened by rising water temperatures and limited habitat connectivity (WADOE, 2005; Huang *et al.*, 2011). Currently, there are 16 critical Columbia sub-basins experiencing flow conditions too low for sustaining endangered salmon populations (WADOE, 2005). These low flow conditions are a consequence of annual weather patterns, longer term climate change and agricultural water withdrawals, which often occur in late summer.

During this season, peaks in water withdrawal for irrigation coincide with upstream migrations of adult spring Chinook salmon (*Oncorhynchus tshawytscha*), sockeye salmon (*Oncorhynchus nerka*), and to a limited extent, coho salmon (*Oncorhynchus kisutch)* and steelhead (*Oncorhynchus mykiss*) as they move to their spawning grounds (Table 2) (Columbia River Data Access in Real Time [DART], 2012; Washington Department of Fish & Wildlife, 2002). Juvenile spring Chinook and coho salmon may also be present during periods of intensive irrigation as they move downstream in search of overwintering habitat (Washington Department of Fish & Wildlife, 2002). Low flows also cause the instream thermal regime to become too warm for migrating adults and resident juveniles, thereby reducing the fitness of some populations (Quinn, 2005). In addition, certain species of salmon have only a few weeks in which to migrate and spawn after entering freshwater. Extended migration times due to low flow conditions may result in pre-spawn mortalities (Quinn, 2005).

In the future, portions of the Columbia River basin may experience increasingly drastic low flow conditions during the dry season (Naik & Jay, 2011), and ultimately become inhospitable for salmon and other aquatic species (Stanford *et al.*, 2006; Mantua *et al.*, 2010). At

Table 1 Description of land area, average annual discharge, relative health of salmonid species, human water use, and fundamental hydrology of the Okanogan, Methow, Wenatchee and Yakima sub-basins. The transient hydrologic typology is defined as a mixture of snow and rain dominant (Elsner *et al.*, 2010)

Sub-basin Name	Drainage Area (km^2)	Average Annual Discharge (cms)	ESUs listed as Threatened or Endangered under ESA	Irrigated agriculture		Hydrologic Typology
				Km^2	% Perennial Crops	
Okanogan	6677	85.5	Steelhead, spring Chinook salmon	135	40%	Snow/Transient
Methow	4675	45.3	Steelhead	56	10%	Snow Dominant
Wenatchee	3548	93.4	spring Chinook salmon, bull trout, steelhead	100	90%	Snow Dominant
Yakima	15 929	102.0	Spring Chinook salmon, steelhead, coho salmon	2341	30%	Transient

Table 2 Peak migration months for Chinook salmon, steelhead, sockeye salmon and coho salmon at the Wells Dam, Rock Island Dam and McNary Dam

Salmonid species	Peak migration months at the Wells Dam (corresponds to estimated migration timing in Okanogan and Methow sub-basins)	Peak migration months at Rock Island Dam (corresponds to estimated migration timing in Wenatchee sub-basin)	Peak migration months at McNary Dam (corresponds to estimated migration timing in Yakima sub-basin)
Chinook salmon	June through August	Mid-May through mid-September	May through September
Steelhead	August through October	August through September	Mid-July through mid-October
Sockeye salmon	July	July	July
Coho salmon	October	Mid-September through October	September through October

The Wells Dam is a reservoir on the mainstem of the Columbia River downstream of the confluences of the Okanogan River and Methow River with the Columbia River. Rock Island Dam is a reservoir on the mainstem of the Columbia River, downstream of the Wenatchee River confluence with the Columbia River. McNary Dam is a reservoir on the mainstem of the Columbia River downstream of the Yakima River confluence with the Columbia River. The peak migration months were obtained from the University of Washington School of Aquatic and Fishery Sciences, Columbia Basin Research, Data Access in Real Time (DART) (http://www.cbr.washington.edu/dart/adult_hrt.html). The peak migration months represent the period of time during which approximately 80% of the individuals of the given species passed the given dam.

present, 27 distinct salmonid populations, or Evolutionarily Significant Units (ESUs) of salmonids, are currently listed as Threatened or Endangered under the ESA (NOAA, 2009). Several of the flow-limited critical sub-basins contain habitat for ESA-listed salmonids including spring and summer Chinook salmon, steelhead, coho salmon and bull trout (*Salvelinus confluentus*).

In addition to low flow conditions, Columbia River basin salmonids may also be impacted by high flows during the winter months. Winter high flow impacts may include redd disturbance during incubation and resulting reductions in embryo to fry survival (Battin *et al.*, 2007). Although winter flows and associated high-impact scouring of redds warrant consideration by water resource managers, forecasting the likelihood of such events is beyond the scope of this article.

Salmonids of the central Columbia River basin also face challenges in the existing system of water resource governance. The Revised Code of Washington (RCW) contains several statutes relating to the governance of instream flows in Washington's river and stream systems (WADOE, 2010). From a regulatory perspective, "an instream flow is, in essence, a water right for fish and other instream resources. While an instream flow does not affect existing water rights, water rights issued after the rule adoption are junior to the instream flow, and can only be exercised when the instream flow is being met" (WADOE, 2010) http://www.ecy.wa.gov/programs/wr/rules/rul-home.html). Regulation of instream flows serves as a critical safety net for endangered salmonid populations. However, none of the existing instream flow-rules was adopted until after the passage of the Minimum Water Flows and Levels Act of 1967. In contrast, the vast majority of potential water withdrawals associated with existing water rights were issued before this date. The portion of water right holders that is junior to the instream flow-rule in the water allocation system represents a minority of total water right holders. Furthermore, the determination of flow quantity for an instream flow-rule need not be based on the physiological requirements of particular fish species. Therefore, many of the existing instream flow-rules represent flow quantities that may not be aligned with the biological needs of species present.

Our results provide insights to guide conservation and restoration planning over the next 10–30 years of instream flow restoration for the central Columbia River sub-basins in Washington State. Although this case study provides valuable information for restoration, it is not a comprehensive framework. Rather, the case study should be used in combination with other assessments for the development of landscape-level instream flow restoration plans for ESA-listed salmonids (Northwest Power & Conservation Council [NWPCC], 2011; Washington State Department of Ecology [WADOE], 2011).

Forecasting future hydrologic flows for salmonids in the central Columbia River basin

Modeling capabilities are advancing quickly for climate forecasting as well as for ecosystem processes and biological populations (e.g., Hamlet & Lettenmaier, 1999a,b; Morrison *et al*., 2002; Pulwarty & Melis, 2001; Purkey *et al*., 2007; Whited, *et al*., 2012; Hague *et al*., 2011). Currently, several efforts are under way to examine the potential impacts of climate change on the hydrology of the Columbia River basin system and impacts on salmonid populations (e.g., Martin, 2006; Battin *et al*., 2007; ISAB, 2007; Elsner *et al*., 2009; Mantua *et al*., 2009, 2010; Vano *et al*., 2009; Jay & Naik, 2011). However, these examples are exceptional in their inclusion of climate change in research and planning, and are not reflective of the vast majority of natural resource studies and plans (Bernhardt *et al*., 2005; Schindler *et al*., 2008). Our study supports the work of existing projects in the Columbia River basin. We use scenario analysis to provide management recommendations to prioritize instream flow restoration efforts in a limited funding environment.

Materials and methods

Case study system

The study area is comprised of four sub-basins within the central Columbia River basin in Washington State (Fig. 1): the Okanogan, Methow, Wenatchee, and Yakima (sometimes referred to as Water Resource Inventory Areas - WRIAs). These sub-basins comprise a total of 30 830 km^2.

We selected these sub-basins for evaluation because they possess qualities that may make them highly sensitive to the impacts of climate change on low flow conditions for ESA-listed salmonids (Table 1). For example, all four sub-basins have high relative potential for future hydrologic change as a result of shifting from snow-dominant to transient or rain-dominant systems (transient sub-basins can be a mixture of snow- and rain-dominant) (Elsner *et al*., 2010); listed ESUs of salmon are present; are designated as "Critical basin" status as defined by the Washington State Department of Ecology (WADOE); and have high relative water withdrawals for irrigation. We selected sub-basins using a GIS spatial analysis of all sub-basins in the central Columbia River basin and their associated hydrologic and regulatory characteristics. The sub-basins of interest share one additional commonality: agricultural water uses represent the majority of the overall water withdrawals. Therefore, streamflow in the sub-basins is also highly sensitive to marginal changes in the water quantity used for irrigation.

Modeling framework

We modeled potential future instream flows in the sub-basins using the Water Evaluation and Planning System (WEAP) (http://www.weap21.org/), (Yates, 2005). The model was driven by outputs from two linked models: HadCM General Circulation Model (GCM) under the A1B greenhouse gas emission scenario generated by the Intergovernmental Panel on Climate Change (IPCC, 2007) and processed by the University of Washington's Climate Impacts Group (CIG) (Climate Impacts Group (CIG), 2011); the macroscale Variable Infiltration Capacity (VIC) hydrology model (Liang *et al*., 1994) generated by (CIG) (Appendix S1). The forecasts of naturalized hydrology were for a historical period (1916–2006) and for the potential climate conditions of 2020 and 2040 (Vano *et al*., 2009).

WEAP modeling

We imported spatial data layers, including rivers and lakes, WRIAs, reservoirs, water right holdings, and counties into the WEAP mapping interface to lay a graphical foundation for the water balance accounting and simulation model. We specified supply sources, tributaries, reservoir management, water withdrawals and return flows, and instream flow requirements (Table 3). We used outputs from the VIC hydrology model as water supply inputs for WEAP. The VIC outputs are naturalized flows and required bias correction. To ensure that simulated VIC flows reflect observed conditions, we performed a simple bias correction by comparing the simulated flows to USGS stream-gage flows using a 'conservation of mass' approach (ASCE, 1996) (Appendix S2).

WEAP reservoir management. As the VIC model does not account for reservoir operations, we created reservoir rule curves for each sub-basin to simulate the influence of the reservoir system on the modeled annual hydrograph. We aggregated all the existing reservoirs for each sub-basin containing over 1.2×10^6 m^3 (~1000 acre-feet) of storage volume. For the entire historical time series between 1916 and 2006, we optimized reservoir rule curves by minimizing the difference between the observed USGS stream-gage hydrographs and the bias-corrected VIC flows. Then we applied the rule curves to the bias-corrected VIC flows to generate modeled flows that combine the pattern and variability of the natural flows with the attenuating influence of the reservoir operations. Evaporative losses from reservoirs were estimated by considering the total surface area and total storage volume, and by applying Class A pan evaporation methods (ASCE, 1949) (Appendix S3).

Water withdrawals and management. We obtained sub-basin specific water use information for agricultural withdrawals, municipal/domestic consumption and commercial/industrial uses by contacting local water managers. Approximate annual water withdrawals, return flows, and management information were also obtained from the Watershed Planning Documents for each respective sub-basin (Tri-County Water Resource Agency, 2003; OCBC, 2005; WADOE, 2006; OCD, 2009). We estimated monthly agricultural consumption using the Soil Conservation Service [SCS] Blaney-Criddle Method (Soil Conservation Service (SCS), 1970).

We converted annual municipal/domestic and commercial/industrial withdrawals to monthly values using the USGS' National Handbook of Recommended Methods for Water Data Acquisition (USGS, 1978). We calculated return flows for municipal/domestic, and commercial/industrial water use nodes using reported average return flows (Tri-County Water Resource Agency, 2003; OCBC, 2005; WADOE, 2006; OCD, 2009). We calculated return flows for agriculture by taking the difference between water delivered for agricultural use and the calculated evapotranspiration rate (Appendix S4).

WEAP scenario analysis

To assess relative sensitivity of instream flows to climate change, withdrawals for irrigation and changes in the water resource governance system, we applied five potential future scenarios in the WEAP model for each of two projected climate conditions: those reflecting potential conditions of 2020 and 2040. The results of modeled scenarios under each of these climate conditions were then compared with modeled historical flows that were calibrated with USGS stream-gage data.

The first scenario (Climate_A1B) simulates the potential impact of climate change alone on instream flow in the selected sub-basins. In the second and third scenarios (Ag_Increase and Ag_High_Increase), we impose potential future increases in agricultural water withdrawals of 20 and 40 percent respectively, in combination with the aforementioned influence of climate change. Agricultural water use is the most influential water use sector for determining the amount of streamflow available for ESA-listed fish species. Although recent trends indicate that increases in

Table 3 WEAP Data Sources. Data source for the water supply, reservoir management, water withdrawals, return flows, and ecosystem requirements used to build the water resource management model in WEAP

Data	Water Supply	Reservoir Management	Water Withdrawals	Return Flows	Ecosystem Requirements
Source	Naturalized streamflow generated by the UW Climate Impacts Group using the VIC hydrology model (1/16th degree resolution) (Liang *et al.*, 1994)	Spatial data from the Washington state Department of Ecology; United States Department of Reclamation, Hydromet Data (USBR, 2010) (http://www.usbr.gov/pn/hydromet/)	Basin Planning Documents (Tri-County Water Resource Agency, 2003; OCBC, 2005; WADOE, 2006; OCD, 2009)	Basin Planning Documents (OCBC, 2005; WADOE, 2006; OCD, 2009); Tri-County Water Resource Agency, 2003) and calculated evaporative losses	WADOE existing instream flow-rules (WADOE, 2010) (http://www.ecy.wa.gov/laws-rules/ecywac.html#wr); Basin Fish Habitat Analyses Using the Instream Flow Incremental Methodology (DOI, 1984; USFWS, 1988; WADOE, 1992; CCNRD, 2005)

agricultural water use of the magnitude modeled in this article may not be likely (Naik and Jay, 2005), we include these scenarios as a means of assessing the sensitivity of instream flows to changes in the primary water-using sector. Restoration planners are tasked with considering the most sensitive aspects of their study systems not only in terms of expected conditions, but also in terms of "worst case scenario" conditions, even if these conditions are not predicted to be highly likely.

We use the fourth and fifth scenarios to simulate the relative influence of changes to the water governance system on the modeled instream flow. These scenarios represent proposed changes to the priority system of the existing instream flow-rules as well as proposed changes to the quantity of flow mandated by the existing rules. The fourth scenario (Fish_First) involves changing the existing instream flow-rule, as defined by WADOE, to the first priority in the allocation scheme (WADOE, 1992). The fifth scenario (Bio_Flo_First) includes creating a biologically based instream flow-rule using Weighted Usable Area (WUA) curves created by the Washington State Department of Fish and Wildlife (DOI, 1984; USFWS, 1988; WADOE, 1992; CCNRD, 2005) and setting it as the first priority in the allocation scheme. WUA is an index which uses available instream flow to quantify fish habitat. WUA is expressed as a percentage of habitat area predicted to be available per unit length of stream at a given flow (WADOE, 1992). Many other qualities also determine habitat suitability (channel profile, lateral connection to the floodplain, extent of riparian vegetation, etc.). In the absence of more comprehensive habitat quality measures we employ WUA curves for our scenario analysis.

As in any integrative modeling effort, we gathered data from several sources (Table 3). Inherent in this process is the inclusion of some degree of uncertainty and error (Regan *et al.*, 2002). A comparison of the following graphical data is provided in Fig. 2 to show the accuracy of the modeling effort: USGS observed stream-gage data, VIC bias-corrected flow (naturalized flow), and WEAP modeled historical flows. In addition, as a basic measure of uncertainty, we provide confidence intervals for all forecasted flows under all scenarios in Tables 5 and 6. The streamflow projections in this article are not intended to be absolute predictions of discharge at a given point in time. Instead, we intend for our projected estimates of streamflow to elucidate the potential effect size of climate change on the streamflow of each sub-basin. From a landscape perspective, this information is valuable for prioritizing sub-basins for instream flow restoration.

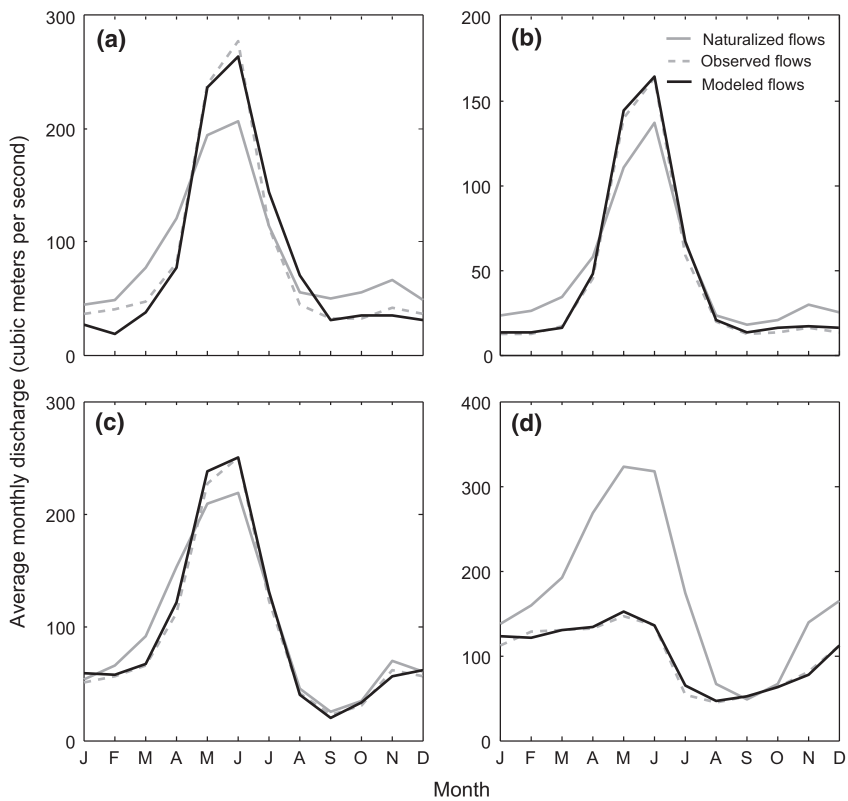

Fig. 2 Comparison of modeled WEAP streamflow to bias-corrected VIC flow (naturalized flow) and observed USGS gage data in the Okanogan (a), Methow (b), Wenatchee (c) and Yakima (d) sub-basins. Comparison of modeled and observed flows indicates overestimation of modeled flows during the months of July in all sub-basins and during the month of August in the Okanogan sub-basin. Given that our analysis focuses on low flow conditions, model estimates should be considered conservative estimates.

Table 4 Comparison of historical average monthly summer stream discharge and average monthly summer water use (cubic meters per second). This table shows that water withdrawals for agriculture account for the majority of water use in all sub-basins

	Historical Average Monthly Summer Flow (m^3/s) (before withdrawals)			Average Monthly Summer Water Use (m^3/s) (for the entire sub-basin)					
				Agriculture		Domestic		Commercial	
Sub-basin Name	July	August	September	Water Use m^3/s	% of average summer discharge	Water Use m^3/s	% of average summer discharge	Water Use m^3/s	% of average summer discharge
Okanogan	145.9	81.3	48.1	10.3	11.24%	0.55	0.60%	0.53	0.58%
Methow	69.3	23.5	17.4	4.2	11.35%	0.06	0.17%	2.52	6.70%
Wenatchee	137.7	45.4	25.3	6.0	8.65%	0.24	0.35%	2.52	3.63%
Yakima	212.6	182.5	155.4	124.9	68.05%	5.97	3.30%	1.34	0.73%

Results

Model accuracy

Modeled WEAP streamflows are relatively similar to observed USGS gage data in all sub-basins. In comparison to the other sub-basins, the modeled flows in the Yakima sub-basin are most similar to observed gage data (R^2 = 0.98) (Fig. 2d). However, during the month of July, the model overestimates streamflows in the Yakima River by an average of approximately 21%. The modeled streamflows in the Methow and Wenatchee sub-basins also closely resemble observed data (R^2 = 0.93 and R^2 = 0.92, respectively) (Fig. 2b and c). Much like the bias (overestimation) observed in the modeled Yakima sub-basin streamflows, July modeled Methow streamflows are on average 14% higher than observed data; modeled flows in the Wenatchee for the same time period are only overestimated by an average of 7%. The Okanogan sub-basin shows the most discrepancy between observed and modeled flows (R^2 = 0.87) (Fig. 2a). On average, the modeled values in the Okanogan sub-basin are 29% greater than observed values during the month of July and 56% greater during the month of August. Given that our study focuses on the impacts of low flow conditions, the instances in which our model overestimates summer flows should be considered conservative estimates.

Climate_AIB scenario: modeled flows under climate change only

Comparison of sub-basins for the A1B greenhouse gas emission scenario under 2020 climate conditions indicates that the Yakima sub-basin is projected to experience the greatest summer reductions in streamflow (22–58%) during the dry months relative to the historical simulation. Similarly, for 2040 climate conditions, the simulated streamflows for the Yakima sub-basin in later summer were even lower: on average, 78% less in July, 53% less in August and 32% less in September, relative to the historical simulation (Fig. 3a).

Simulated streamflows in the Wenatchee sub-basin also indicate substantial reductions under a warming climate but generally less than that projected for the Yakima sub-basin. Under 2020 climate conditions, streamflows in the month of July are 15% lower than that of the historical simulation. The months of August and September show reductions of 40% and 34%, respectively. For 2040 climate conditions, the Wenatchee sub-basin is projected to experience 33%, 61%, and 56% reductions in streamflow relative to simulated historical conditions for the months of July, August, and September (Fig. 3b). Although the Yakima sub-basin tends to be most flow limited at the beginning of the summer months, the Wenatchee sub-basin tends to be most flow limited at the end of the summer months.

Simulations in the Methow sub-basin exhibit the third most severe reductions in streamflow relative to simulated historical conditions (Fig. 3c). For the months of July, August, and September, the Methow sub-basin is projected to experience a reduction of 25%, 36%, and 24%, respectively, for the period 2020. For the period 2040, the Methow experienced 44%, 43%, and 33% reductions in streamflow for the same dry months (Fig. 3c).

Finally, simulated streamflows in the Okanogan sub-basin exhibit the least severe reductions in streamflow relative to historical conditions for both 2020 and 2040 (Fig. 3d). For the period 2020, Okanogan sub-basin

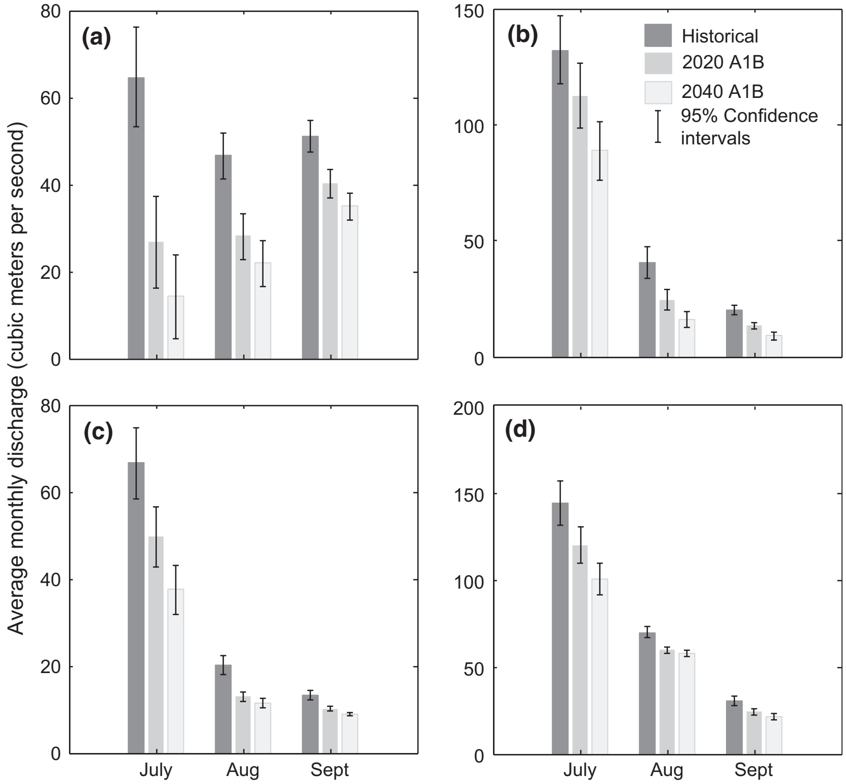

Fig. 3 Projected average monthly discharge (cubic meters per second) in all sub-basins. (a) Projected average monthly discharge in the Yakima River for the years 2020 and 2040 under the A1B carbon dioxide emission scenario relative to historical conditions. (b) Projected average monthly discharge in the Wenatchee River for the years 2020 and 2040 under the A1B carbon dioxide emission scenario relative to historical conditions. (c) Projected average monthly discharge in the Methow River for the years 2020 and 2040 under the A1B carbon dioxide emission scenario relative to historical conditions. (d) Projected average monthly discharge in the Okanogan River for the years 2020 and 2040 under the A1B carbon dioxide emission scenario relative to historical conditions.

streamflow simulations are 17%, 15%, and 21% lower than historical conditions for the months of July, August, and September. Similarly, for the 2040 climate conditions, the dry summer months exhibit 30%, 17%, and 30% reductions in streamflow relative to the historical scenario (Fig. 3d).

Ag_Increase scenarios: modeled flows under climate change and increases in agricultural water use

Agricultural water use accounts for the majority of water use in all sub-basins (Table 4). In the Methow and Wenatchee sub-basins, agricultural water use accounts for 56% and 60% of the overall water use, respectively. Whereas in the Okanogan and Yakima sub-basins, agricultural water use accounts for 87% and 95% of the overall water use, respectively. Therefore, changes in withdrawals in the agricultural sector potentially have the greatest influence on water availability for instream habitat in the Yakima River relative to other sub-basins. Simulations of increased withdrawals in the Yakima indicate that under a 20% increase in agricultural withdrawals (Ag_Increase), instream flow declines an average of 78% during the summer months in 2020. Similarly, a simulated increase of 40% agricultural withdrawals (Ag_ High_Increase) yields an average reduction of 92% during the summer months under the climate conditions of 2040 (Fig. 4).

The Wenatchee sub-basin serves as an example of a system less dominated by the influence of irrigation than the Yakima. The Wenatchee sub-basin is projected to experience average streamflow reductions of 24% in 2020 relative to the historical simulation. Whereas under 2040 climate conditions, the Wenatchee sub-basin is projected to experience average streamflow reductions of 44% during summer months relative to the modeled historical flows (Fig. 5). Therefore, on average, the Wenatchee sub-basin is projected to be less impacted by increases in irrigation than the Yakima sub-basin.

Modeled flows in the Okanogan and Methow Rivers also exhibit flow reductions under simulations of a 20% increase in irrigation. Under these scenarios,

Table 5 Simulated average monthly streamflow in cubic meters per second, including 95% confidence interval, in the Okanogan and Methow sub-basins under all scenarios for the climate conditions of 2020 and 2040.

	Okanogan						Methow					
	July		August		September		July		August		September	
Scenario	Average	95% Confidence Interval (Lower, Upper)	Average	95% Confidence Interval (Lower, Upper)	Average	95% Confidence Interval (Lower, Upper)	Average	95% Confidence Interval (Lower, Upper)	Average	95% Confidence Interval (Lower, Upper)	Average	95% Confidence Interval (Lower, Upper)
Historical	144	132,157	70	67,73	30	28,33	67	58,75	20	18,22	13	12,14
Climate 2020A1B	120	109,131	59	58,61	24	22,26	50	43,56	13	12,14	10	10,11
Climate 2040A1B	101	92,109	58	56,60	21	20,23	37	32,43	11	10,13	9	8,9
AgIncrease2020	118	107,129	58	56,60	23	21,24	49	42,56	12	11,13	10	9,10
AgIncrease 2040	99	90,108	56	54,58	20	18,22	37	31,42	11	10,12	8	8,9
AgIncreaseHigh2020	116	106,127	56	54,58	22	20,23	48	41,55	11	10,13	9	8,9
AgIncreaseHigh2040	97	88,106	55	53,57	19	17,21	36	30,42	10	9,11	8	7,8
FishFirst2020A1B	123	113,134	58	56,61	24	23,26	54	48,60	19	18,19	10	9,10
FishFirst2040A1B	106	99,114	56	53,58	23	21,24	43	38,48	18	17,19	9	9,10
BioFloFirst2020A1B	120	109,131	62	60,63	32	31,34	55	49,61	20	19,21	15	14,15
BioFloFirst2040A1B	101	92,109	60	59,62	30	29,31	44	39,50	18	17,19	14	13,14

The historical scenario represents the historical period from 1916 to 2006. Climate_2020A1B and Climate_2040A1B simulate the potential impact of climate change, under the A1B emission scenario, on instream flow in the selected sub-basins for the projected conditions of the years 2020 and 2040, respectively. Ag_Increase2020 and Ag_Increase2040 scenarios, as well as the Ag_High_Increase2020 and Ag_High_Increase2040, includes the imposition of potential future increases in agricultural water withdrawals of 20 and 40 percent respectively, in combination with the aforementioned influence of climate change, for the projected conditions of the years 2020 and 2040. FishFirst sets the existing instream flow-rule, as defined by WADOE, as the first priority in the allocation scheme (WADOE, 1992). Bio_Flo_First uses a biologically based instream flow-rule using Weighted Usable Area (WUA) curves created by the Washington State Department of Fish and Wildlife (DOI, 1984; USFWS, 1988; WADOE, 1992; CCNRD, 2005) and sets it as the first priority in the allocation scheme.

Table 6 Simulated average monthly streamflow in cubic meters per second, including 95% confidence interval, in the Wenatchee and Yakima sub-basins under all scenarios for the climate conditions of 2020 and 2040

	Wenatchee						Yakima					
	July		August		September		July		August		September	
Scenario	Average	95% Confidence Interval (Lower, Upper)	Average	95% Confidence Interval (Lower, Upper)	Average	95% Confidence Interval (Lower, Upper)	Average	95% Confidence Interval (Lower, Upper)	Average	95% Confidence Interval (Lower, Upper)	Average	95% Confidence Interval (Lower, Upper)
Historical	132	118,147	41	34,47	20	18,22	65	53,76	47	41,52	51	47,55
Climate 2020A1B	112	98,126	24	20,29	13	12,15	27	16,37	28	23,33	40	37,43
Climate 2040A1B	89	76,101	16	12,19	9	7,10	14	5,24	22	17,27	35	32,38
AgIncrease 2020	111	97,125	23	19,28	12	11,14	13	3,23	6	1,12	17	14,21
AgIncrease 2040	88	75,100	15	11,18	8	7,10	8	−0,17	4	0,9	10	6,13
AgIncreaseHigh 2020	110	96,124	22	18,27	12	10,13	9	0,19	4	0,9	4	0,8
AgIncreaseHigh 2040	86	74,99	14	10,17	7	6,9	7	−0,16	4	0,9	3	0,6
FishFirst 2020A1B	113	99,127	29	25,33	18	17,19	34	24,44	29	24,34	40	37,43
FishFirst 2040A1B	91	79,103	22	19,25	15	14,16	27	18,36	23	18,28	35	32,38
BioFloFirst 2020A1B	115	102,128	33	29,37	19	18,20	53	45,62	46	42,50	43	41,46
BioFloFirst 2040A1B	93	81,105	25	21,28	15	13,16	50	42,58	45	41,49	40	38,43

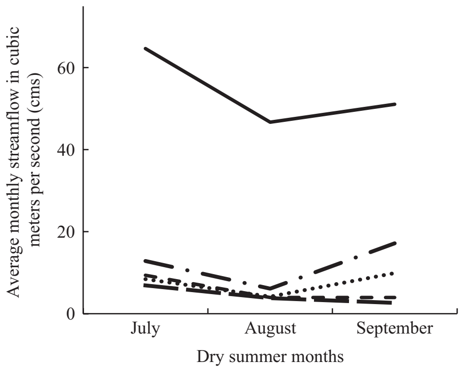

Fig. 4 Changes in stream discharge (cubic meters per second) in the Yakima sub-basin in response to increased agricultural water withdrawals and climate change. This figure depicts a simulation of a 20% and 40% increase in agricultural water withdrawals in the historical, 2020 and 2040 time periods. All increases in water withdrawals greatly reduce streamflow availability in the Yakima. The solid line represents the historical scenario. The line with the dash-dot-dash pattern represents a 20% increase in agricultural water use in combination with climate change in 2020. The dotted line represents a 20% increase in agricultural water use in combination with climate change in 2040. The short dashed line represents a 40% increase in agricultural water use in the year 2020. The long dashed line represents a 40% increase in agricultural water use in the year 2040.

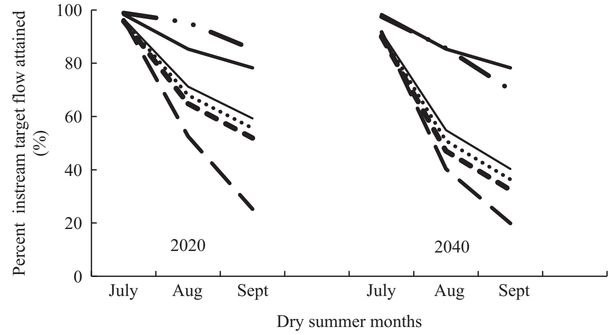

Fig. 5 Changes in the percentage of instream target flow attained in the Wenatchee sub-basin in response to climate change, increased agricultural water withdrawals and simulated policy change. This figure depicts a simulation of a 20% and 40% increase in agricultural water withdrawals in the 2020 (left side) and 2040 (right side) time periods relative to historical conditions. It also demonstrates changes to the existing instream flow-rule in which fish receive the first priority in the water allocation system (FishFirst) and at biologically relevant flows (BioFloFirst). The thick solid line represents the historical simulation. The dash-dot-dash line represents the FishFirst scenario. The thin solid line represents the climate change scenario. The dotted line represents a 20% increase in agricultural water use. The thick dashed line represents a 40% increase in agricultural water use. The long dashed line represents the BioFloFirst scenario. As a sub-basin that is substantially less dominated by agriculture, streamflow, the Wenatchee River is less responsive to increases in agricultural water use and more responsive to changes in climate. The Wenatchee sub-basin is also less responsive to simulated policy changes than the Yakima sub-basin.

the Methow sub-basin is projected to experience streamflow reductions in 2020 that are on average 29% less than historical conditions; under 2040 climate conditions, it is projected to experience streamflow reductions of 46% on average, relative to the historical simulation. Similarly, considering a 20% increase in irrigation, the Okanogan sub-basin is projected to experience reductions in streamflow of 19% on average relative to historical conditions in 2020, and 30% in 2040 (Table 5).

Fish_First: modeled flows using the existing instream flow-rule as the first priority in the water allocation scheme

Even under historical conditions, differences exist between each sub-basin in the degree to which instream flow-rules are met (or the percentage of flow-rule that is attained). For example, in the Okanogan sub-basin, simulated historical flow is sufficient to meet 99% of the existing instream flow-rule. However, in the Methow and the Wenatchee sub-basins, only 89% and 88% the instream flow-rule discharge is attained, respectively (Table 6). Streamflow in the Yakima sub-basin meets 98% of the instream flow-rule under the historical simulation (Table 7). Under simulated climate change, all sub-basins are projected to require a greater proportion of overall discharge to meet existing instream flow-rules. The Wenatchee and Yakima sub-basins experience the greatest average reduction in the percent of the flow-rule met during the summer months relative to other sub-basins under simulated climate conditions for 2020 and 2040 (Table 7). The percent of the instream flow-rule discharge met in the Wenatchee decreases by 12% under 2020 climate conditions and 27% under 2040 climate conditions, relative to historical conditions. The Yakima sub-basin experienced similar average reductions in the percent of instream flow-rule that is attained, with reductions in the volume of instream flow that is attained of 15% under 2020 climate conditions and 28% under 2040 climate conditions. The Methow sub-basin was also projected to experience similar average reductions in the percentage of instream flow-rule that is met with reductions in coverage at 10% under 2020 climate conditions and 18% under the potential climate conditions of 2040.The Okanogan sub-basin is projected to experience only a 1-4% reduction in the percent of instream flow-rule that is met by available flow.

Table 7 Percent of WADOE instream flow-rule or biologically based target flow that is attained in sub-basins of interest under all scenarios for the climate conditions of 2020 and 2040

	Okanogan			Methow			Wenatchee			Yakima		
Scenario	July	August	September	July	August	September	July	August	September	July	August	September
Historical	98.1	100.0	99.1	86.5	80.0	99.1	98.5	88.1	80.7	94.2	100.0	99.0
Climate 2020A1B	95.9	100.0	97.9	78.5	62.5	98.1	96.9	75.0	62.3	57.2	93.7	98.9
Climate 2040A1B	92.9	100.0	93.0	68.8	55.6	93.2	92.1	59.2	42.8	25.2	87.2	98.7
AgIncrease 2020	95.2	100.0	95.8	77.5	59.2	96.0	96.5	71.9	58.7	15.6	21.7	86.5
AgIncrease 2040	91.9	100.0	89.1	67.6	52.1	88.7	91.4	55.2	38.8	8.2	6.2	63.2
AgIncreaseHigh 2020	94.4	100.0	92.9	76.6	55.8	93.1	96.1	68.7	55.0	9.0	2.8	15.4
AgIncreaseHigh 2040	90.8	100.0	84.6	66.4	48.5	83.6	90.5	51.3	34.9	4.2	2.2	3.6
FishFirst 2020A1B	100.0	100.0	100.0	88.0	91.0	100.0	98.9	96.6	87.2	100.0	100.0	100.0
FishFirst 2040A1B	99.9	100.0	100.0	81.5	87.4	100.0	97.7	87.9	72.4	100.0	100.0	100.0
BioFloFirst 2020A1B	100.0	100.0	76.8	78.8	35.8	36.4	96.6	55.0	26.2	100.0	100.0	100.0
BioFloFirst 2040A1B	100.0	100.0	71.5	70.3	32.8	33.9	92.2	42.5	20.6	100.0	100.0	100.0
Historical BioFlow	100.0	100.0	100.0	93.2	95.8	100.0	99.6	99.7	96.7	100.0	100.0	100.0

Bio_Flo_First: modeled flows using biologically based instream flow-rules as the first priority in the water allocation scheme

As a stricter standard than the existing instream flow-rules, the biologically based Bio_Flo_First scenario (which is a minimum flow rate based on weighted usable area [WUA] curves and set as the first priority in the allocation scheme), is not met during particularly dry years, even when other water users are not receiving their allotment. To attain streamflow discharge quantities that meet biologically based flow requirements under historical conditions, out-of-stream water users would be allowed to make withdrawals from rivers only after flow requirements had been met. Even under these circumstances, streamflow in the Methow River is only adequate to attain 95% of the biologically based instream flow-rule (Table 7). Furthermore, under simulated climate change, even when other water users are forced to forego water withdrawals, streamflow is insufficient to meet biological flow needs. For instance, under a changed climate in 2020, streamflow in the Methow River is only able to meet an average of 36% of the biologically based flow-rule during the months of August and September (Table 7).

Similar reductions are projected to occur in the Wenatchee sub-basin with ~26% of the biologically based target flow attained during the month of September under 2020 climate conditions (Table 7). Under climate conditions of 2040, the Methow and Wenatchee sub-basins are projected to experience even greater reductions in the percentage of the biologically based target flow that can be attained with available river flow. For example, during the month of September under 2040 climate conditions, the Methow sub-basin is projected to attain ~34% of the biologically based target flow and the Wenatchee sub-basin is projected to attain only ~21% of the biologically based target flow (Table 7).

In summary, the assessment of the five scenarios indicates that the Yakima sub-basin is projected to be the most flow limited, on average, during the summer months for both the 2020 and 2040 periods. Under the climate change only scenario, the Wenatchee sub-basin is also projected to experience similar flow limitations later in the summer, specifically during September. Although the Methow and Okanogan sub-basins are also projected to experience flow reductions as a result of climate change, they experience moderate reductions in comparison to the Wenatchee and Yakima sub-basins for the periods 2020 and 2040. Similarly, the Yakima sub-basin is projected to be the most impacted by increased agricultural water use, where there is a strong trade-off between meeting the water needs of irrigators and maintaining instream flow requirements. As a result of the projected reductions in streamflow under the climate change only scenario, the Wenatchee and Yakima sub-basins are also the least likely to meet their instream flow requirements in both the 2020 and 2040 periods. Under these "worst case scenario" increases in agricultural diversions, streamflow in the Yakima sub-basin is projected to be reduced to the point that they only meet approximately 10–30% of the existing instream flow-rule. However, changes to the allocation scheme, including setting instream flow-rules as the first priority, are projected to maintain streamflows in the Yakima sub-basin at flows that can attain the existing flow-rule determined by WADOE.

Discussion

Regional assessment of flow availability for instream purposes

Our assessment of simulated historical and future scenarios for instream flow quantities in the Okanogan, Methow, Wenatchee, and Yakima sub-basins of Washington State suggests that serious biological consequences for central Columbia River basin salmonids may occur in the absence of restoration, conservation, and policy interventions. With the percentages of instream target flow attained in the Yakima sub-basin as low as 25–57% under simulated changes in climate and 20% increases in irrigation in the years 2020 and 2040, salmonids may face severe challenges to their survival. First, the potential loss of longitudinal and lateral hydrologic connectivity may preclude upstream migration in some portions of the Yakima River. In addition, even if the river channel remains marginally wetted, fish present under simulated physical conditions of only 25% instream target flow attainment would be subject to extreme thermal impacts (Battin *et al*., 2007). For example, the number of cold water refugia available to salmonids under the reduced flows would be greatly diminished and water temperatures could easily surpass biological thresholds (e.g., temperatures >21 °C; Mantua *et al*., 2010). With high hydrologic sensitivity to climate change, and especially to agricultural water use, future instream conditions in the Yakima sub-basin are projected to be poor in July and August because of the low percentage instream target flow attainment.

To a lesser extent, the other sub-basins are also projected to experience low streamflows which will have serious negative consequences for salmonids. For example, the hydrology of the Methow sub-basin, a region with far less agricultural influence than the Yakima sub-basin, appears to be more sensitive to climate change with instream target flow attainment down to approximately 80% during the climate conditions of 2020 and 73% in 2040. Whereas the Wenatchee sub-basin serves as an intermediate example – one that may be equally impacted by climate change and irrigation – with streamflow reductions resulting in a range of 65–78% of the instream target flow being attained in 2020 and 2040. While experiencing less extreme conditions than salmonids the Yakima sub-basin, salmonids in the Wenatchee sub-basin would also likely face challenges due to the instream thermal regime and the degree to which the river channel is hydrologically connected. The Okanogan sub-basin, however, may not pose the same physical threats to salmonids. In comparison to the other sub-basins examined, the Okanogan sub-basin does not appear to be as highly sensitive to either climate or agricultural water use, with the lowest instream target flow attainment estimated at 92% under conditions of climate change and a 40% increase in agricultural water use.

Growing trade-offs between instream and out-of-stream water users

Tensions over water availability for instream and out-of-stream purposes will continue to escalate in the central Columbia River basin in the next 10–30 years. Our results and those of others (e.g., Hamlet & Lettenmaier, 1999a; ISAB, 2007; Schindler *et al*., 2008; Mantua *et al*., 2009, 2010; Vano *et al*., 2009; Elsner *et al*., 2010) suggest that climate change will aggravate the current state of water scarcity in the central Columbia sub-basins of Washington State, and especially in the Yakima and Wenatchee. Our simulations suggest that under the projected climate conditions of the year 2020, the trade-off between agricultural water withdrawals and instream flow requirements for fish will be increasingly contentious. Under the simulated climate conditions of 2020, the Methow and Yakima sub-basins provide nearly 100% of the water for agriculture during the summer months - but only 57–62% of the water needed to satisfy existing instream flow-rules during July and August.

Our results indicate that flow restoration, and especially changes in policy, have the potential to off-set projected low flow conditions in some of the sub-basins explored in our scenario analysis. For example, under the simulated Fish_First scenario – a fundamental change in policy in which the existing instream flow-rule is set as the first priority in the allocation scheme – the sub-basins of interest provide, on average, between 93% and 100% of instream flow-rule coverage in 2020. Specifically, in the Yakima sub-basin, 100% of the target flow is attainted under the Fish_First scenario for the periods 2020 and 2040. However, an average of only 51% of agricultural water needs is met under the Fish_First scenario for the period 2020 and 34% for the period 2040. Further, under the Bio_Flo_First scenario – in which the existing instream flow-rule is set as the first priority for water allocation and at biologically relevant flows, the Yakima sub-basin attains 100% of target flow. Under the same scenario, an average of only 15.3% of agricultural water needs is met for 2020 and less still (8.7%) for 2040. Conversely, under simulated increases in agricultural water withdrawals for the period 2020, the Yakima River provides nearly 100% of the agricultural water needs, but only an average of 10% of the required instream flow discharge. This trade-off is projected to be even starker in 2040, with agricultural water demand in the Yakima sub-basin still met nearly 100% of the time and only 4% of instream flow attained for ESA-listed species. Overall, the scenario analysis shows that in the absence of water rights trading mechanisms, or other conservation policy approaches, there is insufficient flow in the sub-basins of interest to satisfy both instream flow requirements for listed salmonid populations and agricultural water demand using conventional irrigation methods. The Yakima provides the most salient example of the conflict inducing trade-off between agricultural withdrawals and instream water use. In the future, planners and managers will need to consider this trade-off in their conservation planning and include conflict resolution tactics in combination with restoration objectives. However, this study also clearly demonstrates the potential effectiveness of changes to existing policy for ensuring sufficient instream flows for salmonids that warrant protection under the ESA.

Mitigating conflicts and impacts of scarce water conditions in the central Columbia River basin

Analyses used here can alert planners and decision makers about sub-regions and conditions in the central Columbia River basin that require ecological as well as assistance through potential policy changes. However, all parties are imminently faced with the daunting task of establishing a strategy for restoring instream flow quantities for ESA-listed salmonids. A suite of techniques are emerging for mitigating the impacts of climate change on instream flows for ESA-listed salmonids. For example, Schindler *et al.* (2008) suggest policy mechanisms to support ground-level physical mitigation measures, including coordinated international and regional visions for habitat restoration. In addition, entities including the Northwest Power and Conservation Council (http://www.nwcouncil.org/), Bonneville Power Administration (http://www.bpa.gov) and the National Fish and Wildlife Foundation (http://www.nfwf.org) in partnership with organizations like the Washington Water Trust (http://washingtonwatertrust.org/) are employing market-based techniques such as water rights trading and/or acquisition on a willing-buyer, willing-seller basis to conserve and restore instream flows for ESA-listed salmonids (Columbia Basin Water Transactions Program [CBWTP], 2011). The latter technique is gaining visibility in the instream flow conservation, restoration, and regulatory communities.

Other mitigation methods are already in place. Mantua and his colleagues (2009, 2010) describe methods of altering reservoir operations to provide cold water releases during the warm summer months, as well as reducing stream withdrawals during the dry season to bolster instream flows. A portfolio approach using several of these mitigation techniques may be useful for restoring instream flows for ESA-listed salmonids.

Strategic planning to prioritize restoration areas and improve the return on investment of restoration funding

As this study demonstrates, coordinated landscape-level strategic planning can target ecological conditions and regions that require urgent restoration as well as potentially conserve limited agency budgets for ecological restoration. The most likely future for state and federal agencies is one of declining budgets and cutbacks to assets and resources (Government Accountability Office [GAO], 2011). Furthermore, the current state of ESA-listed fish in the Columbia River basin demonstrates that funding alone, without adequate assessment, monitoring, and evaluation cannot reverse the course of declining populations. As a consequence, planners and managers require new skills and strategies to function in the current reality of dwindling funds and mandates for quantitative demonstrations of project success. This study does not provide information concerning potential return on investment of restoration dollars – an estimate of project success. Establishing such an estimate is a critical step in strategic planning for restoration. Fortunately, several frameworks exist for prioritizing projects in combination with estimates of project cost and project success (Thom *et al.*, 2004; Evans *et al.*, 2006). These methods can be used in combination with results of this study to prioritize restoration areas. By considering not only risks and threats, but also projected probability of restoration success, restoration practitioners can improve return on investment of restoration funding – bolstering biological conditions while maximizing the usefulness of limited funds.

Recommendation

Based on our findings, we provide short-term and long-term recommendations for instream flow restoration for ESA-listed salmonids. In the short term, we recommend the parties target regions that may be most flow limited during the summer months. Accordingly, we suggest that those concerned with instream flows for ESA-listed salmonids focus on the Yakima sub-basin during the first portion of summer, when Chinook salmon are migrating, and the Wenatchee sub-basin during the latter portion of summer, when steelhead are migrating. These time periods represent the greatest reductions in streamflow for each region.

In the long term, we recommend restoration planners also take action in the sub-basins that may be more resilient to changes in climate and agricultural water use (Okanogan and Methow). We aim to highlight the importance of not only funding the restoration of degraded ecosystems, but also bolstering and preserving ecosystem processes that may persist in the event that degraded ecosystems and their functionality cannot be recovered (Ostrom, 2007).

Although the physical act of restoring instream flows for salmonids is our primary recommendation, we also recommend that policy makers consider the types of policy changes explored in this study. Such potential changes to the existing instream flow-rules in the State of Washington may supplement the effectiveness of the suite of restoration and conservation activities that are currently in place to provide instream habitat for ESA-listed salmonids. Finally, we suggest that the tools and methods in this study be considered in the context of other regional planning tools used for selecting restoration areas, approximating restoration project success, and estimating the potential ecological return on investment of limited conservation and restoration funding dollars.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Climate and hydrology data.
Appdenix S2. Bias correction of naturalized VIC hydrology.
Appendix S3. Evaporative losses for the reservoir systems.
Appendix S4. Water Withdrawals and Management.

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