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Will future climate change increase the risk of violating minimum flow and maximum temperature thresholds below dams in the Pacific Northwest?

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ABSTRACT

Detecting and avoiding environmental thresholds that lead to catastrophic change in ecological communities is an important goal, and one that is especially challenging to address over broad geographic extents. Here, we conducted a regional-scale climate vulnerability assessment (RCVA) to quantify the risk of violating thermal and minimum-flow thresholds below reservoirs. Our analysis used hybrid (process-based and empirical) models of tailwater temperature and flow driven by 4-km downscaled CMIP5 climate projections. Downscaling employed a combination of process-based models, quantile mapping, and a non-linear 'reservoir' transform function. RCVA can be applied at regional scales without proprietary and data-intensive physical models of reservoir systems or ecological models of species that comprise tailwater communities. Using RCVA, we produced ensemble projections of risk and duration of extreme high-temperature or low-flow events below federal reservoirs in the Pacific Northwest (PNW), USA. Bayesian modeling of simulated results allowed us to evaluate differences between risk under a future and baseline scenario relative to model uncertainties and to quantify uncertainty in modeled risks. Based on assumptions that historical patterns of reservoir dynamics and operation will continue, and that regulatory thresholds will not change, the risk of thermal exceedance was projected to increase by an average of 0.27 and extend into late-spring and fall (average change in duration of 10.3 d). For flow, RCVA projected an increase of 0.07 in the average risk below-thresholds flows, with an average increase in duration of 4.6 d. Both results raise concerns that cold-water salmonids of the PNW will be at increased risk under a future climate scenario.

1. Introduction

As climate warms, maintaining adequate water and water quality for freshwater biota will become more difficult, especially for cold-water fishes (Battin et al., 2007; Beechie et al., 2013; McCullough et al., 2009; Roberts et al., 2013). A primary concern is that water temperatures will exceed the thermal tolerances of fishes and other freshwater taxa, reducing the amount of habitat with suitable temperatures (Eaton and Scheller, 1996; McCullough et al., 2009). On a regional scale, aquatic communities vary in their seasonal habitat requirements. Population models have been used to evaluate responses to temperature and flow changes associated

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with climate change (Jager et al., 1999), but results from species-specific models cannot easily be generalized to diverse aquatic communities on a regional scale. In the US, local water standards have already been assigned to water bodies by states, with guidance from the US Environmental Protection Agency, and an important purpose for these standards is to protect aquatic communities. Thresholds can be used to assess the future risk of violating locally-relevant water standards in river reaches ('tailwaters') below reservoirs on broad regional scales without detailed physical (e.g., bathymetry) or biological information.

The paradigm for understanding drought and water shortages is shifting from a supply-side to a demand-side view (Mann and Gleick, 2015). On the supply side, rain-on-snow events that cause earlier snowmelt and runoff could alter the timing of reservoir inflows, particularly for river sections with a relatively large portion of their catchments near the current mid-winter snow-line (Graves and Chang, 2007; Mote et al., 2003). Yet, scientists now recognize that the indirect effects of rising air temperatures on water demands (including those of fish, irrigators, and natural vegetation) are more important than the supply of inflows driven by changing precipitation patterns (Mann and Gleick, 2015). Climate changes that alter the amount, timing, and temperatures of river flow can potentially intensify stress among competing water demands including municipal water use, irrigation, environmental flows, and hydropower generation. This is particularly true in the Pacific Northwest (PNW) (Lanini et al., 2014; Lee et al., 2009). These stresses are not limited to water availability. Future changes in climate could significantly impair habitat quality for migratory salmon and steelhead (*Oncorhynchus mykiss*) and resident salmonids (Jonsson et al., 2003; Wade et al., 2013).

Streams in the US are projected to show increased water temperatures as they track air temperatures (Kaushal et al., 2010). Historical trends have been detected. For example, Bartholow (2005) reported a rise of 0.5 °C/decade since the 1960s in the lower Klamath River, California. A warming trend has also been detected in the Lower Columbia River (Army, 2013). Crozier et al. (2011) report a rise in mean July water temperature from 16.9 °C in 1950 to 20.9 °C in 2005 below Bonneville Dam. The sequential addition of reservoirs in the Columbia River over time may have contributed to this trend, but long-term historical water-temperatures in unregulated gauges in the PNW also track the increasing historical trend in air temperatures (Isaak et al., 2012).

Thermal effects below reservoirs may differ from unregulated streams, and this has received relatively little attention at regional scales. Reservoirs can have complex effects on downstream thermal regimes in tailwaters, but in general thermal regimes are both shifted and moderated. A 'cold-block' of stored water develops during winter and downstream temperatures are therefore influenced by reservoir stratification. Reservoirs in Canada impounding more than 10% of median annual runoff reduced variation in downstream temperatures at seasonal, daily, and sub-daily time scales (Maheu et al., 2016). Regulation also increased fall temperatures (Maheu et al., 2016).

Managing risk will be more difficult as we encounter uncertain future climate conditions (Dale et al., 2018). Although freshwater ecosystems are considered at risk, infrastructure (e.g., dams, reservoirs) may be deployed in a manner that helps to manage the risk of irreversible loss of aquatic species. Because species' vulnerability to climate change are usually controlled by threshold tolerances to environmental conditions, threshold-based management is useful (Liu et al., 2015).

Climate change vulnerability assessment is a form of risk assessment used to evaluate the impacts of climate stress on specific endpoints valued by society (El-Zein and Tonmoy, 2015; Gaichas et al., 2014; Ghile et al., 2014; Higgins and Steinbuck, 2014). We developed a Regional Climate Vulnerability Assessment (RCVA) framework for regional-scale assessment of current and future risk of violating water standards in tailwaters below hydropower reservoirs. Our framework integrates several attractive features needed to make regional-scale assessments feasible. First, we assume that site-specific water standards (Coutant, 1999) adequately represent the local habitat needs of aquatic communities below reservoirs. Second, we used a hybrid modeling approach to integrate process-based with empirical models to project future changes in water temperature and flow. Climate projections from an ensemble of ten dynamically downscaled climate models (models detail is shown in Supplementary Information (SI) Table S.1) in the CMIP5 experiment (IPCC (Intergovernmental Panel on Climate Change), 2013) was bias corrected at 4-km resolution before its use as forcing in the Variable Infiltration Capacity (VIC) model to represent regional surface hydrology (Naz et al., 2016). The experimental details and future projections in 10-member 18-km dynamically downscaled ensemble are described in Ashfaq et al. (2016) and the methodology for bias correction is described in Ashfaq et al. (2010). The hybrid model incorporates this downscaled hydrology with an empirical correction to represent the local effects of reservoirs as they shift the timing and magnitude of seasonal thermal regimes downstream. In a last step, we characterized uncertainty to appropriately account for ensemble and regional variation. We demonstrated the approach for federal reservoirs in the PNW region of the US as part of an assessment of climate impacts on federal hydropower (Kao et al., 2016). At each step, the RCVA performed well against historical data and allowed us to characterize seasonal patterns in anticipated risk increases to evaluate when and where adaptive management will be most beneficial. We propose using RCVA as a threshold-based approach to managing climate risk in freshwater ecosystems (Liu et al., 2015) at scales ranging from large river basins to continental.

2. Methods

The goal of RCVA (Fig. 1) is to compare future and baseline risk of extreme events under climate change. We achieved this goal 1) by estimating risk of extreme events under current and future scenarios for each case (week, period, gage, GCM) and 2) by developing Bayesian seasonal risk models to summarize results. The main advantages of this approach are the ability to assess risk at large spatial scales and characterize uncertainty. These are summarized, along with disadvantages, in Table 1.

We evaluated the risk of violating water standards in a projected future period relative to a current baseline. Our analysis is motivated by the need to assess risk to aquatic biota in tailwaters. In general, extreme values (i.e., high temperatures and low flows) are of the greatest interest when evaluating vulnerability of habitat supporting aquatic life (Magnuson, 2010). Two types of water standards that are regulated to protect aquatic life are stream temperature and flow. Here, we define 'risk' as the fraction of replicate