Thermal extremes in regulated river systems under climate change: an application to the southeastern U.S. rivers

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Abstract
High river temperatures, or ‘thermal extremes’, can cause fish mortality and thermoelectric powerplant derating. Under climate change, projected higher air temperature and stronger surface energy fluxes will lead to increased water temperatures, exacerbating thermal extremes. However, cold hypolimnetic releases from thermally stratified reservoirs can depress tailwater temperatures and therefore alleviate thermal extremes. Thermal extremes are more harmful when they coincide with low flows, which we refer to as ‘hydrologic hot-dry events’. To assess multi-sectoral impacts of climate change over large regions, we evaluate thermal events according to three impact attributes: duration (D), intensity (I), and severity (S). We apply an established model framework to simulate streamflow and stream temperature over the southeastern US regulated river system. We quantify climate change impacts (by the 2080s under RCP8.5) by comparing historical and future periods and quantify regulation impacts by comparing unregulated and regulated model setups. We find that climate change will exacerbate thermal extremes (all three metrics) in both unregulated and regulated model setups, albeit less in the regulated setup. Thermal mitigation from reservoir regulation will be stronger under climate change, decreasing the three metrics compared to the unregulated case. Even so, thermal extremes in the regulated setup will still be more severe under climate change, and only 12.2%, 19.7%, and 26.0% of D, I, and S can be mitigated by reservoirs. Despite stronger reservoir stratification, the number of regulated river segments that experience simultaneous high temperature and low flow events (hydrologic hot-dry events) will increase by 21.4% by the 2080s under RCP8.5. These events will have a median annual duration of 10.3 day/year, over 10 times the historical value.

1. Introduction
High river temperatures have negative impacts on aquatic ecosystems and power sectors (Sauter et al 2001, Koch & Vogele, 2009, Ketabchy et al 2018). Excessive heat reduces dissolved oxygen and increases metabolism of cool- and cold-water fish, causing them to burn essential energy at a faster rate (Coutant 1990, Breau et al 2007) and results in death when river temperature exceeds their physiological limits (Eaton et al 1995). Furthermore, high river temperatures can disrupt the operations of thermoelectric power plants by (1) lowering power plant operating efficiency and maximum generation capacity and (2) causing power curtailment or even shutdown to avoid violating environmental regulations (Liu et al 2017). McCall et al (2016) assessed that 27 of 36 US power plant curtailments during 2000–2015 resulted from high river temperatures. Studies have shown that the projected climate change trend of increasing global river temperatures will impose greater thermal stress (Eaton and Scheller 1996, van Vliet et al 2011, 2013). In this study we focus on extreme high river temperature events in regulated river systems, referred to as ‘thermal extremes’. Cold hypolimnetic outflow from reservoirs, i.e. releases from deeper reservoir layers, can alleviate thermal extremes in regulated river systems. During warm seasons, deep reservoirs with long residence times are thermally stratified and cold hypolim-
ngetic releases depress downstream river temperature (Chapra 1997). As a result, peak river temperature and the annual temperature range decrease at tailwater locations, suppressing the occurrence of thermal extremes (Cheng et al 2020). As almost all global major river systems are highly regulated, quantifying the mitigation impacts due to reservoir regulation is valuable for regional risk management.

The detrimental impacts of thermal extremes will be exacerbated when they coincide with low flows. Besides intense thermal stress, concurrent low flow can expose the shallow river system to strong insolation, elevate solute concentrations, and constrain fish mobility, preventing them from seeking more favorable shelters (Matthews and Zimmerman 1990, Bradford and Heinonen 2008). Under these circumstances, thermoelectric power plants may also be unable to generate at full capacity due to a lack of sufficient cooling water (Rutberg 2012, van Vliet et al 2012).

We focus on the southeastern United States (SEUS), which is a global hotspot of freshwater biodiversity. Two-thirds of US fish species exist here, and these fish are vulnerable to changes in river thermal regimes (Elkins et al 2016). Historical river temperatures in the region already approach the limit set by environmental regulations (Madden et al 2013, Liu et al 2017, Cheng et al 2020). High air temperatures in the region result in a high electricity demand for air conditioning (Auffhammer et al 2017). These conditions often coincide with river thermal extremes and low flows, thus limiting the cooling potential for power plants that depend on river water. As a result, the electricity sector in the SEUS may be exposed to higher risks under climate change (Kimmell and Veil 2009).

The objective of this study is to characterize extreme thermal events with attributes that can support risk management, i.e. duration-intensity-severity, and evaluate climate change impacts on thermal extreme events in a large, regulated river system. This characterization is standard in drought research but has not been applied to fluvial thermal events due to limited capability in simulating river temperatures for complicated river-reservoir systems. A recent innovation of a regional-scale spatially-distributed modeling framework enables us to directly quantify the impact of reservoir regulation on thermal extremes (Cheng et al 2020). We use this framework to examine the impact of climate change on thermal extremes and on concurrent high stream temperature, low flow events, which we term hydrologic hot-dry events. This work can be used to inform existing multi-sectoral impact assessments as well as adaptation planning at relevant scales, especially for the freshwater fisheries and power sectors.

2. Methods

2.1. Study domain and reservoir information

Our study domain (figure 1(a)) consists of the SEUS and contains 271 major reservoirs. In our model setup (see section 2.2) 21% of river segments are located downstream of these 271 reservoirs and therefore are subject to regulation. This includes all river segments in large rivers, those with average annual flow ($Q_{a}$) greater than 200 m$^3$ s$^{-1}$ (figure 1(b)). About half the reservoirs are located in small streams, for which $Q_{a}$ is less than 10 m$^3$ s$^{-1}$. The remaining 79% of river segments are located upstream of one of these reservoirs.

Reservoir outflow and residence times determine the extent to which reservoirs impact tailwater temperatures. Reservoirs with larger outflow influence temperature farther downstream because 1) their outflows are less affected by mixing of flows from smaller tributaries and 2) larger rivers respond less rapidly to surface energy fluxes because they generally have a smaller surface area to volume ratio. Reservoirs with longer residence times have stronger seasonal thermal stratification and therefore have stronger cooling impacts on downstream river temperatures. Reservoir residence time generally decreases with increasing river sizes (figure 1(c)). In the following analysis only grid cells influenced by reservoir regulation (black segments in figure 1(a)) will be analyzed.

2.2. Model setup

In this study, we used the physically-based modeling framework as applied in Cheng et al (2020) to simulate streamflow and stream temperature for the entire river network of the SEUS, considering reservoir regulation and thermal stratification. This model framework includes a spatially distributed hydrological model (Variable Infiltration Capacity model or VIC, Liang et al 1994, Hamman et al 2018), a large-scale river routing model (Model for Scale Adaptive River Transport or MOSART, Li et al 2013) that is dynamically coupled with a water management model (WM, Voisin et al 2013), and a distributed river temperature model (River Basin Model or RBM, Yearsley 2009, 2012). RBM includes a two-layer thermal stratification module (2L, Niemeyer et al 2018).

This model framework was run at a daily time step with a latitude-longitude resolution of 1/8 degree (~12 km). For the historical period (1980–2009), we used gridded meteorological forcing data, gridMET (Abatzoglou 2013), as input into the model chain. The future period spans from 2070–2099 and is referred to as the 2080s. For the 2080s, we used an ensemble of meteorological forcing data from 20 global climate models (GCMs; table S1) based on a high carbon emission scenario (RCP8.5) from the Coupled Model Intercomparison Project, Phase 5 (CMIP5; Taylor et al 2011), downscaled using the
Multivariate Constructed Analog (MACA; Abatzoglou and Brown 2012) method. We selected RCP8.5 because it is the highest carbon emission scenario and represents the greatest warming among RCPs. To quantify the impacts of reservoir regulation, we conducted an experiment in which we simulated streamflow and stream temperature for both regulated and unregulated model setups. The baseline (unregulated) setup is one in which there are no impoundments in the river system. In the regulated setup, we explicitly considered reservoir regulation, thermal stratification, and water withdrawal. To isolate the impacts of climate change in a regulated system, reservoir regulations remain the same for both historical and future periods. Because release information for individual reservoirs is generally lacking, we assume that all reservoirs release water from the hypolimnion, as in Cheng et al (2020). Consequently, our results provide a lower bound estimate of reservoir release temperatures and thus an upper bound estimate of the extent to which reservoir regulation can alleviate thermal extremes. For more details concerning the model configuration, evaluation and errors, we refer to Cheng et al (2020). A summary of model performance for the historic period is provided in the supporting information (Text S1), which is available online at stacks.iop.org/ERL/15/094012/mmedia.

2.3. Three metrics to evaluate thermal extremes
We define thermal extreme events as periods when river temperatures exceed a threshold temperature \( T_{\text{thres}} \). We used three metrics to characterize thermal extreme events: duration, intensity and severity, each explained below. These three metrics, when combined, provide a comprehensive characterization to support multi-sectoral impact assessments and adaptation strategies.

Duration, \( D \) (day/period), measures the length of thermal extreme events within a defined period (e.g. per month). Extreme event durations are compared to the maximum lengths of bearable stressful periods for fish or power plants. While limited durations may be acceptable, durations that are too long can result in fish mortality and power plant shutdowns. For a defined period of time (from \( t_{\text{start}} \) to \( t_{\text{end}} \) in figure 2(a)), duration is the total time during which the river temperature exceeds \( T_{\text{thres}} \) as in

\[
D = \sum_{i=1}^{n} (t_{i\text{e}} - t_{i\text{ts}})
\]

where \( t_{i\text{ts}} \) and \( t_{i\text{e}} \) represent the starting and ending time, respectively, of intervals during which the river temperature exceeds \( T_{\text{thres}} \) and \( n \) represents the number of periods.

Intensity, \( I \) (°C), is the maximum excursion of the stream temperature above \( T_{\text{thres}} \) during a specific interval,

\[
I = \begin{cases} 
T_{\max} - T_{\text{thres}} & \text{if } T_{\max} > T_{\text{thres}} \\
0 & \text{if } T_{\max} \leq T_{\text{thres}}
\end{cases}
\]

where \( T_{\max} \) is the maximum river temperature within the defined time period. Intensity is zero if the river temperature never exceeds \( T_{\text{thres}} \). When intensity reaches a certain value, it may lead to immediate fish mortality or complete shutdown of power plants if environmental regulations are enforced.

Severity, \( S \) (°C day/period), quantifies the cumulative impacts of thermal extremes and is widely used in fish models (Trudgill et al 2005, Chezik et al 2014) and power curtailment models (McDermott and Nilsen 2014). Severity is the time integrated value of the river temperature above \( T_{\text{thres}} \) within a defined period (red highlighted area in figure 2(a)).

Defining a single \( T_{\text{thres}} \) for the entire region is infeasible as a result of the diversity of fish species and the different power plant regulations in an area.

Figure 1. (a) Spatial map of the study’s regulated river system. Panel (b) displays the number of grid cells at different river sizes, with the bars divided according to grid cells influenced by regulation (black) and unregulated grid cells (light blue). Numbers on top of each column denote number of regulated grid cells (left) and its percentage of total grid cells under each river size. The color scheme of panel (b) is also used to label streams in the domain map. Panels (c) and (d) show the number of reservoirs and distribution of residence time at different river sizes.
as large as our study region. We use the simulations for the historical period to define a spatially-varying \( T_{\text{thres}} \) with a separate value for each model grid cell. We selected the maximum weekly average stream temperature with a recurrence interval of 2 years or 7T2 as our threshold temperature. Each 7T2 value was calculated from the 30-year time series of simulated unregulated temperatures for the historical period. While the maximum weekly average temperature is a widely used metric in defining an upper temperature tolerance for freshwater fishery (Eaton et al 1995, Welsh et al 2001), the addition of a return period (as in the 7T2) makes the method more robust to individual outliers. The 7T2 is analogous to the widely used 7Q2 metric mentioned in the next section. We calculate each of the three metrics for both regulated and unregulated model setups to quantify the regulation impacts on thermal extremes, and for both historical and future periods to quantify the overall impacts of climate change.

We conducted a sensitivity analysis to evaluate the robustness of our findings to our selection of thresholds values. We selected the maximum weekly average stream temperature with recurrence intervals of two, five, ten and twenty years, or 7T2, 7T5, 7T10, and 7T20, respectively, and repeated our analysis (see section 4).

2.4. Concordance of thermal extremes and low flows

Low flow events, also known as hydrologic drought, are defined as periods when streamflow falls below a threshold \( (Q_{\text{thres}}) \). We use the 7Q2 value, which is the minimum weekly average streamflow with a recurrence interval of 2 years. The 7Q2 value has been widely used as a low flow metric for maintenance of aquatic ecosystems and water quality (Ontario Ministry of Natural Resources 1994, Pyrce 2004). The 7Q2 values were based on simulations under the regulated setup to account for water withdrawals. Concordance of thermal extremes (TE) and low flows (LF) is defined as a period when the river temperature exceeds \( T_{\text{thres}} \) while streamflow falls below \( Q_{\text{thres}} \). We refer to these periods as hydrologic hot-dry events \( (TE \cap LF) \).

To summarize the spatial and temporal heterogeneity of hydrologic hot-dry events, we grouped all regulated grid cells into different river size categories and organized the time series by month for each category. We calculated the conditional probability of hydrologic hot-dry events given that thermal extreme events had already happened, i.e. \( P_{R,M}(TE \cap LF | TE) \), and the conditional probability of hydrologic hot-dry events given that low flow events had already happened, i.e. \( P_{R,M}(TE \cap LF | LF) \).
shows the effects of climate change rather than a low flow event. Likely to occur in case of a thermal extreme event that reservoirs can strongly mitigate through releasing cold hypolimnetic water. Under regulated river segments in each river size category from the historical period reservoirs alleviated thermal extremes, with hori-zontal lines denoting median values. Historical regulation impacts on thermal extremes are quantified by the distance between the orange and blue horizontal lines in figure 2, i.e. the median values in the regulated model setup minus those in the unregulated setup ($\Delta M_{\text{hist}}$, where M is the metric of interest; table 1); the more negative $\Delta M_{\text{hist}}$, the greater the mitigation by reservoir regulation of thermal extreme events. For all three metrics, lower blue lines indicate that reservoirs can de-press downstream thermal extremes by releasing cold hypolimnetic water. Under reservoir regulation, median values of mean annual duration, intensity, and severity are 3.0 day/year ($-5.1$ day/year), 0 $^\circ$C ($-0.8$ $^\circ$C), and 1.6 $^\circ$C day/year ($-3.9$ $^\circ$C day/year) for all regulated river segments. Values in parentheses indicate the regulation-induced offset in the historical period.

Regulator regulation has stronger impacts on smaller rivers. We grouped all segments into two size categories (smaller and larger rivers) based on a threshold of $Q_{90}$ of 100 m³ s⁻¹. For larger rivers reservoir regulation leads to a change in median duration, intensity, and severity of $-3.3$ day/year, $-0.6$ $^\circ$C, and $-2.6$ $^\circ$C day/year in the historical period, respectively. For smaller rivers these metrics are $-7.3$ day/year, $-0.9$ $^\circ$C, and $-5.0$ $^\circ$C day/year, respectively, indicat-ing that reservoir regulation can strongly mitigate thermal extremes in smaller rivers during the historical period. Smaller rivers experience stronger regulation impacts for two main reasons, namely, a greater number of reservoirs in smaller rivers (figure 1(c)), and longer residence times of reservoirs in smaller rivers (figure 1(d)). Reservoirs with longer residence times tend to be more stratified with colder hypolimn-netic releases than those with shorter residence times, resulting in a stronger mitigating impact on down-stream thermal extremes.

3. Results

3.1. Regulation modulates thermal extremes

Within the historical period reservoirs alleviated thermal extreme events. Figures 2(b)–(d) show the distributions of duration, intensity, and severity as probability density functions (PDFs) for all regulated river segments in each river size category from figure 1. We used the unregulated model setup (left side in each violin plot) as a baseline and compared it with the regulated setup (right side) to evaluate reservoir impacts on thermal extremes, with horizon-tal lines denoting median values. Historical regulation impacts on thermal extremes are calculated by the distance between the orange and blue horizontal lines in figure 2, i.e. the median values in the regulated model setup minus those in the unregulated setup ($\Delta M_{\text{hist}}$, where M is the metric of interest; table 1); the more negative $\Delta M_{\text{hist}}$, the greater the mitigation by reservoir regulation of thermal extreme events. For all three metrics, lower blue lines indicate that reservoirs can de-press downstream thermal extremes by releasing cold hypolimnetic water. Under reservoir regulation, median values of mean annual duration, intensity, and severity are 3.0 day/year ($-5.1$ day/year), 0 $^\circ$C ($-0.8$ $^\circ$C), and 1.6 $^\circ$C day/year ($-3.9$ $^\circ$C day/year) for all regulated river segments. Values in parentheses indicate the regulation-induced offset in the historical period.

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3.2. Regulation impacts are reinforced under climate change

Climate change will exacerbate thermal extreme events. Figure 2 shows the effects of climate change for an unregulated system (red traces). Without regulation, duration, intensity, and severity increase to 85.6 day/year (+7.7 day/year), 5.2 $^\circ$C (+4.4 $^\circ$C), and 193.4 $^\circ$C day/year (+187.9 $^\circ$C day/year), respectively by the 2080s under RCP8.5, with values in parentheses indicating the changes relative to the historical, unregulated values. These values are determined by calculating the median across all river segments for each GCM and then taking the median across all 20 GCMs. Severity, as an integral of time and temperature, increases faster than both duration and intensity under climate change.

In general, climate change will also exacerbate thermal extremes in the regulated river system. Median duration, intensity, and severity in the regulated model setup are projected to increase to 75.2 day/year (+72.1 day/year), 4.2 $^\circ$C (+4.2 $^\circ$C), and 143.1 $^\circ$C day/year (+141.5 $^\circ$C day/year), respectively, which are only slightly lower than climate-induced increases in the unregulated setup. Furthermore, for all regulated river segments, reservoir regulation can only mitigate 12.2% ($-10.4$ day/year), 19.7% ($-1.0$ $^\circ$C), and 26.0% ($-50.3$ $^\circ$C day/year) of duration, intensity, and severity, respectively, by the 2080s under RCP8.5, with values in parentheses indicating the regulation-induced offset under climate change.

While climate change will exacerbate thermal extreme events in both the regulated and unregulated model setups, the differences between them will be larger under future conditions. The distance between the red and navy horizontal lines in figure 2 ($\Delta M_{2080s}$; in table 1) quantifies the regulation impacts in the future. We quantify the change in regulation impacts between the 2080s and the historical period ($\Delta M_{2080s−\text{hist}}$) as

\[
\Delta M_{2080s−\text{hist}} = \Delta M_{2080s} - \Delta M_{\text{hist}}
\]

Positive values of $\Delta M_{2080s−\text{hist}}$ indicate that reservoir regulation will have a weaker impact on stream temperature in the future than in the past. Negative values indicate that regulation will have a stronger impact in the future than in the past. For all regulated river segments, $\Delta M_{2080s−\text{hist}}$ for duration, intensity, and severity is $-5.3$ day/year, $-0.2$ $^\circ$C, and $-46.4$ $^\circ$C day/year, which indicates that by the
Table 1. Summary of baseline and regulation impacts on duration, intensity, and severity for each river size category. We also group the river segments by smaller and larger sizes, i.e. \( Q_a \) below and exceeding 100 m\(^3\) s\(^{-1}\). \( M \) denotes median values of selected metrics for all regulated river segments in each river size category, subscripts hist and 2080s denote historical period and 2080s under RCP8.5 respectively, subscripts unreg and reg denote unregulated and regulated model setups. \( M_{2080, \text{unreg}} \) denotes median of PDF median values among all 20 GCMs for the future period, i.e. red and navy horizontal lines for unregulated and regulated model setups in figure 2.

| Variable           | River size (mean annual flow, \( Q_a \), m\(^3\)/s) | Baseline | Regulated model setup | Regulation impact | Historical | 2080s | Projected changes |
|--------------------|-----------------------------------------------|----------|-----------------------|-------------------|------------|-------|------------------|
|                    | \( M_{2080, \text{unreg}} \) | \( M_{2080, \text{reg}} \) | \( M_{\text{hist}, \text{reg}} \) | \( \Delta M_{2080} = \frac{\Delta M_{\text{hist}}}{M_{\text{hist}, \text{reg}}} \) | \( \Delta M_{2080} = \frac{\Delta M_{\text{hist}}}{M_{\text{hist}, \text{reg}}} \) | \( \Delta M_{2080} = \frac{\Delta M_{\text{hist}}}{M_{\text{hist}, \text{reg}}} \) | \( \Delta M_{2080} = \Delta M_{\text{hist}} \) |
| Duration (day/year)| 0–10                                         | 9.53     | 100.80                | 0.25              | 50.47      | -9.28 | -97.4%           | -50.33 | -49.9%          | -41.05          |
|                    | 10–20                                        | 8.72     | 94.12                 | 0.88              | 76.97      | -7.84 | -90.0%           | -17.15 | -18.2%          | -9.31           |
|                    | 20–50                                        | 8.38     | 89.07                 | 2.28              | 78.78      | -6.10 | -72.8%           | -10.29 | -11.5%          | -4.19           |
|                    | 50–100                                       | 8.39     | 84.91                 | 3.31              | 76.76      | -5.08 | -65.6%           | -8.15  | -9.6%           | -3.07           |
|                    | 100–200                                      | 8.00     | 82.13                 | 2.75              | 72.03      | -5.25 | -65.6%           | -10.10 | -12.3%          | -4.85           |
|                    | 200–500                                      | 7.56     | 81.75                 | 3.88              | 70.75      | -3.69 | -48.7%           | -11.00 | -13.5%          | -7.32           |
|                    | >500                                         | 8.03     | 82.53                 | 2.75              | 79.62      | -0.78 | -9.7%            | -2.91  | -3.5%           | -2.13           |
|                    | Smaller river (\( Q_a \leq 100 \))          | 8.78     | 91.23                 | 1.50              | 75.95      | -7.28 | -82.9%           | -15.28 | -16.8%          | -8.09           |
|                    | Larger river (\( Q_a > 100 \))              | 7.81     | 81.65                 | 4.50              | 74.32      | -3.31 | -42.4%           | -7.33  | -9.0%           | -4.02           |
|                    | All regulated grid cells                     | 8.16     | 85.57                 | 3.03              | 75.15      | -5.13 | -62.9%           | -10.42 | -12.2%          | -5.29           |
| Intensity (°C)     | 0–10                                         | 0.52     | 4.56                  | 0.00              | 1.92       | -0.52 | -100.0%          | -2.65  | -58.0%          | -2.12           |
|                    | 10–20                                        | 0.74     | 5.45                  | 0.00              | 3.70       | -0.74 | -100.0%          | -1.75  | -32.1%          | -1.01           |
|                    | 20–50                                        | 0.94     | 5.50                  | 0.17              | 4.37       | -0.89 | -84.3%           | -0.84  | -15.6%          | 0.05            |
|                    | 50–100                                       | 1.06     | 5.40                  | 0.17              | 4.56       | -0.96 | -99.6%           | -0.93  | -17.9%          | 0.03            |
|                    | 100–200                                      | 0.94     | 5.19                  | 0.00              | 4.26       | -0.49 | -71.7%           | -0.82  | -16.4%          | -0.33           |
|                    | 200–500                                      | 0.68     | 4.99                  | 0.19              | 4.17       | -0.27 | -57.2%           | -0.35  | -7.6%           | -0.08           |
|                    | >500                                         | 0.48     | 4.63                  | 0.21              | 4.28       | -0.88 | -100.0%          | -1.45  | -27.0%          | -0.57           |
|                    | Smaller river (\( Q_a \leq 100 \))          | 0.88     | 5.38                  | 0.00              | 3.93       | -0.88 | -100.0%          | -1.45  | -27.0%          | -0.57           |
|                    | Larger river (\( Q_a > 100 \))              | 0.78     | 4.99                  | 0.18              | 4.21       | -0.60 | -76.8%           | -0.78  | -15.6%          | -0.18           |
|                    | All regulated grid cells                     | 0.82     | 5.19                  | 0.00              | 4.17       | -0.82 | -100.0%          | -1.02  | -19.7%          | -0.20           |
| Severity (°C day/year) | 0–10                                         | 4.85     | 224.98                | 0.08              | 57.20      | -4.77 | -98.4%           | -166.88 | -74.5%         | -162.11         |
|                    | 10–20                                        | 5.36     | 245.72                | 0.28              | 145.45     | -5.08 | -94.8%           | -100.27 | -40.8%         | -95.19          |
|                    | 20–50                                        | 5.77     | 219.55                | 1.02              | 162.28     | -4.75 | -82.4%           | -57.27  | -26.1%         | -52.52          |
|                    | 50–100                                       | 6.16     | 191.54                | 1.78              | 156.56     | -4.38 | -71.1%           | -34.98  | -18.3%         | -30.60          |
|                    | 100–200                                      | 5.77     | 169.30                | 1.44              | 134.82     | -4.33 | -75.0%           | -34.48  | -20.4%         | -30.16          |
|                    | 200–500                                      | 5.28     | 168.42                | 2.51              | 128.68     | -2.77 | -52.5%           | -39.74  | -23.6%         | -36.97          |
|                    | >500                                         | 5.15     | 178.12                | 4.48              | 162.90     | -0.67 | -13.1%           | -15.22  | -8.5%          | -14.54          |
|                    | Smaller river (\( Q_a \leq 100 \))          | 5.66     | 211.94                | 0.66              | 137.87     | -5.01 | -88.4%           | -74.07  | -34.9%         | -69.07          |
|                    | Larger river (\( Q_a > 100 \))              | 5.35     | 170.23                | 2.74              | 145.91     | -2.61 | -48.7%           | -24.32  | -14.3%         | -21.71          |
|                    | All regulated grid cells                     | 5.53     | 193.44                | 1.62              | 143.13     | -3.91 | -70.8%           | -50.31  | -26.0%         | -46.40          |
2080s, reservoir regulation buffers thermal extremes to a greater extent than in the historical period. For all river size categories and all three metrics, $\Delta M_{2080 \text{-- hist}}$ is generally negative, indicating that reservoir regulation will have stronger mitigating impacts for all river sizes under climate change.

Under climate change, mitigation of thermal extremes as a result of reservoir regulation is stronger for smaller rivers. For smaller river segments, the values of $\Delta M_{2080 \text{-- hist}}$ for duration, intensity, and severity are $-8.0$ day/year, $-0.6 \, ^\circ C$, and $-69.0 \, ^\circ C$ day/year, respectively. For larger river segments, these values are $-4.0$ day/year, $-0.2 \, ^\circ C$, and $-21.7 \, ^\circ C$ day/year, respectively. For all three metrics $\Delta M_{2080 \text{-- hist}}$ generally becomes more negative as river size decreases, indicating that under climate change, stream temperatures in smaller rivers will be more strongly affected by reservoir regulation. As a result, in regulated systems, climate change has somewhat less of an impact on thermal extremes in smaller rivers, especially in river segments with $Q_a$ below $10 \, m^3 \, s^{-1}$.

### 3.3. Prolonged hydrologic hot-dry events will occur at more river segments under climate change

More river segments will experience hydrologic hot-dry events under climate change (hollow circles are larger than solid circles in figure 3). In the following, median values are calculated only for stream segments that experience hot-dry events. In the historical period, 65.7% of regulated river segments experienced hydrologic hot-dry events with a median annual duration of 0.8 day/year, while 34.3% never experienced a hot-dry event. Under climate change hydrologic hot-dry events will occur in 87.1% of regulated river segments, with a median annual duration of 10.3 day/year, over ten times the historical value. The concurrent events increase both because of an increase in thermal extremes as well as an increase in the number of low flow events. Even though the regional mean annual precipitation is projected to increase slightly by 41.4 mm/year (3.4%), the median annual duration of low flow events will be prolonged from 15.9 day/year to 21.8 day/year. Because thermal extremes do not increase as much in smaller regulated rivers under climate change, fewer smaller regulated river segments will experience concurrent extreme events, especially for river segments with $Q_a$ below $10 \, m^3 \, s^{-1}$ (smaller hollow circle sizes for smaller rivers in figure 3(a)).

Under climate change the concurrent events will be more likely to occur if there exist low flow events rather than thermal extremes. In the historical period the duration of low flow events is almost three times the duration of thermal extremes, leading to a higher $P(LF)$ and therefore a lower $P(TE|LF)$. The hydrologic hot-dry events are thus more likely to occur when thermal extremes occur
Regulation can alleviate thermal extremes and this climate change greatly exacerbates thermal extremes. More regulated river segments will experience thermal extremes that increase in the regulated and Buccola voirs at present (e.g. Detroit Dam in Oregon; Rounds stream temperature control at a few select reservoirs). Although reservoir releases are optimized for downstream temperature control at a few select reservoirs (e.g. Detroit Dam in Oregon; Rounds and Buccola 2015), this is currently not a common practice.

4. Discussion

The sensitivity analysis shows that the choice of threshold temperature does not have a large impact on our results. In general, reservoir regulation can alleviate historical thermal extremes to a certain extent. The values of all three metrics increase sharply under climate change for both the unregulated and regulated model setups, but they increase slightly less for the regulated case. In addition, for all three metrics, $ΔM_{2080−\text{hist}}$ generally becomes more negative as river size decreases, a consistent finding under all thresholds (see supporting information figure S1). As a result, our conclusion that regulation impacts are more enhanced for regulated rivers with smaller flows is relatively insensitive to the choice of the threshold value.

Besides the choice of threshold, assumptions in river temperature simulations can also influence the results. In this study, we assumed that all reservoirs released water from the hypolimnion. This assumption was our default because of limited access to reservoir regulation data across different operating agencies. As a result, the regulation impacts shown in this study are the upper limit of mitigation that can be provided by existing reservoir infrastructures. Although reservoir releases are optimized for downstream temperature control at a few select reservoirs (e.g. Detroit Dam in Oregon; Rounds and Buccola 2015), this is currently not a common practice.

5. Conclusions

Leveraging a newly established model framework, we investigated the impacts of climate change and reservoir regulations on thermal extreme characteristics as defined by three metrics: duration, intensity, and severity. Concurrent thermal extremes and low flow events, i.e. hydrologic hot-dry events, can increase damages to local aquatic ecosystems due to low fish mobility and can further reduce the flexibility and ability of the electricity sector to meet electricity demand due to disruption of thermoelectric plant operations. We also determined the conditional probability of hydrologic hot-dry events given the occurrence of either a thermal extreme or low flow event. Our analysis focused on river segments in the study area that are subject to regulation during the historical period. Major findings are as follows:

- Climate change greatly exacerbates thermal extremes. In the unregulated simulations, duration, intensity, and severity are projected to increase to 85.6 day/year (+77.4 day/year), 5.2 °C (+4.4 °C), and 193.4 °C day/year (+187.9 °C day/year), respectively, by the 2080s under RCP8.5, with values in parentheses indicating the changes relative to the historical, unregulated values.

- Thermal extremes will increase in the regulated system under climate change. The climate-induced increases are only slightly lower in the regulated model setup than those in the unregulated model setup. Furthermore, by the 2080s under RCP8.5, only 12.2%, 19.7%, and 26.0% of duration, intensity, and severity, respectively, that would have occurred in the unregulated case can be mitigated by reservoir regulation, assuming all releases come from the hypolimnion.

- Regulation can alleviate thermal extremes and this ability will be enhanced under climate change. Reservoir regulation buffers thermal extremes to a greater extent under climate change, by reducing duration, intensity, and severity by −10.4 day/year, −1.0 °C, and −50.3 °C day/year, which are 2.0, 1.2, and 12.9 times greater than the historical offset due to reservoir regulation. In addition, the mitigating effects of reservoir regulation on thermal extremes are greater on smaller rivers because of a greater number of reservoirs and because of longer reservoir residence times.

- More regulated river segments will experience prolonged hydrologic hot-dry events under climate change, with a median annual duration of 10.3 day/year, over ten times the historical value. In addition, under climate change, the occurrence of thermal extreme events increases more than the occurrence of low flow events. As a result, the occurrence of concurrent hot-dry events becomes more conditionally dependent on the occurrence of a low flow event (since thermal extreme events will become more common).
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Data availability statement

The data that support the findings of this study are openly available at the following DOI: https://doi.org/10.5281/zenodo.3753590.

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