(Graves a [redacted] deman [redacted] cha [redacted] fl [redacted] to r [redacted] threshol [redacted] ts of climate stress o [redacted] Higgins and Steinbuck, 20 [redacted] ssessment of current and future r [redacted] grates several attractive features neede [redacted] rds (Coutant, 1999) adequately represent th [redacted] id modeling approach to integrate process-based [redacted] w. Climate projections from an ensemble of ten dy- [redacted] tary Information (SI) Table S.1) in the CMIP5 experiment [redacted] orrected at 4-km resolution before its use as forcing in the [redacted] ace hydrology (Naz et al., 2016). The experimental details and [redacted] ensemble are described in Ashfaq et al. (2016) and the methodology [redacted] ybrid model incorporates this downscaled hydrology with an empirical [redacted] ey shift the timing and magnitude of seasonal thermal regimes downstream. [redacted] propriately account for ensemble and regional variation. We demonstrated the [redacted] on of the US as part of an assessment of climate impacts on federal hydropower (Kao [redacted] ormed well against historical data and allowed us to characterize seasonal patterns in [redacted] hen and where adaptive management will be most beneficial. We propose using RCVA as a [redacted] ging climate risk in freshwater ecosystems (Liu et al., 2015) at scales ranging from large river [redacted]

[redacted] of RCVA (Fig. 1) is to compare future and baseline risk of extreme events under climate change. We achieved this goal 1) [redacted] ating risk of extreme events under current and future scenarios for each case (week, period, gage, GCM) and 2) by developing [redacted] yesian 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 [redacted] Box 2 describes [redacted] projections. [redacted] data, durations of [redacted] for flow except that the [redacted]

[redacted] RCVA framework in Fig. 1 with Bayesian modeling of [redacted] rivers.

[redacted]	[redacted]	Disadvantages
[redacted]	[redacted] and	Requires monitoring data and regulatory thresholds for flow and water temperature Assumes reservoir operations and water quality and quantity regulations will follow historical patterns into the future
[redacted]	[redacted] the whole ensemble, not from [redacted]	Although the equilibrium temperature model (EWN) accounts for solar radiation and other meteorological variables, there is no input from ground water or sediments-water heat exchanges that may affect heat budgets.
[redacted]	[redacted] Inference can be either to group (i.e., site, [redacted] universe (region, GCM ensemble).	Bayesian post-modeling assumes a parametric model, which reduces the predictive skill relative to the hybrid projections by week and site.
[redacted]	[redacted] model uncertainties are characterized through prediction [redacted] posterior risk distributions and credible intervals or posterior distributions of parameters. Thresholds can be defined by using a logistic model for risk, such as the one used here.	Bayesian models take much longer to fit than their frequentist counterparts.

simulated years projected to experience an extreme event for a given GCM and site. We define ‘extreme event’ as water temperature above a week-and site-specific upper temperature threshold or flow below a low-flow threshold.

Our goal was to quantify the risk of failing to meet environmental thresholds in tailwater reaches below reservoirs under a baseline and future scenario. The first step was to develop empirical models for historical water temperature and flow data from below. [redacted]

2.1. [redacted]

[redacted] aq [redacted]
[redacted] re (*Tw*) [redacted]
[redacted] el included air [redacted]

[redacted] aseflow simulations (Naz et al., 2016) [redacted]
[redacted] ulated by the semi-distributed VIC hydrolog [redacted]
[redacted] network using a linear reservoir model based on [redacted]
[redacted] against gaged historical flows (Fig. 2d) as described

[redacted] ederal hydropower projects by comparing historical and si-
[redacted] ng R^2 and Nash-Sutcliffe Efficiencies (*NSE)* at daily and monthly
[redacted] e PNW was better than that in most other US regions. Both *NSE* and
[redacted] were above 0.5 (Naz et al., 2018; Naz et al., 2016). Our risk assessment
[redacted] eekly minimums of daily average flows (MWAQ).

[redacted] the temperature at which heat fluxes between air and water are in balance. We simulated
[redacted] sely approximates the temperature of unregulated streams (Edinger et al., 1968; Null et al.,
[redacted] al-scale studies such as this one, an EWT model is typically used because heat flux at the water
[redacted] air temperature and other meteorological variables simulated by mesoscale weather models and
[redacted] .g., those used in dynamical downscaling) without local hydrologic information. Local data obtained across
[redacted] are rarely available and, when available, are highly uncertain (Null et al., 2013).
[redacted] am temperature is more-closely approximated at a coarser temporal resolution (e.g., weekly or 7-d moving average)
[redacted] hort-term lags and fluctuations from day-to-day variations in air temperature and solar radiation (Perry et al., 2012).
[redacted] more, regulatory thresholds are usually maximum weekly daily average temperature (MWAT). Therefore, our risk assessment
[redacted] es weekly maximums of EWT, *Tw*.

2.3. Baseline correction

Here, we used a combination of QM (Ashfaq et al., 2010) and an empirical transform function to account for the effect of a reservoir (and other influences) that result in deviations between stream temperature and EWT and between modeled and measured

[redacted]

[redacted] outing of streamflow, b) an example of delineat [redacted] mette River, (c) a schematic of the VIC routing mode [redacted] Naz et al. (2018).

[redacted] ected by using QM and an empirical transform) was used to [redacted] ents (those exceeding or below an environmental threshold) and QM [redacted] the distributions are of interest (Smith et al., 2014). QM has also been [redacted] evaluating higher moments (Lafon et al., 2013). Mapping is between the [redacted] second step, a 'reservoir transform' relates the control to data. Values of both [redacted] replicate simulated years. For a baseline year's value with rank q, we mapped the [redacted] simulation.

[redacted] quantile-mapped projections for the baseline period, $y^{(b)}(t)$ (Eq. (1); Fig. 1, box 3c). We applied [redacted] pirical correction, C_k(t), relating weekly summaries of USGS observed values, $x^{(o)}$, with simulated [redacted], for each outflow gauge, k, week, t, and month of the year, $M(t)$ (Eq. (1)).

$$[redacted] (t) + C_k(t), 0\}$$ (1)

[redacted] rms used to do this represent differences between a 1981–2012 VIC-model control run driven by historical meteor- [redacted] weekly summaries of flow and temperature measured at stream gages (Fig. 1, box 1). For temperature, models specifically [redacted] sent the attenuation and seasonal lag caused by the presence of a reservoir under the assumption that historical operations will continue as they have in the past. This assumes that the temperature changes from reservoir inflow to outflow will continue to follow historical patterns.

2.3.1. *Flow*

For streamflow, values (cubic meters per second, cms) were log-transformed. The correction consisted of subtracting the

2.3.2 [redacted]

[redacted] 'replicate' years with extreme events (e.g., threshold ex- [redacted] period (current or future) (Table S.2). We used the full ensemble [redacted] among the ten models from the CMIP5 ensemble (Table S.1). In [redacted] differences (future – baseline risk), as described by Kuss (2015), to measure [redacted] threshold values of water temperature (or falling below minimum flows). [redacted] current climate conditions is 0.5, then a +0.10 change in risk indicates that extreme [redacted] of every 10 years in future, or 6 out of 10 years. Note that we opted not to use relative [redacted] statistical drawbacks when used to describe rare events (Flueck and Holland, 1976; Kuss, [redacted]

[redacted] thresholds (X^* in Fig. 1. box 5) agreed upon by aquatic ecologists and other stakeholders to [redacted]. Each river reach has an upper temperature threshold associated with a reach-specific designated [redacted] criteria reflected differences in standards among states and designated beneficial uses, which reflect [redacted] and natural thermal conditions. The process by which we determined numeric thresholds first involved [redacted] reaches on state-provided geospatial data describing the designated use of each water body (Fig. 3). The designated [redacted] use was then identified in associated documents listing thermal criteria (Table S.2).

In the PNW, environmental thresholds usually reflect the presence of species of concern. For some tailwaters, migratory species listed under the U.S. Endangered Species Act (ESA) are present only during certain periods. In the Columbia River system, these requirements (NOAA Fisheries, 2014) are incorporated into state-designated uses, leading to seasonally varying standards. A low thermal standard is required year-round for resident and adfluvial bull trout (*Salvelinus confluentus*) and other spawning salmonids in Idaho (Upper Columbia River and Interior Snake Rivers), and for tailwaters with access to the ocean that support migratory salmon and steelhead spawning in the Willamette River, Oregon and other coastal rivers (Fig. 3). Mainstem Lower Snake and Columbia

[redacted]

[redacted] rature) at USGS gages below [redacted] ated beneficial use during some par[redacted] unities and/or serve as migration corrido[redacted] stal Oregon with a different threshold during [redacted]

[redacted] ey do not support spawning of ESA-listed salmonids. [redacted] g. 3).

[redacted] armest 7-d period (MWAT) as a metric because average daily [redacted] e temperatures were (in rare situations where average daily tem- [redacted] of minimum and maximum daily values). MWAT is used as the thermal [redacted] have significant advantages and may be adopted in future (McCullough, [redacted] (e.g., maximum daily average (MDAT), maximum daily maximum (MDMT), [redacted] weekly maxima, for warmest 7-d period]) to MWAT (Essig et al., 2003).

[redacted] rs are more varied and complex than thermal criteria. For privately-owned hydropower [redacted] anticipated hydrologic-year type, which is estimated based on the previous year's snowpack [redacted] uture inflows. In some states (e.g., Idaho), reservoirs may not have legal obligations to maintain [redacted] curves exist for most federal reservoirs, these are not easily accessible and may not be reflected in [redacted] governing the timing of reservoir releases are complex, involving prior water rights for irrigation and [redacted] gical Opinions under the Endangered Species Act, and authorizing legislation for flood control. Given this [redacted] torical estimate provides a workable solution. We estimated MWAQ thresholds from *Qw* below each reservoir during [redacted] period.

[redacted] *Duration modeling of species-specific risk*

The focus of this study is on risk associated with violating regulatory thresholds, regardless of duration. However, the duration of extreme events is important when assessing ecological risk. For example, the stressful impacts of high temperatures on salmonids increase with duration. In streams where diurnal (or other) fluctuations in temperature limit exposures, individuals are able to recover and therefore tolerate higher temperatures (Farless and Brewer, 2017). By contrast, longer exposures increase risk of [redacted]

on 60-d t[redacted]
assum[redacted]
fun[redacted]

[redacted] (5)

[redacted]an approach with the R-package, 'stan.glmer' (Stan [redacted]ommended by Gelman et al. (2008) as follows. We assigned [redacted]n, df = 7 and scale = 10. For all parameters that did not vary by [redacted]prior. For the random effects (GCM-specific intercepts), we specified [redacted] scale = 1 on parameters of the covariance matrix. Two independent [redacted]iltonian Markov Chain Monte Carlo (MCMC). We simulated each chain for [redacted]ons and determined that two MCMC chains converged (see SI). Uncertainty was [redacted]led (temporally smoothed) risk based on 3000 draws of one chain for each variable. [redacted]1) by comparing overlap among chains (Fig. S.1), 2) evaluating overlap between final [redacted] ensuring that *Rhat* statistics comparing chains were within 0.1 of 1 (Sorensen et al., 2016). [redacted]ution of the coefficient *Is.mid* [*I(period)* in Eq. (5)], which measures the effect of climate period [redacted]k. When this distribution does not overlap zero, the climate signal is strong enough to be detected [redacted]on and other sources of uncertainty in RCVA risk estimates. We also produced ridge plots to visualize the [redacted]s of risk by month (averaged over site, GCM, and week).

[redacted]. *Model-data comparisons*

To evaluate the effectiveness of using empirical correction, we compared hybrid simulated *Tw* and *Qw* for the control run (Daymet drivers, 1966 to 2004) against corresponding measured values based on data from USGS gauges (Fig. 1, box 1c and d). We use two measures of goodness of fit for model predictions. The root-mean-square-error (RMSE) measures accuracy as the magnitude of residual error in the original units (e.g., °C or log-cms) and is essentially a measure of bias. Correlation measures the strength of the [redacted]atures (Table 2[redacted] the process-based E[redacted]ermal lag of more than thre[redacted]rmal lag (Fig. 5).

[redacted]gher under the future scenario. An aggregated rose [redacted] MWAT thresholds was highest between spring and fall, [redacted] several sites risk (frequency of exceedance events) in early [redacted]ig. S.3A).

[redacted]torical thresholds will change for weekly minimum average flow. [redacted]cific rose diagrams showing differences among sites are presented in Fig. [redacted]hold flows showed a pattern of higher risk from fall to summer and lower risk [redacted]des of change in risk associated with historical minimum-flow thresholds were [redacted]ature criteria (mean 0.07 versus 0.27).

[redacted]lated results. The average change in the duration of extreme events for below-threshold [redacted]e for high temperature exceedances was 10.3 d. The geographic distributions of changes in [redacted]rations increased least in the lower Columbia River basin and two sites in Montana. Durations of [redacted] to increase in the Upper Columbia, Upper Snake, and Willamette Basins. Sites with notable increases

[redacted] parameters for Eq. (2) quantify seasonal shifts in temperature associated with reservoir and other local influences leading to [redacted]seasonal patterns between EWT simulated temperatures (control simulations) and measured tailwater temperatures. Gage specific [redacted]n be obtained from the corresponding author.

[redacted]iver basin	m (°C)	A	Φ	δ_m	δ_A	δ_Φ
Mountain/Upper Columbia	9.47	12.40	14.74	−2.06	−6.60	5.41
Interior Snake	12.90	14.90	15.00	−3.90	−7.13	3.87
Columbia	14.05	13.82	14.29	−0.88	−4.16	3.28
Coastal	12.99	11.67	14.62	−3.96	−7.21	4.52

[redacted] weekly average flow, [redacted]
[redacted] wedges indicate average [redacted]

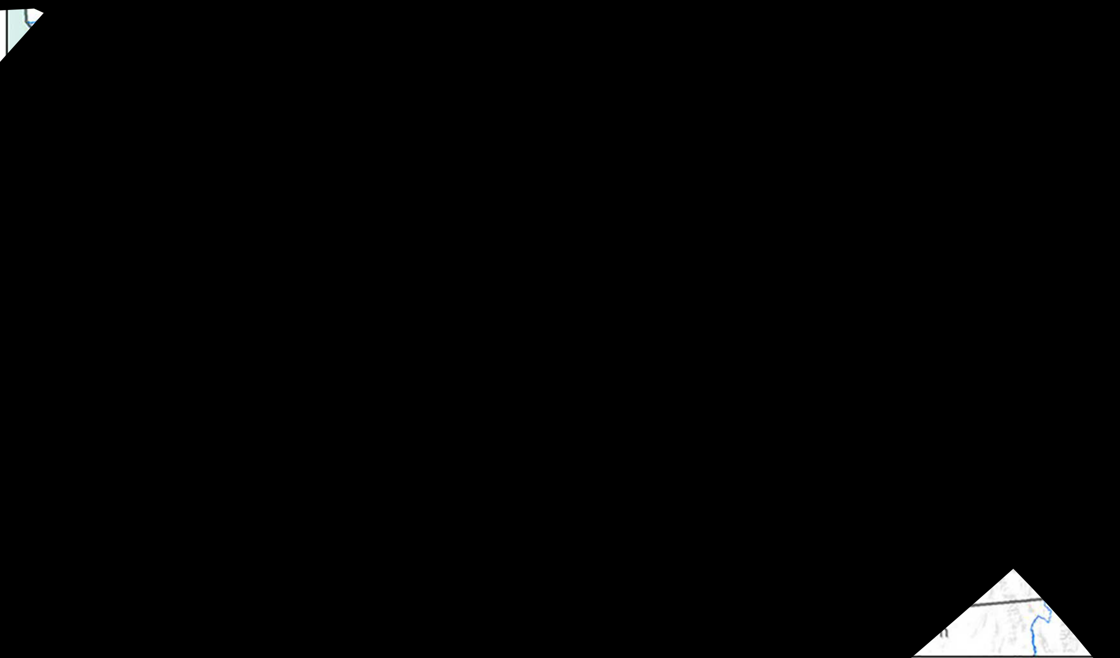
[redacted] River (14145500) and two tributaries of [redacted]

[redacted] effect, and with GCM as a random nested effect or excluded (due to [redacted] as a fixed effect and GCM as a random effect produced the lowest AIC [redacted] 124,165 (random, crossed site and GCM model), and 123,333 (random [redacted] (site as fixed effect) was adopted for flow.

[redacted] for assessing whether the effects of covariates and the magnitudes of projected changes in risk [redacted] uncertainties, as represented by our Bayesian hierarchical model. Convergence was demonstrated [redacted] chains (Fig. S.1) and the posterior distribution of parameters associated with them (SI Fig. S.3). We [redacted] near one for all parameters estimated indicating that the chains converged in fitting the seasonal risk models [redacted] and flow. Having satisfied ourselves that the chains have converged, we reported parameter estimates and [redacted] for all parameters (Tables S.3 and S.4) derived from posteriors from two chains.

[redacted] for a detectable change in risk between the baseline and future period. The lack of overlap with zero of the posterior [redacted] of *Is.mid* gives us confidence that the risk of extreme events will increase for water temperature (Fig. 8A) and for flow (Fig. 8B).

In addition to providing credible intervals on parameters, the Bayesian model produced posterior distributions that approximate uncertainty associated with RCVA risk projections. An example of series of posteriors by month is shown in Fig. 9. The posterior distributions for temperature exceedances were bimodal from spring to fall (Fig. 9A). Risk of below-threshold flows were generally lower in magnitude (Fig. 9B).



[redacted] eks) that weekly maximum o [redacted] m weekly average daily flow thre [redacted]

[redacted] here thresholds are in danger of being crossed (Wu and [redacted] ury future. The RCVA framework described here can be used [redacted] es (Liu et al., 2015). Here, we evaluated seasonal and spatial [redacted] most at risk of being violated under a future climate scenario. We [redacted] g and fall, with the maximum monthly averages of weekly changes for [redacted] the future scenario, we found that risk and duration of events exceeding [redacted] ers that support salmonid spawning and in tributaries of the Middle Snake River [redacted]

[redacted] lower flows and warmer stream temperatures may coincide during summer (Beechie [redacted] ., 2012). This is a concern because episodes of warm temperature and drought would elevate [redacted] in et al., 2007; Wu et al., 2012). Here, tailwaters were projected to experience co-occurring risks [redacted] projected changes in risk of low-flow violations were not as large as those projected for temperature. [redacted] than 0.05 for flow (Fig. S.3B) and the maximum increase in duration of low-flow events was ~eight days [redacted]

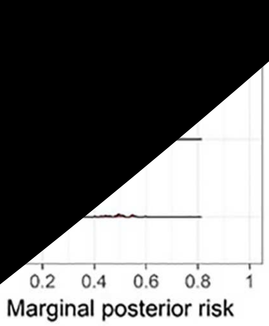
[redacted] eases to meet thermal requirements of cold-water biota in summer (the season for which we projected the highest [redacted] e with times when human demand for hydropower generation of electricity for cooling is high. This demand is likely to [redacted] the same pattern projected by our increase in risk by extending into late spring and fall. However, timing the release of the [redacted] d-water block to lower temperatures in fall might present a significant future challenge (Marce et al., 2010; Matthews et al., 2015). Where water storage is limited, winter releases may be needed to meet flood-control requirements (Lanini et al., 2014; Raymondi et al., 2013). As a result, less stored water would be available to protect fish in spring and fall (Miles et al., 2000; Mote et al., 2003; Payne et al., 2004).

Increased risks of elevated temperatures are likely to have high biological significance for ESA-listed salmonids. Not only do high [redacted] that spawn in [redacted] salmon (*O. nerka*), [redacted] by females (Ferre et al., [redacted] of adult sockeye salmon, [redacted]

[redacted] bull trout. Bull trout have the lowest [redacted] by exposure to water temperatures above 20 °C [redacted] or to areas with groundwater influence, seeking [redacted] of bull trout are rarely found where summer tem- [redacted] River basin, Idaho, simulated future temperature-exceedance [redacted] period (Fig. 9). In Idaho tailwaters that support bull trout [redacted] retreat to cooler headwaters (Eby et al., 2014; Rieman et al., 2007).

[redacted] that measures should be considered to reduce risk to aquatic life in the PNW. [redacted] now address threats posed by climate change (McClure et al., 2013; NOAA Fisheries, 2014). [redacted] to thermal refuge is one logical priority. As a general rule, barriers to thermal mixing (in- [redacted] thermal heterogeneity and cold-water refuges (Jager et al., 1999; McCullough et al., 2009). However, [redacted] be avoided because they prevent fishes and other species from tracking suitable habitat. Dams located in [redacted] additional upstream storage (to replace snowpack) without impeding fish movements (Jager et al., 2015). [redacted] in the way hydrosystems can be managed to avoid risks identified here. Although the basic seasonal [redacted] reservoir operation is unlikely to change (e.g., winter drawdown), regulation to moderate untimely low flows and shifts [redacted] of pulse or augmentation flows might be needed to moderate temperatures during migration (Buccola et al., 2013; Poff [redacted] 2016). In tailwaters, temperature-control features at dams, such as selective-depth reservoir withdrawal and cooling, can be used to avoid downstream violations in water quality during critical times (Buccola et al., 2013). Off-channel mitigation involving watershed management might also be important. For example, actions that promote groundwater recharge, riparian zones that provide shading to headwater streams (Wu and Skelton-Groth, 2002), and management of wildfires (Isaak et al., 2010; Rosenberger et al., 2015) are all relevant to maintaining suitable instream habitat for spawning salmonids. Hatcheries, which produce a significant fraction of salmonids, use water sources that may also be impacted by rising temperatures (Hanson and Ostrand, 2011).

[redacted]



[redacted]eding weekly temperature thresholds (MWAT, °C) and (B) falling below [redacted]ons describe variation among replicates in average risk for sites, GCMs and [redacted]

[redacted]proving or extending RCVA. These include 1) refining the 'reservoir' model, 2) assembling [redacted]m flow requirements or standards, and 3) bridging from assessments based on regulatory [redacted]s-specific risks through duration modeling (illustrated below).

[redacted]CVA framework presented here is the ability to produce well-founded climate-risk projections at large [redacted]omplex integrated physical models of reservoir systems that require proprietary information or information [redacted]onal scale from US agencies such as the US Corps of Engineers. The approach here assumed that the reservoir [redacted]mperature would not change under future climate due to in-reservoir processes or changes in operation. It may not be [redacted]e to assume a continued pattern of seasonal releases, which are constrained by legal requirements. However, further [redacted]ments to the model, including perhaps a more mechanistic representation, would be needed to evaluate scenarios that involve [redacted]ture changes in reservoir stratification or operation, especially when near thresholds. This might be accomplished by summarizing responses simulated by process-based models to operations for a taxonomy of hypothetical reservoirs with attributes such as upstream storage volume, type of operation (Jager and Bevelhimer, 2007; McManamay et al., 2016), or configuration (elevation) of dam-release infrastructure. While our results are informative, analysis with more process-based modeling of the reservoir physics and operations will be required to evaluate the assumptions we have made here.

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[redacted]ergy Efficiency and [redacted]tory (ORNL), under the lea[redacted]ntract DE-AC05-00OR22725. T[redacted]ges that the US Government retains a [redacted]ed form of this manuscript, or allow others [redacted]ic access to these results of federally sponsored[redacted]wnloads/doe-public-access-plan). Dr. Shih-Chieh Kao [redacted]te the statistical advice of Dr. Nels Johnson (National [redacted] anonymous reviewers who provided excellent suggestions [redacted]

[redacted] can be found, in the online version, at https://doi.org/10.1016/j.crm.2018.07.

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