Quantifying hydropower flexibility during extreme temperature events

Kyongho Son[a,1], Cameron Bracken[a,2], Erfaneh Sharifi[b,3], Sohom Datta[a,4], Abhishek Somani[a,5],

[a] Pacific Northwest National Laboratory
[c] Department of Energy

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[1] kyongho.son@pnnl.gov
[2] cameron.bracken@pnnl.gov
[3] erfaneh.sharifi@ee.doe.gov
[4] sohom.datta@pnnl.gov
[5] abhishek.somani@pnnl.gov

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[1]Pacific Northwest National Laboratory
[2]Department of Energy

Corresponding author: Kyongho Son, `kyongho.son@pnnl.gov`

Abstract

Extreme weather events can impose substantial stress on the electrical grid. Hydropower offers unique operational flexibility, enhancing grid resilience and reliability. Despite this value of flexibility, systematic assessments of hydropower flexibility – particularly during extreme events – remain limited. This study is the first to quantify hydropower operational flexibility using 25 years' observed hydropower generation data during cold snaps and heat waves, across ten federally operated reservoirs (the "Big-10") in the Pacific Northwest region of the United States. Among the Big-10, the Upper Columbia reservoirs—Grand Coulee (GCL) and Chief Joseph (CHJ)—have the largest storage capacities and exhibit the greatest operational flexibility, followed by the Lower Columbia and Lower Snake reservoirs. Flexibility is generally higher during cold snaps than during heat waves; however, the relationship between installed capacity and exercised flexibility is statistically significant only during cold snaps. Heat wave events, however, exert a more pronounced marginal impact on excess hydropower production, as indicated by the steeper slope of excess generation with respect to event severity. Overall, this study not only quantifies the system's flexibility under extreme conditions but also enhances understanding of how individual reservoirs respond to temperature-driven stressors, providing valuable insights for grid management and future hydropower planning.

1 Introduction

Extreme weather events place increasing pressure on the reliable operation of the U.S. electrical grid (Garland et al., 2024), particularly in regions with a large proportion of weather-dependent generating resources, such as wind, solar, and hydropower. Among renewable energy sources, hydropower is unique due to its dispatchability and its ability to respond to short-term needs of the electrical system (e.g., load factoring, operating reserves, voltage support, and blackstart) (Somani et al., 2021), as well as providing long-duration energy storage (Kieper et al., 2025; Somani et al., 2021). Although many modern hydropower systems are highly constrained due to their multi-purpose nature, they may have operational flexibility to meet loads during periods of high demand, but only within the other operational constraints of the system, such as flood control, environmental, transportation, irrigation, water demands, and recreation. Here, we refer to flexibility as the ability of a reservoir to store water during periods of low demand and release it during periods of high demand, effectively acting as an energy storage system or "water battery" (Kieper et al., 2025). For example, extreme weather events such as cold snaps and heat waves often drive surges in energy demand. During these periods, in the Pacific Northwest, other renewable sources may be less reliable – for instance solar panels generate less power during extreme heat due to reduced efficiency(Garland et al., 2024), and wind generation is typically suppressed by atmospheric conditions that cause extreme heat in the region (Lledó et al., 2018). On the other hand, hydropower can rapidly generate additional power to relieve grid stress during extreme events if sufficient water is available, providing hydropower producers with valuable arbitrage opportunities that incentivize storing water for high-price periods(Kieper et al., 2025).

Given its inherent flexibility, the value of hydropower to the grid has been emphasized in recent years, especially in the context of optimal reservoir operation (Wang et al., 2025; Sharifi et al., 2017; Chen et al., 2021), the rising frequency of extreme weather events (Garland et al., 2024), and its ability to compensate for forecast errors in load, wind, and solar (Somani et al., 2021). For example, Wang et al. (2025) showed that increasing hydropower flexibility leads to greater operating revenue in the Bonneville Power Administration (BPA) and California Independent System Operator (CAISO) balancing areas. Although the importance of accounting for operational flexibility in hydropower licensing is widely recognized, current regulatory frameworks often fail to capture the true value of hydropower's flexibility (Roni et al., 2023). Production cost models and other optimization tools have been used to quantify hydropower value (Papadopoulos et al., 2014), but most approaches emphasize only certain aspects of hydropower operations and neglect key constraints—particularly environmental requirements. To overcome this limitation, Roni et al. (2023) used a two-stage optimization method to meet the a two-stage day-ahead and real-time market optimization under multiple environmental flow and market scenarios to evaluate flexibility by meeting both environmental and power system requirements, but their framework relies on a hypothetical hydropower plant rather than real-world systems. Similarly, Magee et al. (2022) demonstrated that incorporating realistic river dynamics and operational policies into reservoir models coupled with a Production Cost Model (PCM) , can result in up to 9% lower estimated power generation compared to simplified representations, highlighting the importance of accurately modeling storage dynamics in hydropower systems. However, their study does not explicitly quantify hydropower flexibility, particularly under extreme events.

Empirical, observation-based studies of hydropower flexibility are also limited. Although hydropower's role during extreme events has been recognized, systematic quantification of flexibility remains rare (Kieper et al., 2025; Key et al., 2012; Chen et al., 2021). Kieper et al. (2025) provided a generalized framework for analyzing hydropower operations under extreme events, using the January 2024 weekend polar vortex in the Pacific Northwest as a case study. They found that hydropower generation became more strongly and positively correlated with load during the event, suggesting that BPA's hydropower system prioritized meeting regional energy demand. By examining the forebay elevation and turbine flow data, the study also found that Grand Coulee Dam was used for energy storage and that operators ramped up energy production by increasing turbine outflows during the event. This indicates that reservoir operators responded to peak energy demand by strategically storing water before and during the event in response to weather and hydrology forecasts.However, their study focused on a single reservoir and a single extreme event; therefore, a systematic evaluation of flexibility across multiple reservoirs and different types of events remains underexplored.

To address this gap, this study uses observed daily hydropower and reservoir operation data from the 10 largest federal reservoirs in the Columbia River Basin to quantify the flexibility of hydropower production during extreme temperature events from 2001 to 2025. Specifically, we aim to 1) assess reservoir operational flexibility in energy production, 2) evaluate variability of operational flexibility for two extreme event types (cold snaps vs heat waves), and 3) examine the relationship between the severity of extreme events and hydropower generation response. Through this analysis, we can enables a systematic assessment of how hydropower flexibility varies across reservoirs and event types, and improve the understanding of how each reservoir operator under extreme events.

2 Methods

2.1 Study region

Our study focuses on the "Big-10" federally owned and operated hydropower plants in the Columbia River Basin (CRB) (Figure 1). The power from these plants is marketed by Bonneville Power Administration (BPA), one of four U.S. federal power marketing agencies (PMAs). Hydropower accounts for 85% of BPA's generation portfolio and 62% of the total electricity supply in the region (Bonneville Power Administration, 2025). The Big-10 are some of the largest facilities in the U.S., with capacities ranging from approximately 600 to 6,800 MW. We created three logical project groups based on geographic proximity and operational characteristics. The first group, the Upper Columbia, includes Grand Coulee (GCL) and Chief Joseph (CHJ), which have the largest capacities (6809 and 2456 MW, respectively). The second group, the Lower Columbia, includes four dams with capacities ranging from 990 MW to 2,160 MW. Finally, the Lower Snake projects consist of four smaller facilities, each with a capacity between 603 MW and 810 MW (Table 1). Within each group, the reservoirs are geographically proximate, and their hydropower

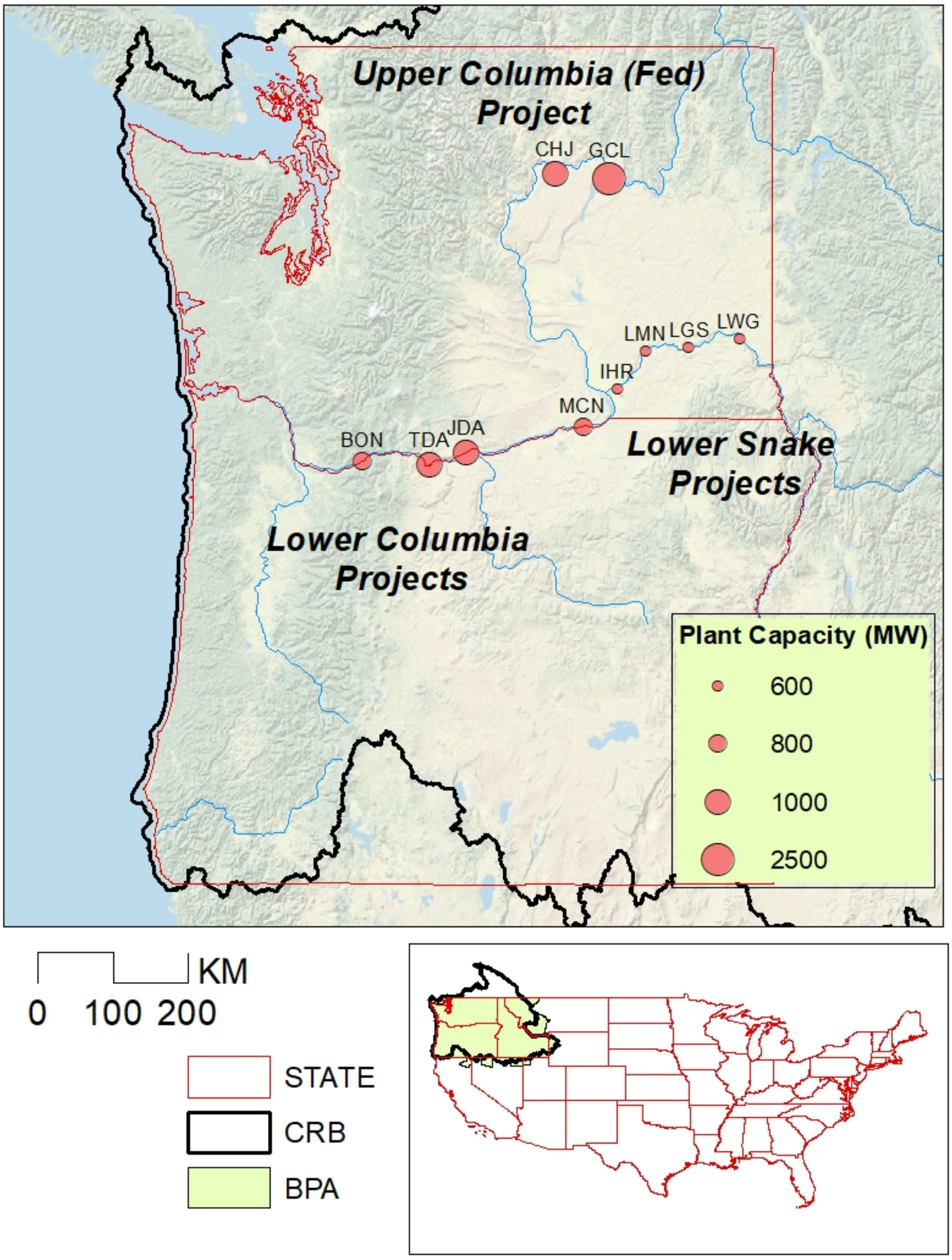

Figure 1. Locations of the 10 largest reservoirs by energy generation in the Federal Columbia River Basin Power System (FCRPS), whose power is marketed by the Bonneville Power Administration (BPA). Reservoirs are grouped into three categories: (1) Upper Columbia: Grand Coulee (GCL), Chief Joseph (CHJ); (2) Lower Snake: Ice Harbor (IHR), Lower Granite (LWG), Little Goose (LGS), Lower Monumental (LMN); and (3) Lower Columbia: McNary (MCN), John Day (JDA), The Dalles (TDA), and Bonneville (BON).

operations are highly synchronized. When an upstream dam releases water, it cascades downstream and is subsequently used to generate electricity at the next dam. As a result, the power generation patterns of dams within the same group are often very similar. Therefore, we examine the operation of individual dams during extreme events and the behavior between dam groups.

Table 1. Information on the Big-10 federally owned and operated hydropower plants in the Columbia River Basin (CRB).

Name	**Capacity (MW)**	**Maximum Storage (10^3 acre-feet)**	**Reservoir Type**	**Group**
Grand Coulee (GCL)	6,809	9,562	Storage	Upper Columbia
Chief Joseph (CHJ)	2,456	597	Run-of-river	Upper Columbia
Lower Granite (LWG)	810	485	Run-of-river	Lower Snake
Little Goose (LGS)	810	569	Run-of-river	Lower Snake
Ice Harbor (IHR)	603	409	Run-of-river	Lower Snake
Lower Monumental (LMN)	810	379	Run-of-river	Lower Snake
McNary (MCN)	990	1,350	Run-of-river	Lower Columbia
John Day (JDA)	2,160	2,520	Run-of-river	Lower Columbia
The Dalles (TDA)	1,820	328	Run-of-river	Lower Columbia
Bonneville (BON)	1,162	731	Run-of-river	Lower Columbia

2.2 Quantification of Hydropower Flexibility

Our approach to quantifying hydropower flexibility during extreme events is based on the assumption that the system operates to fully utilize its available flexibility during periods of high electricity demand. This is a reasonable assumption because hydropower producers typically seek to maximize revenue during extreme temperature periods that coincide with elevated energy demand and high market prices. To achieve this, hydropower producers may hold water back prior to the event (during lower-price periods) and release it during the event period to maximize revenue and meet demand, to the extent possible given other higher-priority system constraints (Kieper et al., 2025). This assumption enables us to quantify the flexibility realized during extreme events and compare it with that in non-extreme conditions, where the system is not fully utilizing its available flexibility. It should be noted that the flexibility estimated from observed hydropower generation represents the system-wide flexibility of the Big-10 dams, rather than the maximum flexibility that could be achieved by each individual dam.

The approach used to quantify flexibility is illustrated in (Figure 2) and can be summarized in three main steps:

1. Identify historical extreme temperature events (cold snap and heat wave) based on observed temperature data.
2. Using observed hydropower data, compute the generation for the period prior to the event and during the event window.
3. Quantify the exercised flexibility of each hydropower project for each event by differencing the generation before and during the event relative to some precomputed baseline.

More details are given in the following sections.

2.3 Identification of extreme temperature events

County-level air temperature data were obtained from National Centers For Environmental Information (NCEI)'s nClimGrid-Daily product (Durre et al., 2022), which provides gridded fields and area-averaged values of daily maximum, minimum, and average temperatures, as well as daily precipitation, for the contiguous United States (CONUS). To represent BPA load area temperature conditions relevant to power demand, we selected five counties with large populations within the BPA service area – Multnomah, Clark, Spokane, Pierce, and Washington. We then computed a population-weighted average of daily temperatures across these counties to characterize BPA load area temperature variability. The locations and population distributions of these counties are provided in the supplemental materials (Figure S1).

Extreme events were defined using the 1st and 99th percentiles of historical daily temperature distributions, spanning periods of at least two consecutive days (Anderson & Bell, 2011; Barnett et al., 2012). Cold snaps were identified when population-weighted daily temperatures fell below the 1st percentile threshold (i.e., -3.34 °C), while heat waves were identified when values exceeded the 99th percentile threshold (i.e., 23.84 °C). A total of 24 cold snap events and 23 heat wave events were identified from 2001 to 2025. The duration of cold snap events ranged from 2 to 6 days, with a median duration of 3 days. Similarly, heat wave events persisted for 2 to 7 days, also exhibiting a median duration of 3 days. The identified events, along with additional methodological details, are presented in the supplemental materials (Figures S2 and S3).

2.4 Quantifying reservoir operational flexibility

To explore the operations of each reservoir during extreme events, we used observed daily hydropower production data (MW) for each facility and identified corresponding extreme events. Hydropower data were obtained from the U.S. Army Corps of Engineers (USACE) data query site (U.S. Army Corps of Engineers, 2025). We used hourly generation for each plant, along with other reservoir operations data, including inflow, outflow, forebay elevation, spill, and turbine flow. We conduct all flexibility calculations for this study at the daily time scale due to measurement error in the hourly data.

In this study, we define reservoir operational flexibility as the ability of reservoir operators to adjust daily water storage and releases in response to extreme events. Specifically, operators may conserve water (and thus potential energy) prior to an event (e.g., cold snap) and increase power generation during the event. Water and energy are mostly interchangeable in this context; however, energy provides a more accurate estimate of flexibility because it implicitly represents what water was available to generate after the operators meet the other operational constraints of the system. We quantify flexibility as the surplus power generated during the event relative to the pre-event baseline, where a higher surplus indicates greater operational flexibility.

To assess the flexibility of reservoir operations for energy production across different reservoirs, we calculate the mean generation during the pre-event and event periods (Equations 1 and 2)

$$\bar{E}_r^{\mathrm{pre}} = \frac{1}{T^{\mathrm{pre}}} \sum_{t \in T^{\mathrm{pre}}} E_{r,t} \tag{1}$$

$$\bar{E}_r^{\mathrm{ev}} = \frac{1}{T^{\mathrm{ev}}} \sum_{t \in T^{\mathrm{ev}}} E_{r,t} \tag{2}$$

where $E_{r,t}$ denotes the energy production of reservoir r at time t, and T^{pre} and T^{ev} represent the sets of pre-event and event time steps, respectively.

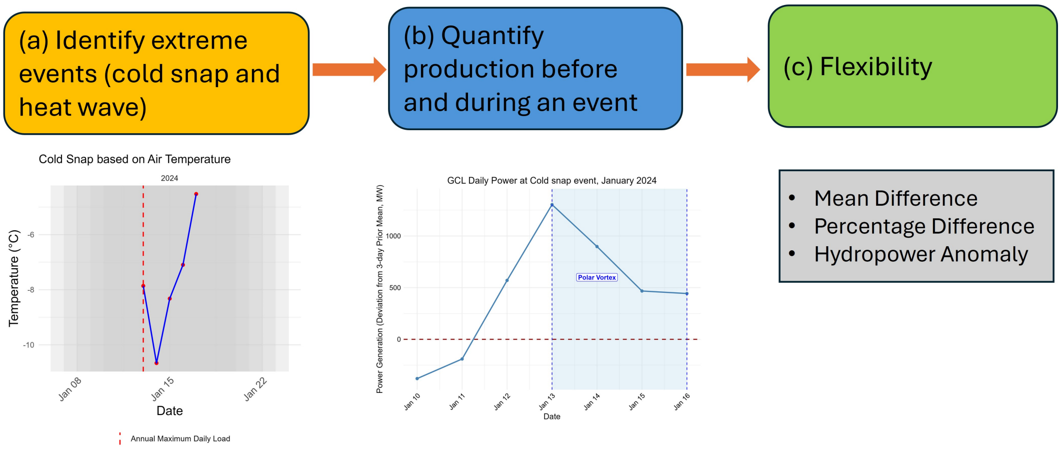

Figure 2. The process for quantifying the impact of extreme events on flexibility of reservoir operation in hydropower production: (a) detect the extreme temperature events from data (cold snap and heat wave), (b) compute the power production difference between prior event and event, and (c) compute flexibility using three measures.

The exercised flexibility (Equation 3) is then computed as the difference between Equations 1 and 2, and the associated percentage change in production relative to the pre-event baseline is defined in Equation 4.

$$M_r = \bar{E}_r^{\text{ev}} - \bar{E}_r^{\text{pre}} \tag{3}$$

$$P_r = 100 \times \frac{M_r}{\bar{E}_r^{\text{pre}}}. \tag{4}$$

In calculating hydropower flexibility, events with negative values are treated as zero, since the reservoir operator did not or could not exercise flexibility during those events. We also compute the hydropower anomaly for each event and facility. The hydropower anomaly is defined as the mean generation during the event minus the historical mean generation during the same time window for non-event years (Equation 5). This calculation quantifies the additional hydropower production during extreme temperature events relative to non-extreme event years (or normal years). The hydropower energy anomaly is computed as

$$E_{r,ev}^{\text{anomaly}} = \bar{E}_r^{\text{ev}} - \frac{1}{N^{\text{non-ev}}} \sum_{n \in N^{\text{non-ev}}} \bar{E}_r^{\text{non-ev}} \tag{5}$$

where $\bar{E}_r^{\text{ev}}$ denotes the mean energy production of reservoir r at each event, ev, and $N^{\text{non-ev}}$ is the number of non-event years, and $\bar{E}_r^{\text{non-ev}}$ is the mean energy production of reservoir r at event, ev during the non-event years.

2.5 Impact of event extremity on Hydropower production

We examine the relationship between extreme temperature events and hydropower production in terms of a reservoir's ability to generate excess energy during periods of grid stress. Specifically, we test whether the severity of each event – which accounts for the magnitude of the temperature anomalies and the event duration – explains variations in hydropower generation. We further evaluate whether this relationship differs between individual reservoirs and between event types (cold snaps versus heat waves). To quantify the severity of each event, we calculated the cumulative deviation of temperature from the defined threshold over the duration of the event,

$$\text{Severity of Extreme Event} = \begin{cases} \sum_{t=1}^{T}(T_t - T_{\text{threshold}}), & \text{for heat waves} \\ \sum_{t=1}^{T}(T_{\text{threshold}} - T_t), & \text{for cold snaps} \end{cases} \tag{6}$$

where T_t is the daily temperature on day t ($t = 1$ is the first day of an event) and $T_{\text{threshold}}$ is the event threshold temperature.

3 Results

3.1 Big-10 hydropower generation during cold snaps

Among the Big-10 reservoirs in the FCRPS, the amount of additional power generated during cold snap events varies substantially (Figure 3a and b and Figure S3). To summarize the hydropower generation flexibility for each reservoir and reservoir group during cold snap events, we calculated the mean and percentage differences using equations 3 and 4 (Figure 3a). Regarding the mean difference, the Upper Columbia reservoirs exhibited the largest flexibility during these events. Among 24 cold snap events, in Upper Columbia group, GCL and CHJ have available flexibility (greater than 0 MW) in 83% and 88 % of cold snap events, respectively. The median additional generation is 325 aMW for GCL and 155 aMW for CHJ, both of which are higher than those observed for the Lower Columbia and Lower Snake reservoirs. This is physically plausible, as GCL is the largest of the Big-10 plants by both generation capacity and storage volume, and CHJ has the second largest production capacity, while its storage volume is lower than most reservoirs. In addition, we calculated the total surplus hydropower generation (MWh) for each cold snap event (Figure S7). For GCL, the surplus generation ranged from 0 to 101,465 MWh, with a median of 19,967 MWh. For CHJ, the surplus ranged from 0 to 49,384 MWh, with a median of 11,241 MWh. These values are directly comparable to other energy storage technologies, such as batteries, which are sized based on their discharge capacity and discharge duration.

The Lower Columbia reservoirs have the second-largest flexibility during cold snaps, ranging from 0 to 320 aMW. The median additional power generation across the four reservoirs (JDA, TDA, MCN, and BON) ranged from 37.9 to 91.7 aMW. These reservoirs had operational flexibility ranging in 79% to 92% of cold snaps. Also, the median total surplus hydropower generation (MWh) for each cold snap event (Figure S7) across the Lower Columbia reservoirs ranged from 2944 to 7135 MWh. Compared with the Upper Columbia reservoirs, the Lower Columbia reservoirs has delayed peak power generation given the cold snap event due to the about 3 day travel time from GCL to JDA (Figure S3).

In contrast, the Lower Snake reservoirs have the smallest amount of flexibility ranging from 0 to 134 aMW, with median additional power ranging from 0 to 3.89 aMW. The proportion of events with flexibility in the Lower Snake reservoirs ranged from 41% to 58%. Also, the median of total surplus hydropower generation (MWh) for each cold snap event (Figure S7) across the Lower Snake reservoirs ranged from 0 to 272 MWh.

Similar to the hydropower flexibility measured by the mean difference, the percentage difference in the Upper Columbia reservoirs shows the highest values, ranging from 0 to 42.3 % with the median of approximately 10 % (Figure 3b). The Lower Columbia reservoirs showed the percentage differences ranging from 0 % to 41.8 %, with the median value between 2.8 % and 8.5 %. Compared with the mean difference, the percent-

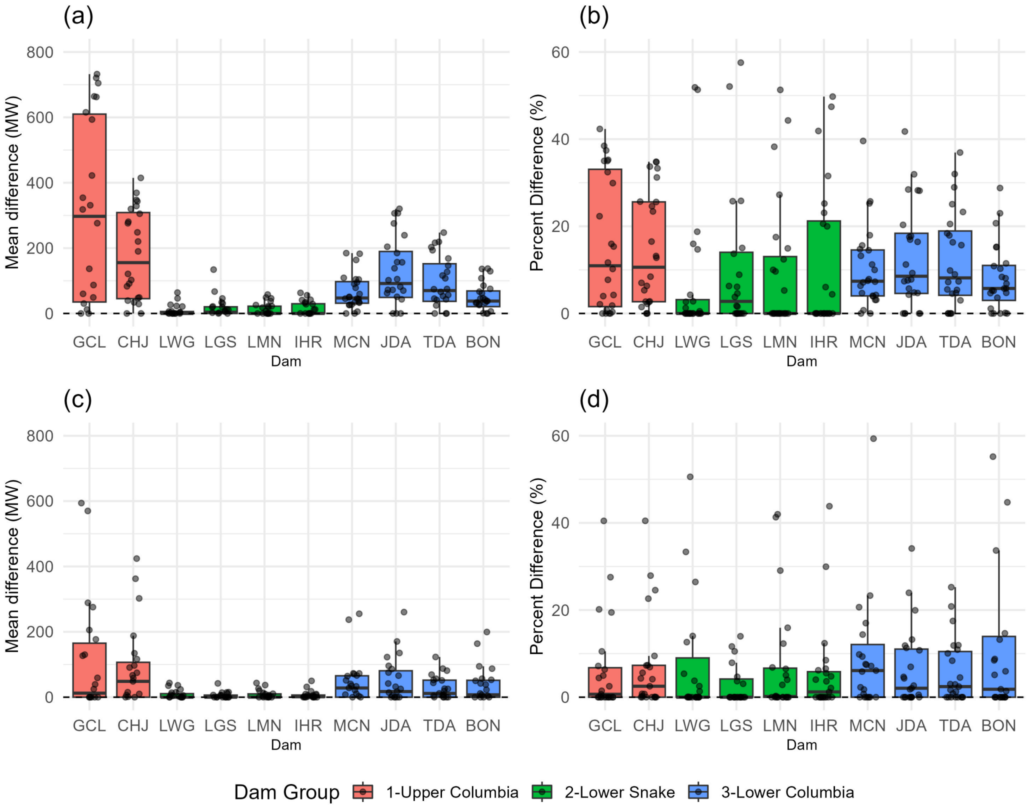

Figure 3. Hydropower flexibility across the Big-10 reservoirs during extreme temperature events. Panels (a) and (b) show flexibility during cold snap events, measured as (a) the mean difference in generation before versus during the event and (b) the percent change relative to pre-event generation. Panels (c) and (d) show the same metrics for heat wave events..

based hydropower flexibility of the Lower Snake has a relatively higher value, especially for the maximum value, and wider ranges. For example, the percentage difference across the Lower Snake ranges from 0 % to 630 %, while the median value ranges between 0 % and 2.8%. The exceptional high value of 630 % is associated with LGS, which has very low pre-event production. Although the Lower Snake reservoirs exercised lower absolute production compared with other reservoirs, they have greater variability in flexibility relative to pre-event level. This highlights that absolute flexibility (MW) and relative flexibility (%) are distinct metrics that answer different operational questions.

3.2 Big-10 hydropower generation during heat waves

In addition to cold snap events, we quantified hydropower flexibility across the Big-10 hydropower projects during heat wave events (Figure 3c and d, and Figure S8). Regarding hydropower flexibility measured by the mean difference during heat wave events, the Upper Columbia reservoirs show the highest values, ranging from 0 to 819 aMW, with median values between 24.8 and 48.5 aMW (Figure 3c). Among 23 heat wave events, GCL and CHJ have available flexibility (greater than 0 MW) in 52% and 69 % of heat wave events, respectively.

Lower Columbia reservoirs have the second largest flexibility, ranging from 0 to 260 aMW, with the median value between 7.37 and 28.2 aMW. The proportion of events with flexibility in the Lower Columbia reservoirs ranged from 56% to 69%. The Lower Snake reservoirs have the lowest values, ranging from 0 to 49.9 aMW, with the median value between 0 and 1.34 aMW. The proportion of events with flexibility in the Lower Snake reservoirs ranged from 34% to 52%. Overall, compared with the cold snap events, the flexibility during the heat wave events is lower across reservoirs. On the other hand, the proportion of events with flexibility in the Lower Columbia reservoir group became similar or slightly larger than the Upper Columbia reservoir group.

During heat waves, surplus energy generation was found to be generally lower than the surplus provided during cold snaps (Figure S9). The Upper Columbia reservoirs, GCL and CHJ, generated a median surplus of 1,190 MWh and 2,326 MWh respectively, representing just 6% and 20% of their median surplus during cold snap events. The Lower Columbia reservoirs produced median surpluses ranging from 546 to 1,539 MWh, which equated to 22% (at JDA) to 19% (at BON) of their surplus generation during cold snaps. Finally, the Lower Snake reservoirs provided the least surplus energy ranging from 0 to 282 MWh. However, surplus energy generation during heat wave has higher maximum value. For example, maximum surplus generation during heat wave ranges from 5,855 to 6,444 MWh, while these during cold snap events ranges from 2,029 to 4,178 MWh.

In contrast, when flexibility is evaluated using the percentage difference metric (Figure 3d), the ranking of reservoirs changes. For example, the MCN reservoir in the Lower Columbia group exhibits the highest median flexibility (6.1%), whereas LGS and LMN in the Lower Snake group show the lowest (0%). Although the Upper Columbia reservoirs GCL and CHJ have the highest absolute generation values, they rank seventh and second in percentage flexibility, with median values of 0.6% and 2.5%, respectively.

3.3 Difference of Hydropower Anomaly across extreme event types and reservoirs

In addition to quantifying the available flexibility during extreme temperature events, we utilized historical generation data as a reference to evaluate the surplus hydropower generated during extreme events relative to non-extreme years (i.e. hydropower anomaly). Figure 4 illustrates the variations in hydropower anomalies (aMW) across reservoirs and event types. During cold snap events, the Upper Columbia group exhibited the highest anomaly values compared to the other two reservoir groups. For instance, anomaly values ranged from 0 aMW to 9201 aMW, with a median value of 3118 aMW. Among all cold snap events, approximately 83% of events resulted in positive hydropower anomalies. Lower Columbia reservoirs reported anomaly values ranging from 0 aMW to 7015 aMW, with a median value of 2081 aMW. Additionally, about 92% of events displayed positive hydropower anomalies. Conversely, the Lower Snake reservoirs recorded the lowest anomaly values, fluctuating between 0 aMW and 1696 aMW, with a median value of 0 aMW. Here, 25% of the events showed positive anomalies.

During heat wave events, the Upper Columbia and Lower Columbia reservoir groups exhibited lower anomaly magnitudes compared to cold snap events, whereas the Lower Snake group showed similar anomaly levels. Relative to cold snap events, the share of events with positive anomalies declined substantially, dropping to 65% for both the Upper Columbia and Lower Columbia reservoirs. In contrast, the Lower Snake reservoirs increased to 39%. The relative ranking among reservoir groups remained consistent: the Upper Columbia reservoirs exhibited the largest anomalies, followed by the Lower Columbia reservoirs and then the Lower Snake reservoirs. Specifically, anomalies in the Upper Columbia ranged from 0 to 10,759 aMW, with a median of 755 aMW; in the Lower Columbia, anomalies ranged from 0 to 4,692 aMW, with a median of 479 aMW; and in the Lower Snake, anomalies ranged from 0 to 752 aMW, with a median of 0 aMW.

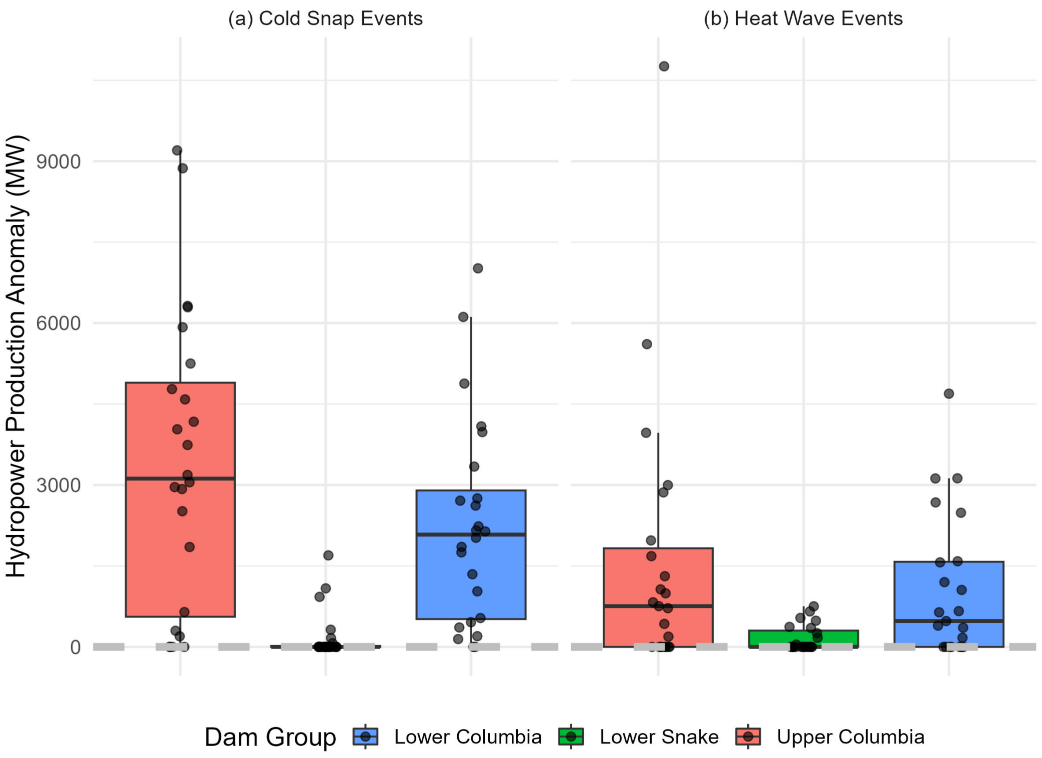

Figure 4. Hydropower production anomaly across dam groups.

3.4 How does extreme event severity impact Big-10 hydropower production?

To better understand how much flexibility is exercised during extreme temperature events, we examined how hydropower flexibility (see Section 2.4 for definition) is related to event severity for each reservoir group (Figure 5, a and b). Hydropower production increases with event severity for both cold snap and heat wave events, though the rate of increase (slope of the regression line) differs depending on the reservoir group and event type.

For cold snap events, the Upper Columbia group provides 617.82 MW of flexibility per degree C of event severity (MW/°C), followed by the Lower Columbia projects at 507.96 MW/°C, and the Lower Snake projects at 86.39 MW/°C. In contrast, heat wave events show overall higher slope values compared to cold snap events, indicating a more pronounced impact on hydropower production during heat waves. The Upper Columbia group again displays the largest response, with a slope of 1,198.95 MW/°C while the Lower Columbia and Lower Snake projects have slopes of 550.26 MW/°C and 139.93 MW/°C, respectively. These findings highlight that both event severity and reservoir group play a critical role in determining hydropower production dynamics during extreme weather events.

However, when examining hydropower anomaly (deviation from historical average generation), its relationship with event severity is not statistically significant for either cold snaps or heat wave events (Figure 5, c and d). This result suggests that event extremity, which reflects only regional climate conditions, cannot fully explain hydropower anomalies. Other factors, such as flow variability and the influence of other energy sources

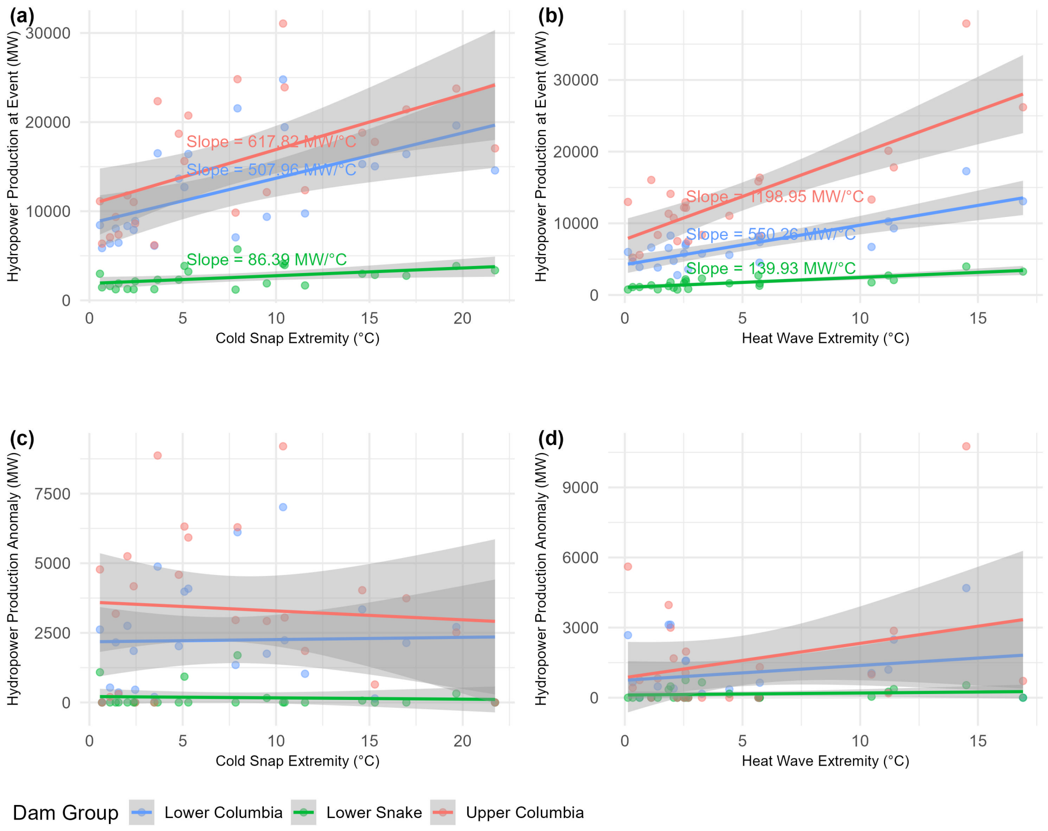

Figure 5. Relationship between extreme temperature event severity, flexibility, and hydropower anomaly by reservoir group.

(e.g., natural gas), may play a more critical role in driving these anomalies. These results highlight the complexity of hydropower production in the Pacific Northwest U.S. and the need to consider multiple contributing factors beyond temperature-based extremes.

4 Discussion

4.1 Impact of extreme events on diverse hydropower responses across reservoirs

This study develops a data-driven approach for quantifying the available flexibility of hydropower plants during extreme temperature events. We examined and quantified hydropower flexibility across the “Big-10” federally owned reservoirs in the Columbia River Basin using observed hydropower generation data and temperature-based extreme events. To our knowledge, this is the first study to quantify observation-based hydropower flexibility, with the exception of Kieper et al. (2025). However, Kieper et al. (2025) focused only on a single cold snap event in 2024 for Grand Coulee (GCL). In contrast, our study evaluated 24 cold snap events and 23 heat wave events over a 25 year period across the Big-10 reservoirs which account for 89 % of the total federal generation in the region. This broader analysis enables a systematic assessment of how hydropower flexibility varies across reservoirs and event types. The flexibility was quantified using two metrics: (1) the mean (or percentage) difference in event-period generation relative to the pre-event 3-day average, and (2) the anomaly, defined as event-period generation minus the mean generation of non-event years. Overall, flexibility during extreme temper-

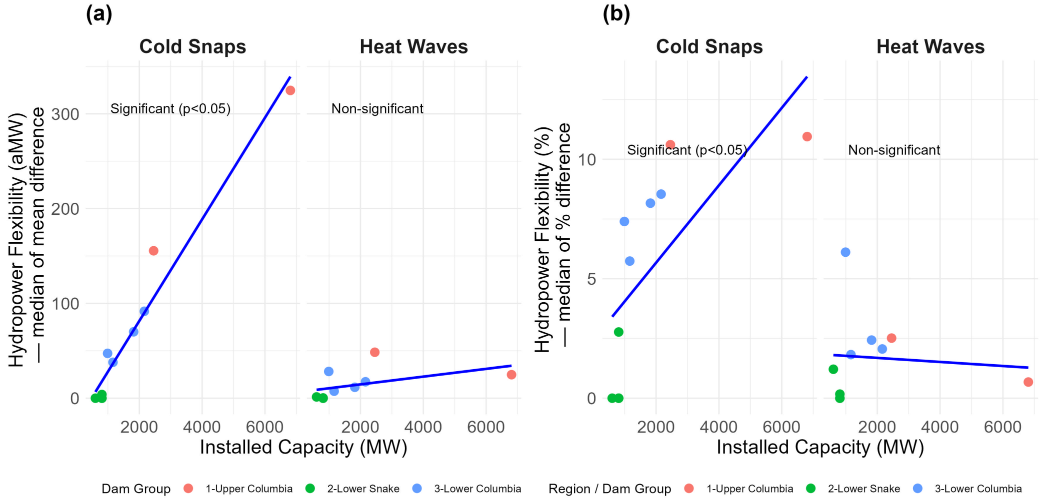

Figure 6. Relationship between installed hydropower capacity and hydropower flexibility by extreme event type: (a) median of mean difference, (b) median of % difference.

ature events is proportional to power production capacity. However, its relationship is only statistically significant during the cold snap events (Figure 6). For example, the Upper Columbia group has the highest flexibility followed by the Lower Columbia and then the Lower Snake. We note that while the capacity-flexibility relationship holds true for the Big-10, it may not hold universally due to how strongly non-power constraints affect the available flexibility.

Available hydropower flexibility also varies between warm and cold extremes. In general, flexibility was higher during cold snap events since they tend to occur during the winter when more flow is available and the federal system is less constrained by environmental flow requirements. For instance, GCL provides approximately 13 times more flexibility, as measured by the mean difference (Equation 3), during cold snaps compared to heat waves. However, the relative ranking of reservoir flexibility changed by event type. GCL displayed greater flexibility than CHJ during cold snaps, but during heat waves, CHJ exhibited higher flexibility than GCL. The greater flexibility of CHJ during heat wave events may be attributed to its minimal operational requirements beyond power generation, whereas GCL faces more stringent hydrologic and other operational constraints during the summer (Bonneville Power Administration et al., 2025). When the percent difference was used, the Lower Snake reservoirs exhibited larger variability and magnitude than indicated by the mean-difference metric (Figures 4 and 6). These results highlight the importance of comparing hydropower flexibility not only across reservoirs and event types, but also across different flexibility metrics.

4.2 How much does the severity of an extreme temperature event explain hydropower flexibility?

This study demonstrated that event severity increased hydropower production, but not hydropower anomalies, across reservoirs and event types. The rate of increase (slope) associated with event extremity is larger for reservoir groups with higher capacity (Figure 6). However, this rate varies by event type; although absolute hydropower production during heat wave events is lower than during cold snap events, the slope associated with heat wave events is substantially larger. Because event extremity incorporates both the temperature deviation and event duration and the median duration of these events is 3 days, the corresponding slopes per day for cold snap events are 205.94, 169.32, and 28.80 MW/(°C · day) for the Upper Columbia, Lower Columbia, and Lower Snake regions, respectively. In contrast, for heat wave events, the corresponding slopes per day are 399.65, 183.42, and 46.64 MW/(°C·day) for the same regions. These findings highlight that both event extremity and dam group (or different capacity) play a critical role in determining hydropower production dynamics during extreme weather events.

On the other hand, the relationship between event extremity and hydropower anomalies across reservoirs and event types is not significant (Figure 6). This result suggests that event extremity, which reflects only regional climate conditions, cannot fully explain hydropower anomalies. In reality, hydropower production is influenced not only by climatic factors but also by hydrologic conditions (e.g., river flow), the availability of other energy sources (such as natural gas, solar, and wind), and electricity market price (Kieper et al., 2025).

4.3 Battery equivalence of storage

This study quantified the surplus energy produced during extreme events relative to both pre-event conditions and non-extreme years. This quantification enables an assessment of the role reservoirs play as large-scale energy storage systems. Based on our estimates, during cold snap events, GCL generates a median surplus of 19,967 MWh, which is equivalent to the storage capacity of approximately 1 battery of 300 MW with a 66-hour duration (Figure S6). In contrast, the Lower Snake reservoirs have much smaller power generation flexibility, ranging from 602 to 810 aMW, and their additional power generation during cold snaps ranges from 0 to 6441 MWh. Except for LGS, all reservoirs show zero median surplus values during cold snap events, indicating no flexibility in these plants.

Similarly, to further enhance the role of hydropower plants as energy storage and to address the challenges associated with constructing large reservoirs, coupling battery storage with hydroelectric facilities has been proposed and implemented (Durvasulu et al., 2024; Chalishazar et al., 2022). Also re-regulation reservoirs are used to minimize the impact of hydropower peaking on the downstream ecosystem, while maintaining the revenue(Anindito et al., 2019). Among the Big-10 reservoirs, we observed that the Lower Snake projects exercised lower flexibility due to low generation capacity and additional operation constraints. Hybridizing the battery with a hydropower plant may enable increasing the flexibility, especially during high demand, or when the operations are constrained by other requirements such as environmental flows or high demand in neighboring regions such as California (Garland et al., 2024).

4.4 Limitations and Future Work

This study used a single definition of extreme events based on the daily temperature (Anderson & Bell, 2011; Barnett et al., 2012); however, different definitions could yield a broader range of events (Garland et al., 2024; Wan et al., 2024). As a result, some extreme events may not be captured in this analysis. Nevertheless, this study quantifies the available hydropower generation flexibility across different reservoirs during a wide range of historical cold snap and heat wave events.

We demonstrated that hydropower generation generally increased during extreme events, with the magnitude of increase varying by reservoir capacity, event severity, and event type, representing BPA's response to high energy demands. However, we observed substantial variation in surplus generation among different events and Big-10 reservoirs (Figure 6), suggesting that additional factors may be needed to explain these differences. Also, this study is limited to explaining the impact of event extremity on hydropower production, and its anomalies (Figure 6). Event extremity increased the hydropower production, but had little relationship with the production anomalies. Similarly, Kieper et al. (2025) showed that milder winter weather spikes in electric prices was explained by the lower supply of natural gas. Future research should therefore focus on identifying the key drivers that affect the flexibility of hydropower during extreme events. Hydrologic conditions and market dynamics – such as the balance between electricity demand and supply – likely play critical roles in shaping operational responses. In particular, fluctuations in electricity and natural gas prices, as well as the availability of alternative energy sources, including variable renewable energy (wind and solar), can strongly influence how reservoirs are managed during these periods. Hydrologic constraints can further limit operational flexibility. For example, during summer months, increasing electricity demand and prices may coincide with reduced streamflow and increased regulatory restrictions, constraining additional hydropower production despite higher potential economic returns. Therefore, future studies should integrate both hydrologic and market factors to better explain the variability in hydropower flexibility across reservoirs and event types.

Also, non-power constraints also may affect flexibility (Bonneville Power Administration et al., 2025). For example the non-power constraints on GCL include (1) flood control, (2) irrigation water supply, (3) environmental operations (eg. fish flows), (4) recreation, and (5) maintenance needs. While the reservoirs in the Lower Columbia and Lower Snake do not have flood control constraints, they have additional non-power constraints which include water – quality, temperature, and navigation requirements – with only John Day (JDA) holding an additional flood-control mandate. Thus, while GCL possesses the greatest physical and power generation capacity for flexible hydropower operations, its non-power operational obligations may constrain the degree to which this flexibility is realized. In addition, evolving environmental regulations introduce non-stationarity in operational rules. Therefore, future studies should account for these factors to more accurately quantify hydropower flexibility across the Big-10 system.

This study is limited to quantifying hydropower generation flexibility during extreme events only. In addition, the observed flexibility during extremes reflects system-wide behavior rather than the full flexibility that could be exercised by individual plants. Therefore, it remains unclear to what extent reservoir operators use available flexibility under normal conditions, and what the maximum flexibility of individual plants is. To fully quantify operational flexibility, future research should incorporate reservoir operation models (Zagona et al., 2000) coupled with production cost models (Papadopoulos et al., 2014; Northwest Power & Conservation Council, 2025), to quantify the impact of flexibility on prices. Such an integrated approach would allow for assessment of hydropower flexibility not only during extreme conditions but also under normal operating periods, providing a more comprehensive understanding of how economic incentives and physical constraints jointly influence reservoir operations.

5 Summary and Conclusion

Hydropower occupies a unique position in the energy grid by providing both short- and long-term operational flexibility, while providing a range of ancillary grid services. Unlike other variable generating resources such as wind and solar, hydropower offers a relatively reliable and dispatchable energy supply. Consequently, previous studies have emphasized hydropower flexibility and developed tools to quantify it (Chen et al., 2021; Kieper et al., 2025). However, observation-based assessments of flexibility remain limited, particularly across diverse reservoirs and different types of extreme events.

This study addresses this gap by using observed hydropower generation data and temperature-based extreme events to quantify hydropower flexibility across the Big-10 reservoirs in the Columbia River Basin. Among these reservoirs, two federal projects, GCL and CHJ in the Upper Columbia, exhibit the highest degree of flexibility. The second most flexible group includes the Lower Columbia reservoirs, whereas the Lower Snake reservoirs show the lowest flexibility. Across event types, hydropower demonstrates greater flexibility during cold snap events compared to heat wave events, largely due to greater storage availability in winter.

We also examined the relationship between event extremity and hydropower generation and found a positive association; however, the rate of increase varies by reservoir group and event type. The slope is larger during heat wave events than during cold snap events, even though absolute hydropower production is higher during cold snaps. Conversely, event extremity did not explain hydropower anomalies, suggesting that climate conditions alone cannot account for these deviations. Other factors—such as hydrologic variability (e.g., river flow), the availability of alternative energy sources (natural gas, solar, and wind), and electricity market dynamics—likely play a more substantial role.

Overall, this study provides an observation-based assessment of hydropower flexibility across reservoir groups and extreme event types. This framework enables quantification of the range of hydropower flexibility and helps clarify the key factors that control hydropower response to extreme temperature events.

Open Research Section

Key data and code are available at: Son, K., & Bracken, C. (2026). Datasets for quantifying hydropower flexibility during extreme temperature events[Data set]. Zenodo. https://doi.org/10.5281/zenodo.19241420.

Acknowledgments

The research was supported by the HydroWIRES Initiative of US Department of Energy—Water Power Technologies Office (WPTO) Grant. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the WPTO.

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