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PAPER

Hydroclimate risk to electricity balancing throughout the U.S

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Abstract

Although hydropower produces a relatively small portion of the electricity we use in the United States, it is a flexible and dispatchable resource that serves various critical functions for managing the electricity grid. Climate-induced changes to water availability will affect future hydropower production, and such changes could impact how the areas where the supply and demand of electricity are balanced, called balancing authority areas, are able to meet decarbonization goals. We calculate hydroclimate risk to hydropower at the balancing authority scale, which is previously underexplored in the literature and has real implications for decarbonization and resilience-building. Our results show that, by 2050, most balancing authority areas could experience significant changes in water availability in areas where they have hydropower. Balancing areas facing the greatest changes are located in diverse geographic areas, not just the Western and Northwestern United States, and vary in hydropower generation capacity. The range of projected changes experienced within each balancing area could exacerbate or offset existing hydropower generation deficits. As power producers and managers undertake increasing regional cooperation to account for introducing more variable renewable energy into the grid, analysis of risk at this regional scale will become increasingly salient.

1. Introduction

Hydropower only makes up 6.7% of all power generation in the United States, but it plays a disproportionately large role in grid management and will increase in importance as we decarbonize the electric grid (Martinez *et al* 2021). As the entities that balance the supply and demand of electricity on the grid transition from relying on fossil fuels as a flexible and dispatchable resource, the availability of hydropower could have key consequences for their success in decarbonization. In many areas, hydropower is a key load-following, dispatchable resource, and hydropower is used more than any other power generation source for hourly ramping flexibility in almost all areas where the supply and demand of electricity is managed (Martinez *et al* 2021). Areas with an abundance of hydropower can also use the resource for their base load, and places like the Pacific Northwest rely on hydropower for about half of their power generation (Northwest Power and Conservation Council 2023). Hydropower can support grid resilience during many different resilience phases from forecasting demand and positioning units appropriately, to recovery and restoration from a disruptive event (Somani *et al* 2021). Black start resources are power sources that can be brought online without any additional power supply in the case of a blackout (Gracia *et al* 2019, NASEO 2020), and hydropower makes up about 40% of these resources (NASEO 2020, Martinez *et al* 2021). Hydropower could play an even more important role as we transition away from non-hydropower black start resources such as natural gas. Not only is hydropower critical for flexibility, frequency regulation, and resilience, but it is also our largest source of reserve power. Pumped hydropower storage (PHS) makes up 93% of grid storage in the U.S. (Martinez *et al* 2021), and PHS development is increasing to account for the integration of increasing variable renewable energy resources.

Since hydropower provides many ancillary services to balancing authority areas, changes in hydropower generation could affect the ability of balancing authorities to balance the supply and demand of electricity (see supplemental information for further background on balancing authorities). Changes in the timing and magnitude of streamflow could impact hydropower generation depending on the configuration, management, and location of a hydropower facility (Wasti *et al* 2022). Several key mechanisms through which climate change affects hydropower production include the melting of permanent glaciers and the loss of ice storage with increasing temperatures, the loss of seasonal storage in snowpack with increasing temperatures during winter, increased variability of precipitation and precipitation events that are more extreme, and increased evaporation (Wasti *et al* 2022). Each of these mechanisms results in changes in both the timing and magnitude of streamflow.

Globally, multiple studies find that hydropower useable capacity is expected to decrease on average, although projections of future hydropower useable capacity vary spatially (van Vliet Michelle *et al* 2016, Turner *et al* 2017). Total annual runoff in the continental U.S. (CONUS) is projected to increase, leading to a projected increase of federal hydropower production on average for the entirety of the U.S (Kao *et al* 2022). Especially in the Pacific Northwest, runoff is expected to increase under scenarios of higher greenhouse gas emissions, which drives higher hydropower generation on average for CONUS (Boehlert *et al* 2016). Runoff within the ninety-fifth percentile of flows is expected to increase for most watersheds in the U.S., while runoff within the fifth percentile of the seven day average is expected to decrease (Kao *et al* 2022). Projected decreased hydropower generation during low flow months has the potential to threaten firm energy from hydropower in areas that rely upon this energy for their baseload (Boehlert *et al* 2016). In much of the CONUS, and especially in watersheds whose flow is primarily driven by snowmelt (Wasti *et al* 2022), hydropower is expected to increase in winter and decrease in summer (Kao *et al* 2022). In places like California, where about 73% of their hydropower is generated at high elevation, shifts in the timing of snowpack-driven runoff could result in large shifts in water management and power generation (Madani *et al* 2014). The pattern of a seasonal winter increase and summer decrease in hydropower is expected to occur in much of the western U.S., along with worsening multi-year droughts that could decrease hydropower production, depending on reservoir storage (Wasti *et al* 2022). Except for in California, the Lower Colorado, and the Rio Grande regions, spring runoff is expected to increase between 2020–2039 (Kao *et al* 2022). In the northeast U.S., increases in extreme precipitation are expected, increasing flood magnitude and frequency (Wasti *et al* 2022). Increased temperatures are also expected in the northeast, along with increased winter precipitation (Wasti *et al* 2022). However, the length of the season of low flows is expected to increase in the Northeast and Midwestern U.S. (Demaria *et al* 2016). In much of the southern U.S., decreasing precipitation and exacerbated drought are expected (Wasti *et al* 2022), which could result in decreased hydropower production.

Previous research has primarily addressed climate risks to hydropower through various scales: some studies have concentrated on individual projects (Chilkoti *et al* 2017, Hou *et al* 2021) or limited numbers of watersheds (Wagner *et al* 2016, Zhao *et al* 2022), while others have expanded their scope to sub-regional scales within specific countries, encompassing multiple watersheds (Hamlet *et al* 2010, Li *et al* 2020) or grid regions (Harto *et al* 2012, Tarroja *et al* 2019, Ralston Fonseca *et al* 2021, Marshall and Chen 2022, Wessel *et al* 2022). Regional studies have examined entire countries (Lehner *et al* 2005, Wang *et al* 2014, Boehlert *et al* 2016, Ruffato-Ferreira *et al* 2017), and global assessments have utilized outputs from global climate models (e.g. (Hamududu and Killingtveit 2012, van Vliet Michelle *et al* 2016, Turner *et al* 2017, Byers *et al* 2018, Wan *et al* 2021)). Balancing authority areas vary greatly in their geographic extent, and existing studies of hydroclimate risk at a regional or watershed scale provide an incomplete picture of how risk to hydropower could affect the grid (figure 1). In the U.S., we find no nationwide analyzes of impacts at the scale at which electricity demand is balanced.

Thus, the goal of this work is to analyze hydroclimate risk to hydropower at the balancing authority scale. This sub-regional, underexplored scale will become increasingly consequential as we incorporate more renewable energy into the grid. As balancing authority areas may rely more heavily upon hydropower for ancillary grid management services such as ramping power or storage in the transition to a grid comprised of more renewable energy sources, risks to hydropower at this scale will likely have real implications for decarbonization and resilience-building.

2. Methods

2.1. Overview

We analyze risk to hydropower within balancing areas by characterizing changes in the timing and volume of streamflow within hydrologic unit code 4 (HUC4) scale watersheds where hydropower plants are located. Because linking detailed models of streamflow and reservoirs with models of electricity generation requires

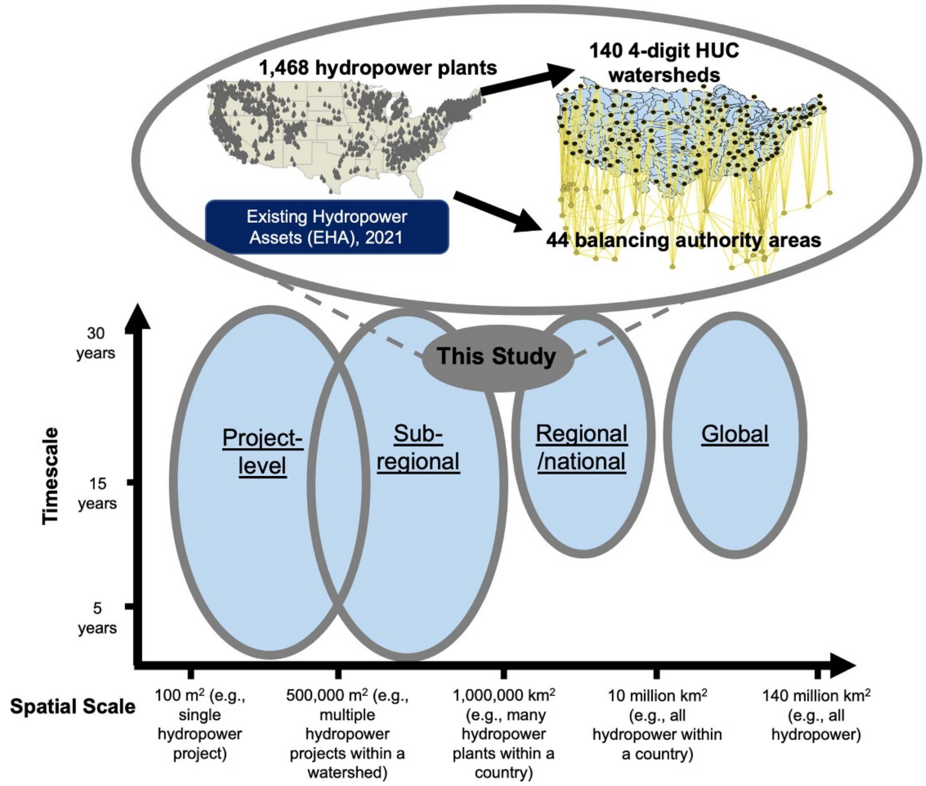

Figure 1. Conceptual overview of scale, timescale and boundaries of this analysis.

computationally intensive analysis that is difficult to utilize over large spatial areas, and streamflow and precipitation are often correlated with hydropower production over long timescales (Kao *et al* 2015, van Vliet Michelle *et al* 2016, Turner and Voisin 2022), we analyze changes in streamflow as a proxy for changes in hydropower. Changes in streamflow do not directly correlate with changes in hydropower generation due to reservoir characteristics, water allocations for other purposes, pricing effects (Madani *et al* 2014), and other factors. However, on long timescales, changes in precipitation and streamflow are generally indicative of the useable capacity of hydropower. Globally, previous scholars found that changes in streamflow were strongly spatially correlated with projected changes in hydropower useable capacities (van Vliet Michelle *et al* 2016). In the Western U.S., hydropower generation and precipitation were found to be correlated on one to two-year timescales (Turner and Voisin 2022), and annual runoff has a high correlation with annual generation (Kao *et al* 2015).

We measure changes in climate risk from a historical (1966–1995) period to a future (2036–2065) time period through four hydroclimate indices measuring changes in streamflow (Byers *et al* 2018): drought intensity, high flow intensity, seasonality, and interannual variability. Streamflow is calculated from hydrologic model output forced with spatially downscaled Coupled Model Intercomparison Project 5 (CMIP5) climate model data from RCP 8.5 (Maurer *et al* 2007). In this analysis, we present two scenarios measuring climate risk: one representing mean change of five selected models from the historical to future period for each hydroclimate index, and one representing a scenario of high variability from a single model output. We created a ten-point scale ranging from negative five to five with which we measure risk for all hydroclimate indices. The scale measures changes from the historical model mean (Mean Scenario) or model index value (High Variability Scenario) in increments of one half of a standard deviation.

2.2. Selection of climate data

We chose to use downscaled climate data from the CMIP5 created by a coalition of universities, government agencies, and non-government agencies (Maurer *et al* 2007). These data include a product that was downscaled using the localized constructed analogs (LOCA) downscaling technique, which we chose due to the advantages of this method in representing precipitation events (Bracken 2016, Pierce and Cayan 2017) (see supplemental information for further detail).

Using LOCA climate data as inputs, the coalition of universities, government agencies, and non-government agencies subsequently created daily hydrology projections using the variable infiltration capacity (VIC) model (Vano *et al* 2020). We selected hydrology outputs forced by five different models within the CMIP5: CCSM4, CanESM2, GFDL_ESM2M, HadGEM2-ES, and MIROC5. These models were selected due to their variation in projected precipitation changes in the U.S. during a future time period (Duan *et al* 2017), and we also selected all available models used by the EPA in their analysis of runoff projections for the Fourth National Climate Assessment (US EPA 2022). We also prioritized variation in the institutions that created the models, as this can be important in creating an ensemble that captures various different uncertainties (Knutti *et al* 2013).

We use these outputs to calculate streamflow at HUC4 scale watersheds by summing the baseflow and runoff outputs from the VIC model within each watershed for historical and future time periods (1966–1995 and 2036–2065). Each of these time periods was selected based on our framework intended for policy relevance. The historic 30 year climate period is centered around when the last large dam was built for hydropower in the United States (∼1980) (US Army Corps of Engineers 2022). The future 30 year climate period is centered around the year 2050, which is a common target for decarbonization goals in the United States (DOE 2021). The HUC4 watershed scale was chosen as the spatial scale for this study since confidence in the climate signals from projections declines at smaller spatial scales. The U.S. Army Corps of Engineers suggests that 'confidence in the driving climate model outputs declines below the level of a reasonable trade-off between precision and accuracy for areas smaller than the watershed scale of the 4-digit HUC' (USACE 2015).

2.3. Hydroclimate risk indices

In this work, we evaluate changes in the quantity and timing of streamflow using metrics created by Byers *et al* (2018). These metrics describe 'hydroclimate risk to power production' (Byers *et al* 2018) by evaluating changes in drought intensity, peak flows risk, seasonality, and interannual variability. The authors developed this metric to assess climate change impacts on both water used for thermoelectric cooling and hydropower, but each index is still appropriate for measuring climate impacts on hydropower alone. We calculate these metrics for HUC4 watersheds in the United States. We assess changes in each hydroclimate risk index between the historical and future periods (1966–1995 and 2036–2065).

2.3.1. Mean seasonality

The first component of the index measuring hydroclimate risk to power production by Byers *et al* (2018) measures the mean change in seasonality. This is calculated as the coefficient of variation of mean monthly discharge:

$$\text{Mean seasonality} = \frac{\sigma_{\text{mean monthly discharge}}}{\mu_{\text{mean monthly discharge}}}$$

where σ represents the standard deviation of monthly mean discharge for all months within the measurement period and μ represents the mean of monthly mean discharge over the entire measurement period. This index measures how much monthly discharge varies throughout the year, where a higher index represents streamflow that is highly variable throughout the year (such as in snowpack-dominated regions), and a low index value represents little change in streamflow throughout the year.

2.3.2. Interannual variability

The second component of the index measuring hydroclimate risk represents streamflow mean interannual variability. It is calculated as the coefficient of variation of mean annual discharges:

$$\text{Mean interannual variability} = \frac{\sigma_{\text{mean annual discharge}}}{\mu_{\text{mean annual discharge}}}$$

where σ represents the standard deviation of mean annual discharge for all years within the measurement period and μ represents the mean of annual discharge over the entire measurement period. This index represents the variability of mean annual discharge from year-to-year, with a higher value representing more variability, and a lower value representing less variability.

2.3.3. Streamflow drought intensity

The third component of the index representing hydroclimate risk to power production measures streamflow drought intensity change. We calculate drought intensity by summing the daily streamflow volume below the 90th percentile on the flow duration curve (Q90) divided by the drought duration:

$$\text{Drought intensity} = \frac{\Sigma Q_{\text{below Q90}}}{d}$$

where Q (m^3) represents the total volume of daily streamflow below the threshold at which flow meets or exceeds this condition for 90% of the time, and d represents the number of days with flow below Q90. A smaller drought intensity index in a future period as compared to a historical period could represent a smaller volume of flow within the same number of drought days, thus a more intense drought. A smaller drought intensity index could also represent a greater number of drought days as compared to the historical period where the flow falls below Q90.

2.3.4. Streamflow high flow intensity
Byers *et al* (2018) identify peak flows risk as locations at which there is 50% or more 'ensemble agreement in a doubling or halving of the 20 year return period for river discharge.' Because the dataset we use in this analysis does not give us access to ensemble output, we substitute our own measure of changes in peak flows. As a complement to the drought intensity index, we measure high flows by calculating the daily streamflow volume above the Q10 threshold, where streamflow meets or exceeds that level of flow 10% of the time, and divide by the duration of the high flow event:

$$\text{High flows} = \frac{\Sigma Q_{\text{above Q10}}}{d}$$

where Q (m^3) represents the total volume of daily streamflow above the threshold at which flow meets or exceeds this condition 10% of the time, and d represents the number of high flow events in days.

2.3.5. Scenario selection
We selected two scenarios that showcase varying ways in which future hydroclimate risk may affect hydropower within balancing areas. The first scenario represents a mean of the hydroclimate index calculated at each 4-digit HUC watershed for runoff forced by the five selected GCMs. This represents a potentially conservative scenario since the mean of the indices forced by each of the five models dampens any extremes. The second scenario represents hydroclimate indices forced by a singular model run where the indices showed high variability in some manner, whether through geographic variation between watersheds or extreme values within the hydroclimate index across the U.S. For the high variability scenario, three of the four hydroclimate indices are calculated from runoff forced by HadGEM2-ES. Only interannual variability is calculated from runoff forced by GFDL-ESM2M. While we could have chosen a range of different plausible scenarios, we chose these two scenarios to illustrate the ways in which hydroclimate risk may aggregate within balancing areas in a potentially conservative or highly variable scenario. Due to limitations stated above, they are not meant for use in detailed future planning, but can serve as an example of the type of analysis framework that may be useful to analyze hydroclimate risk to power production at this scale.

2.3.6. Hydroclimate index values
We developed a scale for all hydroclimate indices which measures change from a historical value to a future value based on the standard deviation of the 5 model mean for each watershed. For our mean scenario, we measure changes from the historical period to the future period on a scale from −5 to 5, where each increment measures one half of a standard deviation of change from the historical mean. For the high variability scenario, we use the same standard deviation from the mean of the five models, but we measure change from the single model historical value. For each hydroclimate risk index, a higher value denotes an increase in the future, except for drought intensity where a higher value indicates a smaller drought intensity index which would indicate more severe streamflow drought (see supplemental information figure 1 for further detail).

2.4. Hydropower dataset

To connect our hydroclimate indices at the watershed scale with balancing authority areas, we use the 2021 existing hydropower assets (EHA) database from Oak Ridge National Labs (Johnson *et al* 2021). This database contains locations and key characteristics of operational hydropower plants, including the balancing authority area to which they contribute. Each balancing authority area may contain hydropower plants located in many different watersheds, and we examine the climate risk to hydropower production within the balancing authority area by looking at projected changes in streamflow in these watersheds (figure 1).

While all information used in our analysis was leveraged from open-source data, we have also provided a curated combined database including all code for this analysis (Dennis and Caitlin 2024).

3. Results

In our mean scenario, we find that over 50% of balancing authority areas will experience changes in streamflow drought intensity (64%) and high flow intensity (82%) greater than one standard deviation from

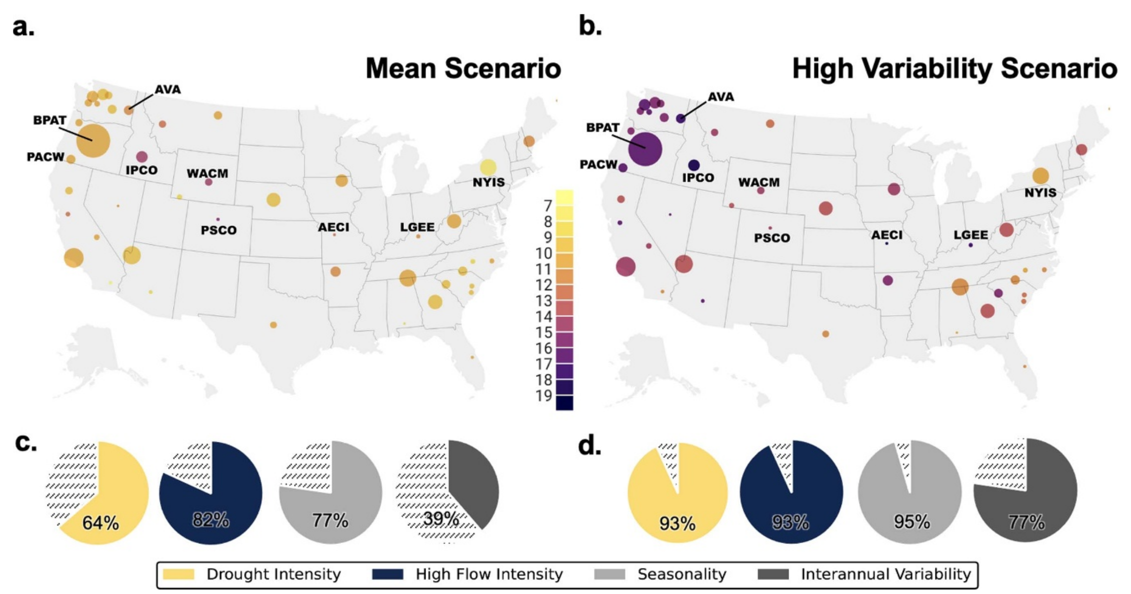

Figure 2. (a) And (b) the geographic variation in hydroclimate risk in the mean scenario (a) and high variability scenario (b) is shown on a map of the contiguous United States. The color of each circle represents an aggregated hydroclimate index for each balancing authority. This aggregate index is calculated as the sum of each hydroclimate index for that balancing authority, where each index for the balancing authority is calculated as the mean of the absolute values for each watershed hydroclimate index in its domain. The size of each circle represents the nameplate capacity of hydropower within the balancing area. The acronyms shown on the figure denote balancing authorities of interest. (c) and (d) Each circle shows the percentage of balancing areas that have at least one watershed that will face a change in the hydroclimate index in the future period greater than one standard deviation from the historical period ((c) mean scenario, (d) high variability scenario). The color of each circle represents the hydroclimate index, and the dashed portion of each circle represents balancing areas with watersheds with hydroclimate indices projected to change less than one standard deviation from the historical mean.

the historical mean in at least one watershed (figure 2). In the high variability scenario, balancing authorities experience even greater significant change within their watersheds: 93% experience significant change in drought intensity in at least one watershed, 93% in high flow intensity, 95% in seasonality, and 77% in interannual variability (figure 2). In both scenarios, balancing authorities more often face increases in each index than decreases (figure 3). For example, in the mean scenario, drought intensity is not projected to decrease in any watershed or balancing authority (figure 3). Areas that face increasing drought intensity coupled with decreasing high flow intensity could receive less water overall, which could threaten hydropower production. In areas where dams are required to prioritize flood prevention, a projected increase in the intensity of high flows could threaten hydropower production if they are forced to direct water through spillways (Tarroja *et al* 2019). Significant changes in the timing of flows within the year could require changes in operations, which presents challenges because operational plans are usually set in place for long periods of time, and permitting processes are difficult to change if substantial operational changes are required (Personal Communications 2022). For hydropower plants that depend upon reservoir storage, changes in interannual variability are less impactful. However, large changes in the interannual variability of streamflow could threaten hydropower production at run-of-river plants.

When measured by the percentage of nameplate capacity affected, the greatest significant changes are projected for high flow intensity and seasonality for both scenarios, with as high as 90% change in seasonality in the high variability scenario. 21% of hydropower capacity within all balancing authorities will face increased drought intensity in the mean scenario, and in the high variability scenario, 65% of capacity is projected to face an increase in drought intensity (figure 3). Similarly, only 10% of capacity faces significant changes in the interannual variability of streamflow in the mean scenario, whereas over 60% faces significant changes in the high variability scenario. In the high variability scenario, over 60% of all hydropower nameplate capacity in the United States is projected to experience a significant change in all four streamflow climate risk indices. Simultaneous changes in the timing and volume of streamflow available to hydropower plants presents complex risk to electricity production, which is further complicated when considered in aggregate at the balancing authority scale.

3.1. Average balancing area risk

We find that the balancing authority areas that face the largest changes in the timing and magnitude of streamflow are located in all parts of the country and vary in generation capacity. To measure the overall

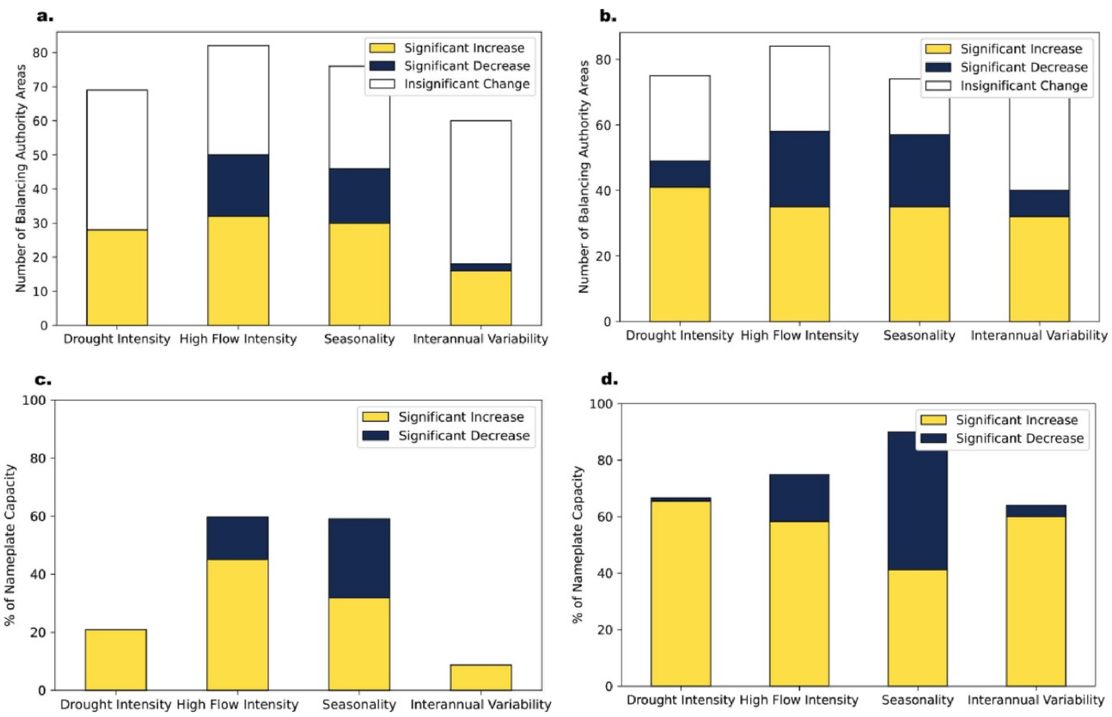

Figure 3. The top two panels show the number of balancing authority areas with at least one watershed that is projected to experience a change shown by the legend in the hydroclimate index denoted on the *x*-axis. The bottom two panels show the percentage of nameplate capacity of hydropower plants in the U.S. projected to face a change shown by the legend in the hydroclimate index denoted on the *x*-axis. Panels (a) and (b) show the mean scenario, while panels (b) and (d) show the high variability scenario. A significant change is defined as a change greater than one standard deviation from the historical to future period.

projected change in streamflow within each individual balancing authority, we calculate the mean of the absolute values of each watershed hydroclimate index and sum each index for each balancing authority (figure 2). We assume that any significant change in streamflow presents risk to hydropower, since changing operations at a hydropower plant in a substantial way could violate the terms of a license or cause a need for re-licensing, as well as complicate competing uses for the dam.[3] Overall, balancing authority areas in the high variability scenario are projected to experience greater changes in streamflow volume and the timing of flows (figure 2). We find no relationship between a balancing authority area's hydropower capacity and its average aggregate change in streamflow (supplemental information figure 2). In the mean scenario, balancing authorities in the west are projected to experience higher aggregate risk: the Public Service Company of Colorado (PSCO), the Western Area Power Administration (WAPA), Colorado-Missouri Region, Idaho Power Company (IPCO), NorthWestern Energy, and the Turlock Irrigation District rank as the top 5 balancing authorities with the greatest projected aggregate change in streamflow. In the scenario of high variability, IPCO ranks most at risk, while balancing authorities in other locations such as Missouri, Oklahoma, and Iowa (AECI), Kentucky (LGEE), and the Northwest (AVA and PACW) face the greatest projected changes in streamflow. Balancing authority areas in a similar geographic area that experience similar projected changes in streamflow could experience power generation deficits at the same time, which could limit their ability to cope by sharing electricity with one another. We found multiple watersheds that contain hydropower plants which contribute to different balancing areas (see supplemental information figure 4). In the Pacific Northwest, two watersheds, the Upper Columbia (HUC 1702) and the Kootenai-Pend Oreille-Spokane (HUC 1701), each have hydropower plants that contribute to five different balancing areas. There are also five other watersheds, distributed throughout the U.S., that have hydropower plants that

[3] The Federal Power Act (10 June 1920, ch. 285, pt. III, §321, formerly §320, as added 26 August 1935, ch. 687, title II, §213, 49 Stat. 863; renumbered Pub. L. 95–617, title II, §212, 9 November 1978, 92 Stat. 3148.) gives the Federal Energy Regulatory Commission (FERC) the authority to issue licenses for the construction and operation of nonfederal hydropower projects. When granting those licenses, the Federal Power Act requires equal consideration to other issues besides power production such as fish and wildlife, recreational opportunities, environmental quality, and other considerations (Vann 2020). The licenses also require licensees to get approval for substantial alterations to their facilities. Through conversations with attendees at the 2022 Clean Currents Conference hosted by the National Hydropower Association, the authors had discussions with owners and operators of hydropower describing the lengthy process and difficulties involved in changes in operations that would require a license amendment or re-licensing.

contribute to four different balancing areas. For example, the Ogeechee-Savannah watershed in the South Atlantic Gulf region (HUC 0306) has plants that contribute to four different balancing areas. If these watersheds are impacted by changes in streamflow, a regional hydropower deficit could ensue (see supplemental information figure 4).

3.2. Diverse impacts within balancing areas

Since balancing authority areas that experience similar hydroclimate risk profiles may not be able to offset impacts by relying on different hydropower assets, whereas balancing areas where climate impacts on hydropower vary may be able to compensate for changes in hydropower production, we analyze the minimum and maximum hydroclimate index values for watersheds within each balancing authority area (figure 4). In both mean and high variability future climate scenarios, drought is expected to increase by varying amounts within the majority of watersheds, meaning that most balancing authority areas could have hydropower plants that face simultaneous drought. Interannual variability is also projected to mostly increase within balancing authority areas in the mean scenario, while in the high variability scenario, projected interannual variability both increases and decreases for watersheds within balancing areas such as midcontinent independent system operator (MISO), SWPP, and PJM. Indices measuring high flow intensity and seasonality show a greater variety of projected changes within each balancing authority. Under both scenarios, most balancing authority areas experience a large range in seasonality within their watersheds, with at least six balancing authority areas containing watersheds whose seasonality is projected to both increase and decrease by over two standard deviations from the historical period in both scenarios (figure 4). High flow intensity is expected to both increase and decrease by over two standard deviations from the historical period in five balancing areas in the mean scenario and nine in the high variability scenario (figure 4).

We hypothesized that the magnitude of watershed area within a balancing authority area and the range of hydroclimate index values within a balancing authority area would be positively correlated. While the MISO has the greatest range of hydroclimate indices within its watersheds and the second greatest watershed area, there is no relationship between the magnitude of the range of hydroclimate indices for each balancing authority and the watershed area or number of watersheds within the balancing area (see supplemental information figure 3). Although the variation in climate conditions for some balancing authority areas could be explained by the large geographic area in which they have hydropower assets, some smaller balancing areas that experience a variety of climate conditions within a small geographic area could face similar risk. For example, MISO and BPAT face a wide variety of changes to streamflow in the mean scenario, however MISO has a watershed area of 6.6 million km^2, whereas BPAT has a watershed area of 4.2 million km^2 (supplemental information table 1).

4. Discussion and conclusions

We made several methodological choices to scope this work with direct policy relevance so that this framework can enable further detailed analysis for balancing authorities or watersheds of interest. Utilities or balancing authorities oftentimes do not have the resources or in-house expertise to analyze climate risk to hydropower assets (Kao *et al* 2022), let alone assess risk at a system level scale, yet system scale analyzes will become increasingly important in a decarbonized grid. Flexible and dispatchable energy resources are increasingly important as resource mixes become comprised of more renewables, and the characteristics of hydropower may allow the resource to play a key role, especially for balancing authorities. Projected changes in water availability could alter the potential for balancing areas to use hydropower as a flexible and dispatchable resource, and since regulatory constraints can limit operational flexibility, careful analysis of this risk is crucial for adaptation and planning.

We intend for this analysis to provide an informative starting place for discussions of climate risk within balancing areas that have not had the opportunity or resources to assess this risk, but we acknowledge that more actionable, specific, climate-informed data support is needed (Kao *et al* 2022). Some methodological choices, such as the choice of climate models or the simplified, streamflow-based hydroclimate risk index, were chosen to allow for a simple and comprehensive comparison of risk between watersheds and balancing authority areas within the CONUS to inform large-scale planning. These methodological choices may represent a more accurate depiction of future conditions for some locations than others. For example, the choice to limit our system boundary to the CONUS, thus excluding Canadian hydropower in our analysis, might provide an incomplete picture of risk to particular regions that rely on that hydropower such as ISO New England (ISO-NE) (which imports a significant amount of hydropower from Quebec) (ISO-NE 2023). Despite this challenge, system-level analyzes such as ours can serve as an important starting point and framework for comprehensive regional assessment, especially since many balancing areas or utilities are also often competitors in energy markets and can only share limited information.

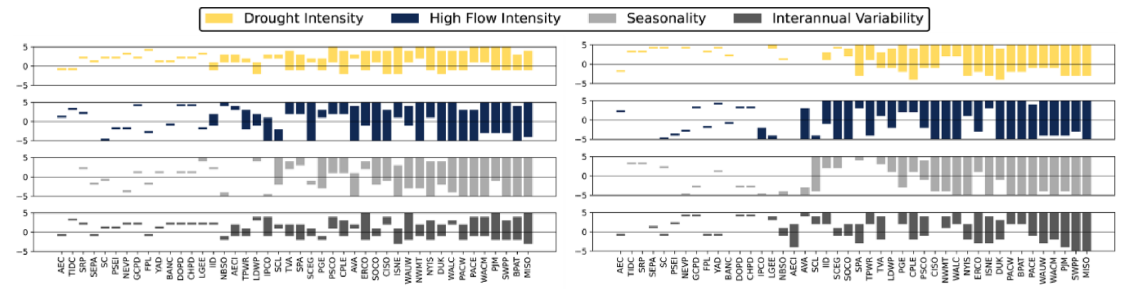

Figure 4. Each bar represents the range of climate index values for watersheds within each balancing authority (denoted by its acronym on the *y*-axis). The left plot represents the mean scenario, and the right plot represents the high variability scenario. Balancing authority areas with hydropower located in only one watershed are represented by a thin line. The balancing authority areas are ordered from smallest to largest range (left to right).

Analysis of risk at the balancing area scale could inform discussions of increasing interconnections and regional cooperation or assessments of resilience. Our analysis shows that more than 50% of balancing authority areas are projected to experience significant changes in streamflow variability under the mean scenario, with up to 93% of balancing areas affected under the high variability scenario. This result should be interpreted as a warning signal to balancing authorities, indicating that operational adjustments may be required to cope with increased variability in water availability. The findings demonstrate that the risk to hydropower is not confined to one region; balancing authorities in both the West (PSCO, WAPA, IPCO) and areas such as Kentucky (LGEE) and Missouri (AECI) are projected to experience significant changes in streamflow patterns. This suggests that diverse regions—from areas traditionally dependent on hydropower to those with less reliance—will need to address varying degrees of climate risk. These results suggest that region-specific climate adaptation plans that take into account both local hydrological conditions and cross-regional power exchanges could be beneficial. Increasing the geographic area over which balancing area coordination occurs has been shown to increase the efficiency of operations and reduce cost by reducing the net variability of renewables within an area (Danholm and Cochran 2015). The projected increases in drought intensity and high flow intensity indicate that balancing authorities might face greater operational challenges in maintaining hydropower as a flexible, dispatchable resource. In particular, areas experiencing both increased drought and more extreme high flows could face situations where reservoir management becomes increasingly difficult. These results suggest that more adaptive reservoir operations and new regulatory frameworks might be necessary to ensure that hydropower can continue to provide critical services like ramping flexibility and frequency regulation.

Many other factors influencing the electric grid at scales both smaller and larger than balancing areas, such as regulatory or power market dynamics, will likely influence the overall impact that changes in hydropower availability have within a particular balancing area in practice. Because market structures vary across the U.S., how changes in water availability affect the cost and use of hydropower could also vary (Loose 2011). Location and market competition with other available resources affect the service value and use of hydropower (Key *et al* 2012). The economic value of hydropower can also vary based on hydropower capacity (Klein and Fox 2022). In some areas and under certain conditions, market dynamics may address the impacts of decreasing availability of hydropower or influence its use when it becomes increasingly available. Because hydropower provides important ancillary services, and demand for these services may increase in the future and become more formally integrated in some markets (Pollitt and Anaya 2020), this could influence the economic value of hydropower and how changes in its availability affect a balancing area. In other areas, non-market dynamics like public opposition around new transmission for increased hydropower production, exacerbated a lack of publicly available information, could affect hydropower use (Calder *et al* 2024). While this analysis does not cover this array of economic, social, and regulatory factors, future studies of hydroclimate risk could benefit from integrating such components.

We find that most balancing areas are likely to face significant changes in water availability upon which their hydropower depends. Some may experience varied climate impacts within their balancing area which would allow them to compensate for changes in hydropower production, whereas others may experience similar hydroclimate risk throughout the area which would prevent them from offsetting impacts by relying on different hydropower assets. As the electricity grid in the U.S. transforms to include more renewable energy resources and increased regional cooperation, assessments of regional risk will become increasingly important to ensure system resilience. This paper provides one example framework for assessing regional hydropower risk to inform system-level resilience building.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.14140496.

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Code availability

The scripts used to produce calculate streamflow and hydroclimate indices at the 4-digit HUC scale are available at Zenodo.org (link forthcoming). Additional scripts used for analysis are available from the corresponding author by request.

Author contributions

Lauren Dennis: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing—Original Draft, Writing—Review & Editing, Visualization.

Caitlin Grady: Conceptualization, Methodology, Resources, Writing—Review & Editing, Supervision, Project administration, Funding Acquisition.

Conflict of interest

The authors declare no competing interests.

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