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Multi-Sector Dynamics: Advancing Complex Adaptive Human-Earth Systems Science in a World of Interconnected Risks

An Integrated Hydroclimatic Assessment of Future Reservoir and Hydropower Operations in the U.S.

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Key Points:

- The majority of U.S. dams project increased streamflow into the late century, leading to a moderate rise in total hydropower generation
- Climate-driven shifts in seasonal hydrology yield gains in winter and spring hydropower, losses in summer, signaling adaptation potential
- General Circulation Model uncertainty is inherent in projections, notably for Western U.S., creating diverse regional outcomes for water and hydropower planning

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

The engineering of rivers by dams is a formative feature of human-nature systems and the interconnectivity of water, energy, and the climate. Sufficient and broad-based representations of dams in large-scale hydrological models prove essential to mapping their extensive regulation of river flow and biogeochemistry and gauging climate-linked provisions, including freshwater supply and hydropower. We present an integrated modeling framework to investigate future streamflow and hydropower generation in the Contiguous U.S. (1990–2075), leveraging an ensemble of six downscaled and bias-corrected General Circulation Models (GCMs) from the high-end SSP585 scenario of the CMIP6. To achieve this, we develop a reservoir operations and parameterization scheme for 1,384 dams in a high-resolution river network, including simulated hydropower generation for 326 dams. For the GCM ensemble mean, we simulate a widespread increase in regulated streamflow into the late-century (11% annual and 17% in winter for the dam median) with region-specific changes in summer streamflow that feature prominent declines in the Northwest (−7%). Mediation by reservoirs is shown to dampen intra-annual streamflow changes, delivering additional summer releases that partially mitigate declining flows. Total hydropower generation is projected to increase modestly (+3%), with boosted generation in the winter (+9%) and spring (+5%) offsetting declined summer generation (−3.4%), suggesting strong adaptation potential for hydropower in the future energy portfolio. Further analysis reveals that the choice of GCM, particularly in western regions, has significant bearing on projected streamflow and hydropower changes.

Plain Language Summary

Dams are a central feature of society's dependence and influence on the natural environment. Simulating the operations of reservoirs is an essential way to understand their impacts on rivers and to assess climate risks to important services like water supply and hydroelectricity. Our study develops a framework composed of multiple climate and hydrological simulation models to examine the impacts of climate change on future streamflow and hydropower in the U.S. We find that streamflow will largely increase in the future across most of the U.S., with dams helping to stabilize the intensity of winter increases and summer declines in streamflow. The nation's hydropower fleet benefits from runoff and streamflow increases in the winter and spring, which more than make up for falling summer generation, suggesting that hydropower can continue to be a reliable renewable energy source by adapting to future climate conditions. Conclusions regarding future streamflow and hydropower generation depend strongly on the climate model driving the future simulations, especially in western regions.

1. Introduction

Anthropogenic alterations to natural flow regimes in rivers have induced profound changes in the modern terrestrial water system, chief among them being impoundments created by dams and manmade reservoirs (Oki & Kanae, 2006; Rockstrom et al., 2009; Wada et al., 2014, 2017; Wisser et al., 2010). Dams currently fragment over 60% of the world's major rivers and store more than triple the mean storage of global rivers (Collins et al., 2024; Grill et al., 2019; Lehner et al., 2024). There is a clear and present need to monitor and simulate dam operations, given the vital importance of water storage and diversions to multi-sector security (e.g., hydropower, irrigation, drinking water) and their substantial impacts on the volume, timing, temperature, quality, and habitability of river systems (Lehner et al., 2011; Nazemi & Wheater, 2015a, 2015b; Tortajada, 2015). Reservoir management in the 21st century is further challenged by projected climate changes, exhibited by spatiotemporal shifts in seasonal flows, the increased prevalence of hydrologic and weather extremes (e.g., droughts, floods), and demand-supply changes as they pertain to hydroelectricity (Bates et al., 2008; Kao et al., 2022; Watts et al., 2011). To address these interconnected challenges, this study generates macro-scale insights for future water and hydropower planning in the Contiguous U.S. (CONUS). Our assessment is underpinned by a new modeling framework that integrates three research themes, detailed in the forthcoming subsections: (a) Hydropower in the U.S.; (b) Simulating Reservoir Operations; and (c) Future Climate Projections.

1.1. Hydropower in the U.S

In the span of important reservoir provisions, our study focuses on hydroelectricity as a key energy-water linkage prone to climate vulnerabilities. In 2022, hydropower represented about 6% of total utility-scale energy generation in the U.S., accounting for roughly 29% of utility-scale renewable generation (Uria-Martinez & Johnson, 2023). Though the generating mechanism of hydroelectricity is free from emissions, the accompanying dam infrastructure may adversely affect downstream aquatic ecosystems and a multitude of natural river characteristics, while at the same time enhancing long-term biogenic emissions of methane and carbon dioxide from water stored behind dams (Baxter, 1977; Jager & Smith, 2008; Nguyen et al., 2018; Poff & Schmidt, 2016). The environmental consequences and associated costs of constructing new dams leave hydropower as a less feasible option to meet growing electricity demands in the 21st century. Conventional hydropower in the U.S. has likely been fully realized, with ongoing dam removal efforts leaving only a 7% projected expansion by 2040 (U.S. EIA, 2016; Osmani et al., 2013). Annual capacity factors have been declining at four-fifths of U.S. hydropower plants, with a cumulative 23% decrease in generation potential since 1980, due to several operational constraints and declining water availability (Turner et al., 2024).

Despite limitations to scaling power production significantly, hydropower is a crucial component of the energy generation portfolio because, unlike solar and wind, it is a dispatchable generation source that can reserve power potential and respond to grid demands (François et al., 2016; Hirth, 2016). While the current class of viable renewables is invariably climate dependent, the interannual and sub-annual intermittency risks of solar and wind will require a systematic expansion of energy storage supported by alternative energy sources to discontinue all reliance on fossil fuel generation (Fekete et al., 2023; Zhang, 2024). Pumped storage hydropower will continue to be an important part of energy systems integration efforts as an established means of clean energy storage, accounting for 96% of utility-scale energy storage in the U.S. in 2022 (Koritarov et al., 2014; Uria-Martinez & Johnson, 2023).

Less clear is the role of conventional hydropower in the future energy portfolio, given the complexity of socio-economic and environmental tradeoffs with other generation options as well as the uncertainty associated with climate change impacts (Waldman et al., 2019; Wasti et al., 2022). Hydropower in the western U.S., accounting for about 60% of the national hydropower capacity, has showcased both the critical risks to plant generation during an historic long-term drought and the surprising stability of regional generation due to the spatiotemporal variability of severe drought (Turner, Voisin, Nelson, & Tidwell, 2022). We aim to assess the future viability of U.S. hydropower at the regional-scale using reservoir operational rules calibrated for the historical period, revealing potential adaptation strategies for long-term energy-water planning.

1.2. Simulating Reservoir Operations

Characterizing the coupling of water and power management with the natural environment at the macroscale necessitates accurate and broad-based simulations of reservoir operations. A principal challenge is the heterogeneous operation of dams, including but not limited to variations in their infrastructural geometry, purposes served, and unique interannual and demand-influenced operating rules for water releases (Pokhrel et al., 2016; Simonovic, 1992; Wisser et al., 2010). Actual reservoir operating rules are largely unreported, and observed records, where available, are insufficient to isolate human-driven impacts from natural hydrologic and climate variabilities (Ehsani et al., 2017; Nazemi & Wheater, 2015a, 2015b; Pokhrel et al., 2017; Shin et al., 2019). Reservoir simulations are crucial to holistically capturing the benefits and impacts of dams. There have been several recent advances in socio-hydrological modeling, with distinct approaches to reservoir operations that span spatiotemporal resolutions and domains (e.g., natural lake methods, inflow-and-demand based methods, neural network-based methods, target storage-and-release based methods), as reviewed in more detail by Shin et al. (2019), Giuliani et al. (2021), and Yassin et al. (2019). However, modeling managed water systems at a large scale remains a prime challenge.

The methodologies developed for our study draw inspiration from prior efforts to incorporate generalizable reservoir operation schemes in continental or global-scale land-surface and water balanced hydrological models (Wisser et al., 2010). Inflow-and-demand based methods were established by Hanasaki et al. (2006) to create a generalized operational scheme for dam releases that can be applied with fair realism to the global population of simulated reservoirs. The original methodology computed dynamic monthly releases as functions of long-term inflow means and initial storage conditions. While the approach is widely recognized for its simplicity to configure and improvement over natural lake methods, the scheme has notable shortcomings including the omission of actual inflow for a given year when determining a reservoir's storage and release strategy, a rigid treatment of interannual variability that is contingent on initial storage for a given year, and the exclusion of storage targets and storage zone-dependent releases (Hanasaki et al., 2006; Yassin et al., 2019).

We developed a reservoir operations (ResOps) module and parameterization scheme that modifies the original methodology by Hanasaki et al. (2006), aiming to improve dam representations in the Water Balance Model (WBM) (Vorosmarty et al., 1989, 1997, 2010). We do this to integrate more accurate reservoir impacts in our national scale hydroclimate study, with the new module replacing WBM's previous implementation of a simplified inflow-based approach developed by Wisser et al. (2010). Our methodology joins several studies that have improved and added new features to the original scheme by Hanasaki et al. (2006). These include the implementation of minimum environmental flows (Biemans et al., 2011; Hanasaki et al., 2008), vertical water fluxes in reservoirs as precipitation and evaporation (Adam et al., 2007), consideration of irrigation and flood control demands (Haddeland et al., 2006; Pokhrel et al., 2012; Voisin et al., 2013), temporal downscaling to the daily timestep (Biemans et al., 2011; Haddeland et al., 2006), the use of higher spatial resolution stream networks (Shin et al., 2019; Vanderkelen et al., 2022), and predictive seasonal dynamics that are important for multi-year operation and hydropower generation (Adam et al., 2007; Solander et al., 2016; van Beek et al., 2011).

While inflow-and-demand based methods are suitable for the challenge of simulating diverse and often obscure reservoir rules, they trade operational simplicity for storage and release accuracy (Coerver et al., 2018; Yassin et al., 2019). To continue bridging this modeling gap, our methodology incorporates sub-annual parameters and dynamic release rules to sufficiently capture long-term streamflow alterations by reservoirs.

1.3. Future Climate Projections

While there is a multitude of expected challenges to future energy-water systems, including rising socio-economic demands for freshwater and electricity, our core motivation is to evaluate the aggregate impacts of future climate change. Annual temperatures in North America have increased at an average rate of 0.27°C per decade since 1981, prompting widespread and intensifying changes in climate that include extreme events such as droughts and spatiotemporally altered precipitation patterns (IPCC, 2023; NOAA, 2023). Local-to-global climate changes are anticipated to significantly influence hydrology in the U.S. through changes in soil moisture, increased total runoff, and pronounced seasonal shifts characterized by increased precipitation in winter and spring months, with earlier snowmelt in the winter leading to declines in summer streamflow (Kao et al., 2022; Naz et al., 2016).

Given the importance of and simultaneous uncertainty in climate projections, several hydroclimate studies have aimed to quantify climate impacts on regional hydrology and water infrastructure using multi-model assessments and ensemble approaches that represent a range of climate pathways (Bosshard et al., 2013; Heidari et al., 2020; Kao et al., 2022; Meresa & Romanowicz, 2017; Pytlak et al., 2018). In the mountainous western U.S., snowpack that is critical to regional water and power supply has been in decline since the previous century largely due to warming trends (Mote et al., 2005). A growing body of literature suggests that the western snowpack will continue to decline with a potential low-to-no snow future at the current rate of global warming, driving significant new challenges to streamflow predictability (Das et al., 2011; Li et al., 2017; Miller et al., 2021; Seager et al., 2013; Siirila-Woodburn et al., 2021).

Many previous studies using an array of spatiotemporal coverages, climate model and pathway inputs, and simulation methodologies have yielded a mixture of conclusions regarding long-term projected changes in streamflow and hydropower generation in the regional U.S. (Bartos & Chester, 2015; Boehlert et al., 2016; Craig et al., 2018; Ehsani et al., 2017; Hamlet et al., 2010; Kao et al., 2016; Sale et al., 2012; Zhao et al., 2021; Zhou et al., 2018). While existing literature generally agree that climate-related signals will be more pronounced at the seasonal level than the annual, the high degree of uncertainty in climate projections remains an important obstacle for future energy-water planning. By analyzing long-term trends and variability for an ensemble of GCM-based projections, this study aims to inform reservoir management strategies on future water availability and hydroelectricity in the regional U.S.

A recent study prepared by Kao et al. (2022), as directed by Section 9505 of the SECURE Water Act of 2009, reports on the long-term impacts of future climate on U.S. federal hydropower plants. Based on six selected general circulation models (GCMs) under the high-end SSP585 emission scenario from the Coupled Model Intercomparison Project phase 6 (CMIP6) effort, the study projects a 9% increase in ensemble median annual streamflow and 4% increase in ensemble median annual hydropower generation into the mid-century. The annual increases are marked by significant seasonal shifts (i.e., generation increasing in winter and spring, decreasing in the summer and fall) that are likely caused by earlier snowmelt trends triggered by rising temperatures as well as regionally dependent changes in precipitation and runoff (Kao et al., 2022).

Broman et al. (2024) presented the first CONUS-wide assessment of future hydropower generation using CMIP6 climate inputs, expanding the 9505 assessment (Kao et al., 2022) using identical GCMs in a multi-model ensemble. The study projects an approximate 10% increase in total generation by the mid-century, with generally increased winter trends and regionally dependent summer trends (Broman et al., 2024). The methodology developed for our study also builds on the 9505 assessment (Kao et al., 2022) by expanding to the CONUS domain and including non-federal plants. The key advancements in our hydropower study include the use of a high-resolution river network, the development of a new reservoir operations scheme, its integration within a routing hydrological model, and the extension of future simulations to 2075.

2. Materials and Methods

2.1. Hydroclimate Simulation Framework

The primary component of the hydroclimatic workflow is the WBM, a modular process-based gridded hydrological model, which can operate at multiple resolutions and incorporates land surface characteristics to predict soil moisture, river discharge, river water temperature, and other hydrological variables at the daily time step (Figure 1) (Vorosmarty et al., 1989, 1997, 2010). For our study, WBM was run using a 1-min (~1.85 km) spatial resolution river-routing network of the CONUS domain. The CMIP6-based hydroclimate projections under the high-end SSP585 emission scenario from Kao et al. (2022), originally processed by the Variable Infiltration Capacity (VIC) hydrological model to produce runoff and evapotranspiration at the 2.5-min resolution (~4 km), were spatially interpolated to the 1-min resolution to provide daily inputs to WBM. This alternative configuration, where WBM utilizes VIC-simulated runoff, resulted in more accurate streamflow predictions than WBM's standard, internally calculated runoff approach (See Text S1 in Supporting Information S1). This model scheme also ensures consistency when comparing our reservoir and hydropower simulations with other models using identical VIC inputs (e.g., WRES and WMP used by Kao et al., 2022), facilitating future multi-model ensemble studies.

For simplification, we only consider the six-member DBCCA-Daymet-VIC subset from Kao et al. (2022) but extend the simulation to 2075 for broader evaluation (see Text S1 in Supporting Information S1). Due to computational resource and data limitations, our study focuses solely on the worst-case SSP585 scenario to establish an upper bound on future risks. See Kao et al. (2022) for a more detailed examination of GCM variability across emissions scenarios. WBM produced six 96-year simulations (1980–2075) under Naturalized conditions (i.e., without direct representations of water infrastructure and anthropogenic influences) as well as six 96-year reservoir operated (ResOps) simulations which incorporate daily reservoir storage and release. Parameterization and calibration for ResOps and the hydropower simulations were supported by the Global Reservoir and Dam (GRanD) database (Lehner et al., 2011), the Existing Hydropower Assets database (Johnson et al., 2022), observed dam records from ResOpsUS (Steyaert et al., 2022), streamflow gauge records from USGS (2016), and hydropower generation estimates from RectifHyd (Turner, Voisin, & Nelson, 2022) (Figure 1).

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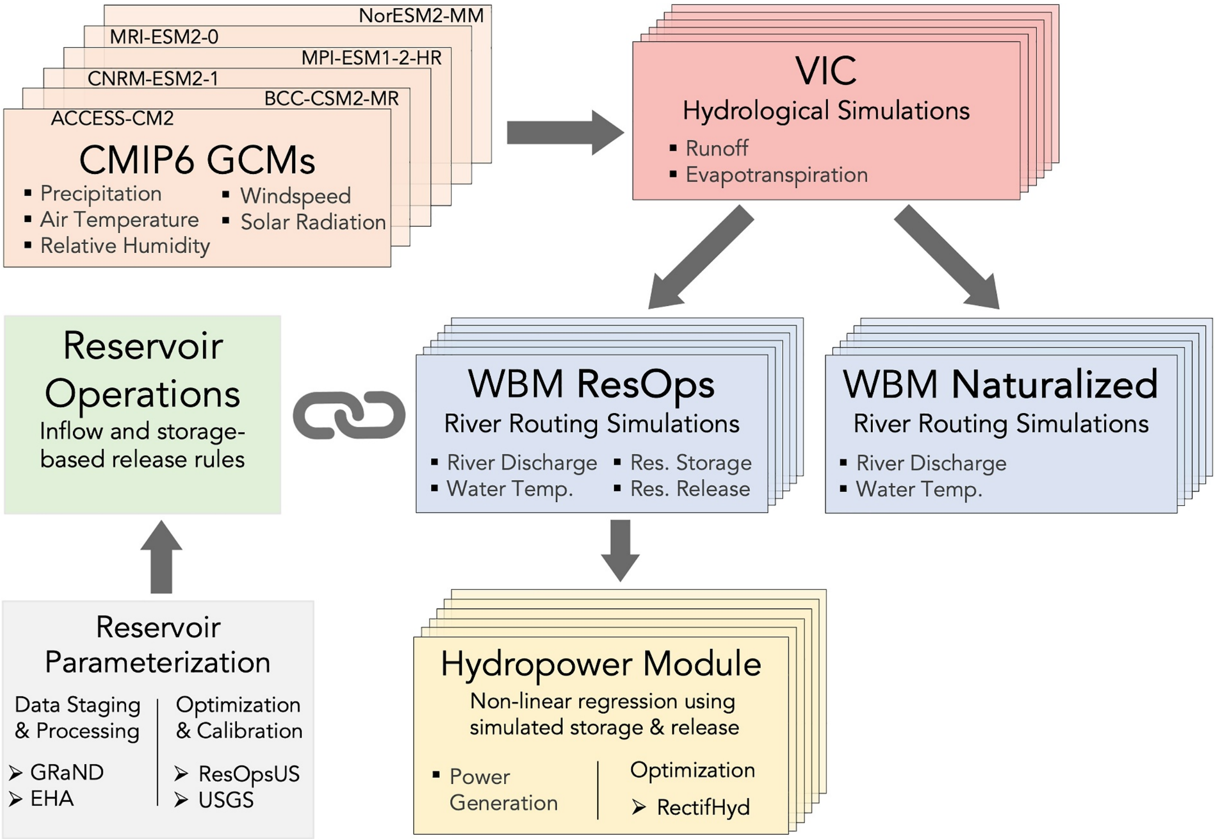

Figure 1. Schematic of hydroclimate simulation workflow. Six downscaled and bias-corrected CMIP6 General Circulation Models are shown in arrayed boxes. The Variable Infiltration Capacity (VIC) model and the Water Balance model (WBM) compute daily hydrological outputs. WBM is simulated with Naturalized conditions as well as with the integrated reservoir operations module (ResOps). The reservoir parameterization scheme is composed of data staging and processing, which rely on the GRanD and Existing Hydropower Assets databases, as well as optimization and calibration using observed reservoir records from ResOpsUS and streamflow gauge records from USGS. The post-processing hydropower module uses simulated reservoir storage and release to compute monthly power generation, optimizing to generation estimates developed by RectifHyd.

2.2. Reservoir Operations and Hydropower Modules

We estimate dam-related impacts in the WBM river network using four modifications of the original methodology by Hanasaki et al. (2006): (a) simulation at the daily time step, (b) integration of reservoirs in a 1-min (~1.85 km) resolution river network, (c) an arrangement of dam-specific monthly and static release parameters that were optimized using observed dam records to better capture seasonal and long-term reservoir strategies, and (d) a series of statistically informed inflow and storage-based rules to determine releases.

$$R_{\text{sim}}(t) = 0.5\,[kR_{\text{target}} + r_a\, I(t)] \tag{1}$$

The daily release simulation (R_{sim}) is defined by a dynamic computed release factor (k) that is based on storage ratios and six inflow-storage conditions, a release target (R_{target}) calculated from long-term inflow means, a calibrated release adjustment factor (r_a), and daily inflow to the reservoir (I). A total of six month-varying parameters are calibrated for each reservoir with available observed dam records (i.e., daily inflow, storage, and release) from the ResOpsUS data set (Steyaert et al., 2022). The averages of calibrated parameters are applied to reservoirs lacking sufficient dam records. A series of conditional release adjustments are also computed for storage depletion and overflow. See Text S2 in Supporting Information S1 for detailed descriptions of the storage and release rules and the parameterization scheme.

The ResOps module was validated and calibrated in the historical period (1980–2019) using observed records of dam variables for 322 dams (i.e., daily inflow, storage, and release) from the ResOpsUS data set (Steyaert et al., 2022) as well as streamflow gauge records (USGS, 2016). While the ResOps module was developed and

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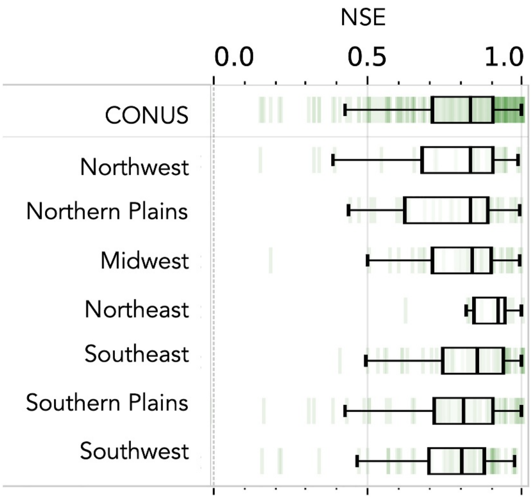

Figure 2. Nash-Sutcliffe Efficiency scores for monthly-averaged reservoir release validation. Performance of ResOps module using observed inflow inputs is measured against observed release for 322 reservoirs (Steyaert et al., 2022) available within a 40-year historical period (1980–2019). Box-and-whisker plots compare score distributions for CONUS and 7 National Climate Assessment regions.

trained with a primary focus on improving reservoir release performance, release and storage time series were also compared with observed records to assess the quality of the parameterization (See Figure S2 in Supporting Information S1 for representative time series). Monthly-averaged release, simulated with observed inflow, exhibits satisfactory performance against observed release, with median Nash-Sutcliffe Efficiency (NSE) scores exceeding 0.8 across the CONUS and 7 National Climate Assessment (NCA) regions (USGCRP, 2018) (Figure 2). Modeled release performance was also compared with validations reported in recent studies for similar time periods (Figure S3 in Supporting Information S1). The ResOps module was then incorporated within WBM's river routing processes, simulating daily release rules for individual dams as a gridded feature of the hydrological simulations (Figure 1). All streamflow and hydropower results in the main body of this paper were simulated using the WBM-ResOps configuration. Comparisons of ResOps performance using WBM-routed streamflow and observed inflow inputs are detailed in Text S4 in Supporting Information S1.

An offline (post-processing) hydropower module was developed to simulate monthly hydropower generation (P_{sim}), in which monthly aggregates of reservoir storage (S_{sim}) and release (R_{sim}) from WBM are applied in a non-linear regression scheme.

$$P_{\text{sim}} = aR_{\text{sim}} + bS_{\text{sim}}R_{\text{sim}} + cS_{\text{sim}} + eR_{\text{sim}}{}^{d} + zR_{\text{sim}}{}^{f} \tag{2}$$

A concrete optimization model was developed using the python package Pyomo (Hart et al., 2011) to solve for 7 bounded coefficients (a, b, c, d, e, f, z) for each hydropower facility. Monthly power generation estimates from the RectifHyd data set (2001–2019) were used to fit the regression for each respective GCM using NSE and Kling-Gupta Efficiency (KGE) scores (Turner, Voisin, & Nelson, 2022). The RectifHyd data set was also used to measure the performance of simulated hydropower generation as a benchmark comparison, with NSE and KGE scores of 0.6 and 0.7 for national total monthly generation (see Text S3 and S4 in Supporting Information S1).

We simulate a total of 1,384 dams and 326 hydropower plants (all greater than 30 MW) across the CONUS domain (Figure 3). While the WBM reservoir operations exclude run-of-river dams, which are assumed to have

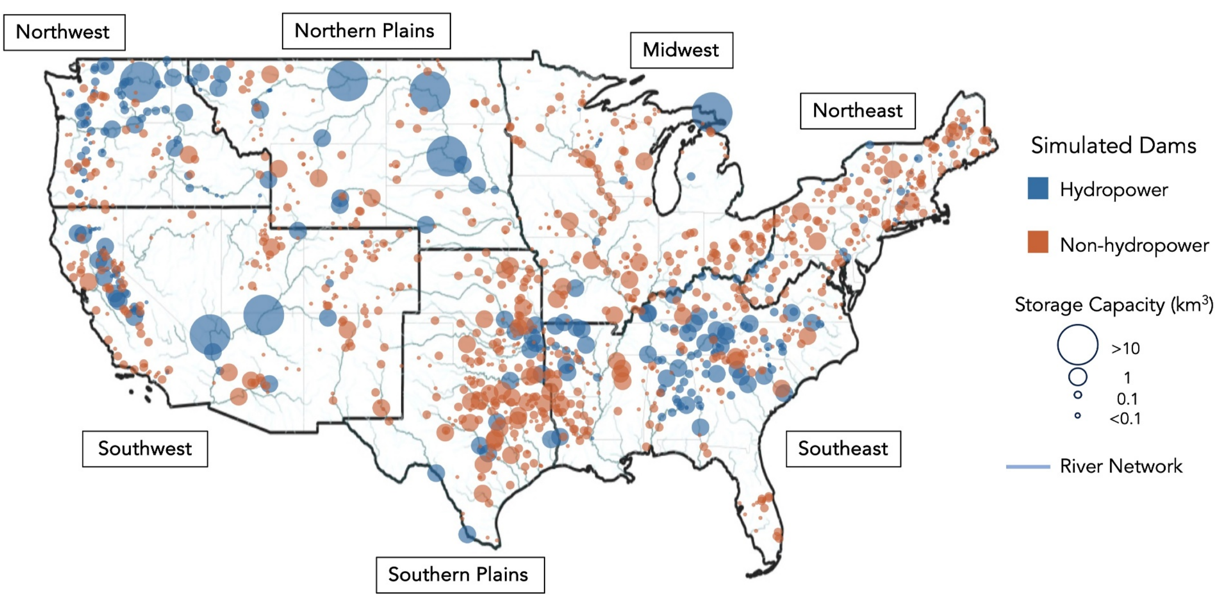

Figure 3. Map of CONUS study area with 7 National Climate Assessment regions outlined and labeled, with a coarse display of the simulated river network and 1,384 simulated dams identified by hydropower generation status (326 hydropower dams and 1,058 non-hydropower dams) and maximum water storage capacity.

no impact on daily river flow, we include 84 run-of-river hydropower dams in our hydropower database to account for their contribution to regional electricity generation. In total, our simulations account for roughly 88% of the installed hydropower generation capacity in the U.S. in 2019 (Uria-Martinez et al., 2021).

2.3. Synthesizing the Results

Regional results are prepared using state boundaries described for 7 NCA regions in the CONUS (USGCRP, 2018). To encapsulate hydroclimatic changes across the simulation timeline, 20-year snapshots for the historical (2000–2019) and future (2056–2075) periods were selected to form the basis for most of the results reported. The temporal coverage of these snapshots, which span the start of the 21st century to the end of the simulation timeline, seeks to capture long-term signatures in simulated outputs by diffusing shorter-term climate variabilities. In the following analyses, future projected changes in river discharge and hydropower generation are calculated as the percent difference of the future snapshot relative to the historical snapshot (Figures 4–7). A statistical significance test was conducted to measure the impacts of reservoir operations on regional and seasonal streamflow (See Text S5 in Supporting Information S1). Two hydropower trend analyses were also conducted that span the simulation period. The total generation for the ensemble mean in each region is averaged in 10-year intervals from 1995 to 2075, expressed as a percent change from the average of the starting decade (1995–2005) to normalize each region for comparison and to assess relative changes from the starting decade (Figure 8a). In a separate analysis, the total generation across the CONUS domain for the ensemble mean and all 6 GCMs is visualized as a 10-year moving average of generation from 1995 to 2075 (Figure 8b).

3. Results

Projected climate of the mid-to-late century is simulated to impress significant changes on the local and regional hydrology of the CONUS. The first set of results (Section 3.1) describe a multitude of hydrological variations at the seasonal and annual time scales through quantitative summaries of river discharge (i.e., ResOps and Naturalized Run). Future hydroclimatic changes directly influence annual and seasonal power generation projections for the regional U.S. (Section 3.2). The final part of the results section explores the temporal variability in simulated power generation across regions and GCMs, discussing in greater detail the sensitivity of future hydropower trends to the choice of GCM.

3.1. Impacts of Future Climate and Reservoir Operation on River Discharge

River discharge directly downstream of our simulated dams is broadly and significantly projected to increase across the U.S. in the future, revealed by relative changes in 20-year average discharge for the GCM ensemble (Figure 4h). A fraction of dams (∼7%) experience decreased future discharge (e.g., Grand Coulee, Libby Dam, Hungry Horse Dam) and are concentrated in the western U.S. However, the vast majority of dams spanning geographic, hydrologic, and climatic profiles experience increased change in future discharge, with a CONUS-wide increase of 11% by dam median.

Accompanying the map of ensemble mean results are plotted distributions of river discharge changes at the dam locations, differentiating both region and GCM (Figures 4a–4g). All seven NCA regions have positive interquartile ranges for the ensemble mean distributions, with the dam median ranging from 4% (Northwest) (Figures 4a) to 12% (Northeast, Southeast, and Southwest) (Figures 4d, 4g, and 4e). The ensemble mean results collectively emphasize that streamflow to and from reservoirs across much of the U.S. is expected to increase in the future, with strong consensus for the Eastern U.S. Unlike their ensemble mean, the six GCMs tend toward a wide range of simulated projections for streamflow, with long-term variabilities among the respective climate inputs translating expectedly to strong geographic variability in streamflow changes at the regional scale. The Northwest (Figure 4a), Northern Plains (Figure 4b), and Southern Plains (Figure 4f) exhibit the clearest conflict among the GCMs, with negative or negligible streamflow changes for multiple GCMs, but significant increases for MRI-ESM2-0 and NorESM2-MM that drive the ensemble mean distribution firmly into the positive range. MRI-ESM2-0 is the only GCM for which future river discharge is consistently projected to increase across the regions, while BCC-CSM2-MR causes the most consistent declines in future discharge, particularly in the western U.S.

Projected changes in the ensemble mean streamflow were also analyzed by season and model configuration (i.e., Naturalized and ResOps) (Figure 5). The statistical significance of reservoir-related impacts on streamflow was

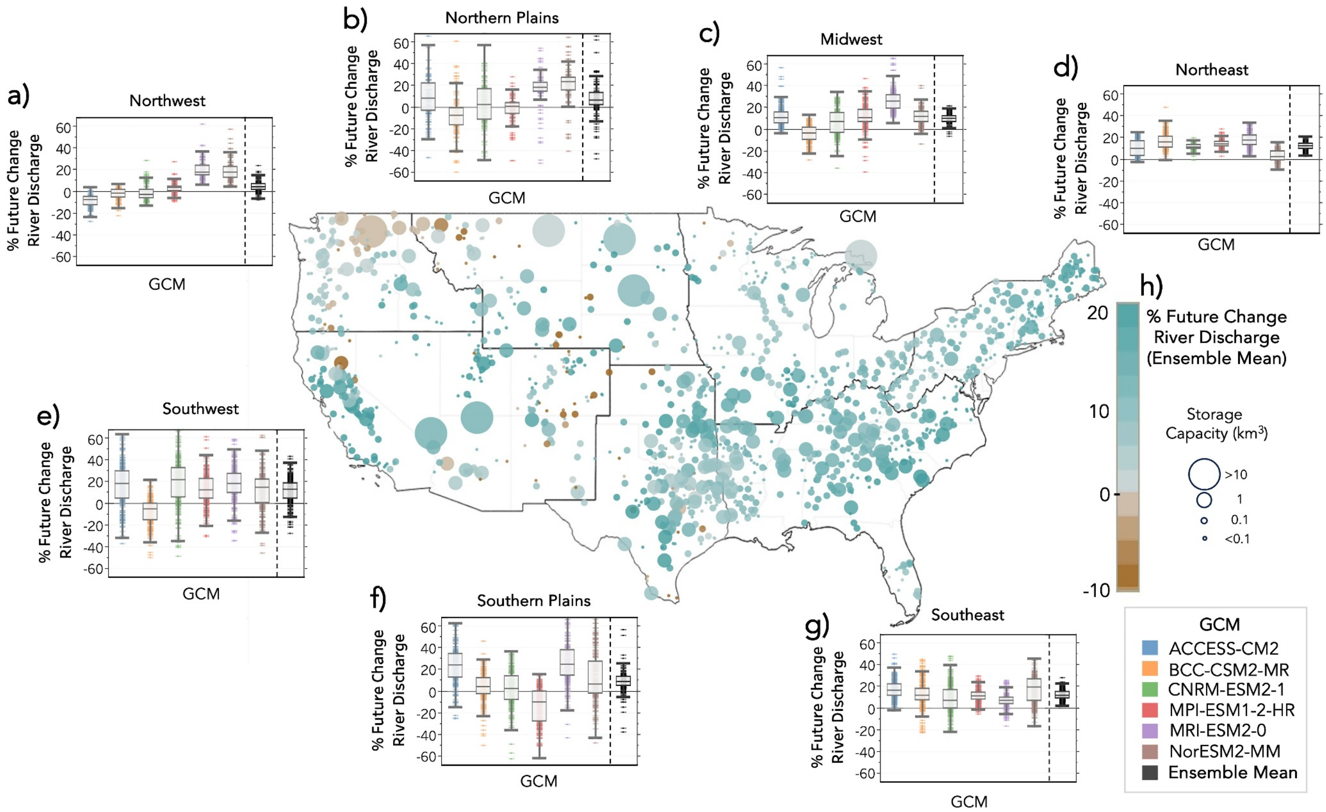

Figure 4. Multi-panel plots showing percent future change in reservoir-operated river discharge for 1,384 dams, where change is calculated as the percent difference of 20-year mean discharge between the historical (2000–2019) and future (2056–2075) periods. The map displays the General Circulation Model (GCM) ensemble with a dam-specific color bar (h), sized by water storage capacity. Surrounding box-and-whisker graphs (a–g) show the distribution of dam-specific changes in discharge by National Climate Assessment region for each of the 6 GCMs (colored) and the GCM ensemble mean (far right in black).

assessed by season and region to affirm the discussions below, except when stated otherwise (Table S2 in Supporting Information S1). In the absence of hydrological interventions by dams, the Naturalized simulation isolates climate-driven changes to long-term streamflow and creates an opportunity to reveal relative impacts of reservoir operation. Naturalized winter flows see the greatest relative change in the future (+21% by dam median), with all regions having positive interquartile ranges in the winter. We also find that regions with comparatively greater snowmelt-driven runoff and mountainous terrain - Northeast (Figure 5d), Northern Plains (Figure 5b), and Southwest (Figure 5e) - experience substantial increases in winter discharge of over 25% for the dam medians and over 42% for the upper quartiles. The ResOps simulation demonstrates the buffering capability of reservoir storage in restraining increased winter flows in all regions, but with greater effect in the Northern Plains and Southwest regions which largely encompass the mountain states of the U.S. Dams in these regions reduce winter-related median increases by 14.7% and 8.5%, respectively.

Naturalized spring discharge in the future is generally projected to increase at most dam locations, but with a CONUS-wide median increase of 8% that is far less than for winter flows. The impacts of reservoir operations contrast by region, enhancing the climate-driven rise in spring discharge for the Midwest by 0.9% (Figure 5c), Northeast by 2.7% (Figure 5d), and Southeast by 1.6% (Figure 5g), while restraining the seasonal rise in the Northern Plains by 4.5% (Figure 5b) and bearing no statistically significant changes for the Northwest (Figure 5a), Southwest (Figure 5e), and Southern Plains (Figure 5f) (Table S2 in Supporting Information S1). The variability in regional sensitivity to reservoir operations in augmenting future spring streamflow changes can be attributed to both region-dependent shifts in the timings of peak flows and dam storage availability following elevated winter flows.

An expected consequence of considerable increases in future discharge during winter and spring, as well as warming trends in summer temperatures, is reduced summer discharge. Our simulations find that changes in

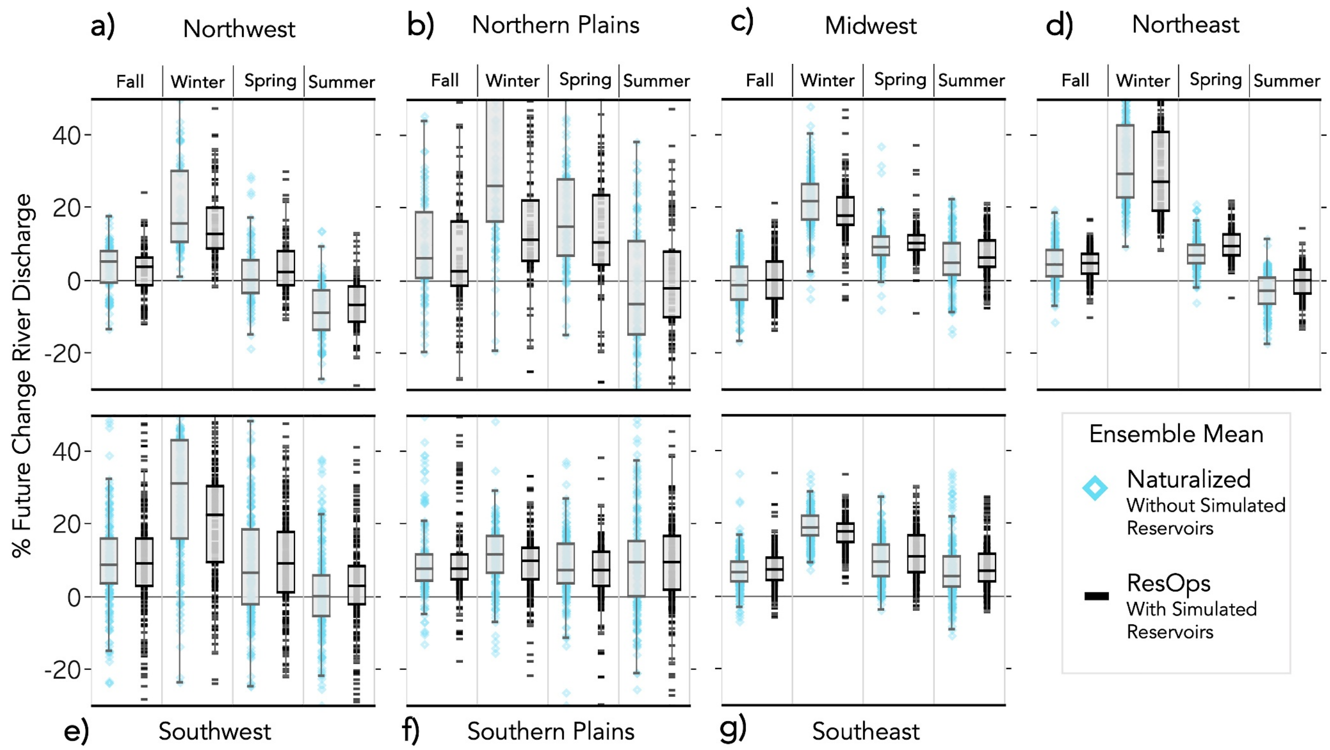

Figure 5. Multi-panel box-and-whisker plots showing percent future change in river discharge for 1,384 dams, where change is calculated as the percent difference of 20-year mean discharge between historical (2000–2019) and future (2056–2075) periods. Distributions are displayed for each of 4 seasons and 7 National Climate Assessment regions (a–g) for the General Circulation Model ensemble mean, comparing results from two Water Balance Model simulations—Naturalized (simulated without reservoirs) and ResOps (simulated with reservoirs).

future naturalized summer flows are strongly dependent on regional hydrology and climate, with a small median change of 2% for the whole of CONUS. Naturalized summer discharge decreases in the Northwest (−9% median), Northern Plains (−6.7% median), and Northeast (−3% median), while increasing in the Southern Plains (+9%), Midwest (+4.4% median), and Southeast (+5.5% median). Southwestern dams are almost equally divided in trend direction, with the smallest relative regional change (−0.2% median). In all regions, reservoir operation delivers additional summer releases that increase future streamflow for most dams; however, this effect is not statistically significant in the Northern and Southern Plains (Table S2 in Supporting Information S1). A product of sub-annual carry-over storage, reservoirs provide an important mitigation of climate-driven declines in summer flows using increased supplies from winter and spring months. This effect is most prominent in the Northeast and Southwest, where the Naturalized median receives a 3% bump and the interquartile range shifts positively by a similar degree. The Northwest has the lowest dam median for reservoir-augmented summer flows (−7%).

3.2. Impacts of Future Climate on Hydropower Generation

A regional analysis of future generation changes is explored for each of the GCMs as well as their ensemble mean (Figure 6). All regions project modest increases in total generation in the future for the ensemble mean. The Southeast (Figure 6g) and Southern Plains (Figure 6f) see the largest increase in future generation (6.5% and 6%, respectively), with all hydropower dams in the two regions projecting increased generation. The dams that experience the strongest declines in future generation are in the Southwest (Figure 6e), with 6 dams in the region seeing power losses greater than 4% and as high as 18%. However, total generation in the region still increases by 5%, driven in part by the 12% increase at the Hoover Dam and Glen Canyon. Generation in the Northwest (Figure 6a) experiences smaller change in comparison, with nominal projected increase in total regional generation (1%).

GCM-based variability is pronounced across the CONUS due to considerable variability in streamflow projections linked to the respective climate inputs. While there is strong consensus among the GCMs in the Southeast

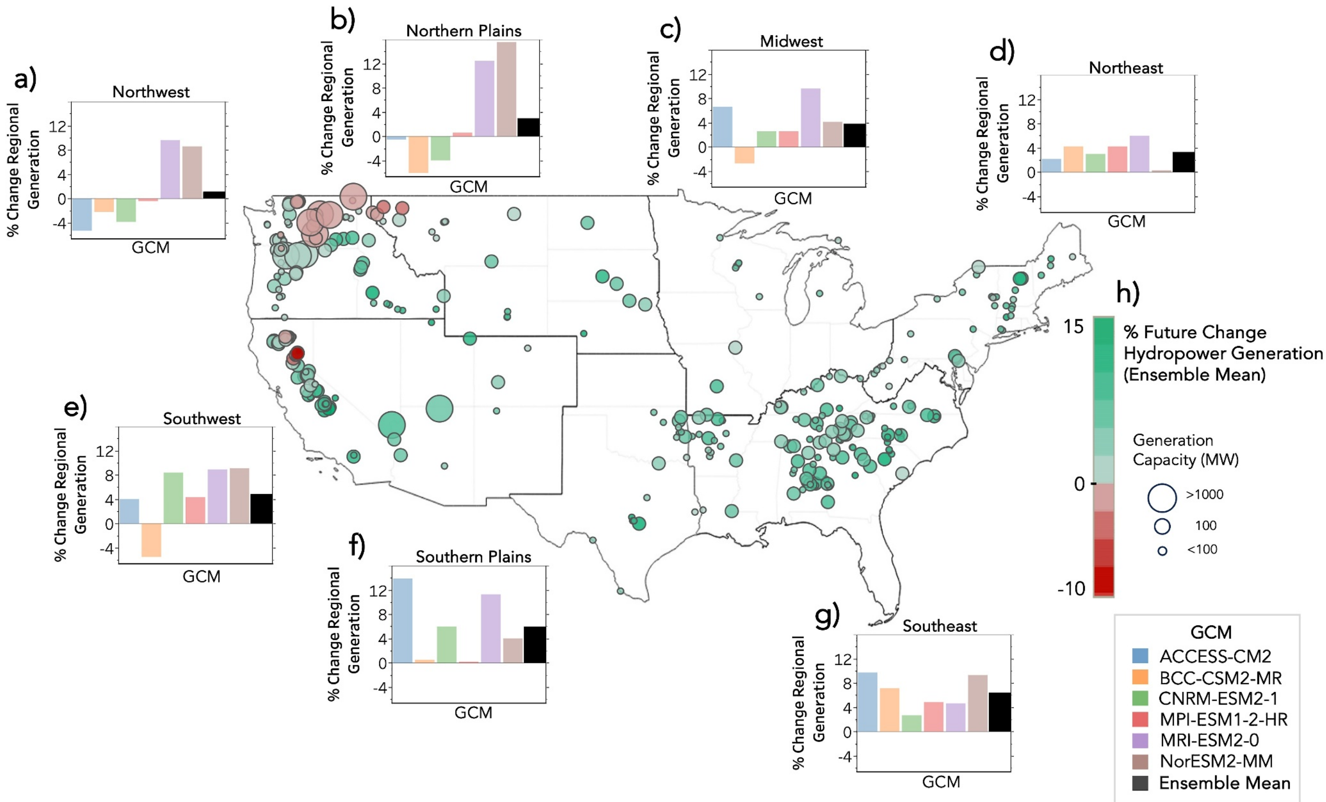

Figure 6. Multi-panel plots showing percent future change in hydropower generation for 326 dams, where change is calculated as percent difference of 20-year mean generation between the historical (2000–2019) and future (2056–2075) periods. The map displays the General Circulation Model (GCM) ensemble with a hydropower-specific color bar and is sized by generation capacity (h). Surrounding box-and-whisker graphs (a–g) plot the percent change in total generation by National Climate Assessment region for each of the 6 GCMs (colored) and the GCM ensemble mean (black).

(i.e., all GCMs project increased future generation with similar magnitude), the remaining regions yield conflicting conclusions based on the GCM considered. Generation changes in the Northwest (Figure 6a) and Northern Plains (Figure 6b) are most conflicted by GCM selection, with significant increases for MRI-ESM2-0 and NorESM2-MM driving the ensemble mean into the positive range. MRI-ESM2-0 and NorESM2-MM consistently project increased future generation in all regions, while the remaining GCMs show strong regional variability and produce minor or declining projections in the Northwest and Northern Plains.

Changes in total seasonal generation by 20-year snapshot (Figure 7) are largely correlated with the seasonal results for streamflow changes (Figure 5). Total hydropower generation increases for all future seasons in 4 regions - Midwest (Figure 7c), Southwest (Figure 7e), Southern Plains (Figure 7f), and Southeast (Figure 7g). The Southwest has the most extreme outliers in its seasonal distribution of dams which range from +34% to −29% of generation change (Figure S5 in Supporting Information S1), but the aggregate regional profile is relatively stable and positive. The remaining regions—Northwest (Figure 7a), Northern Plains (Figure 7b), and Northeast (Figure 7d) - exhibit a characteristic seasonal shift toward elevated winter and spring generation and declined summer generation. The Northwest projects the most intense seasonal variability, with a 9% increase in winter and a near 8% decrease in the summer. Like the Southwest, the Northwest has several notable outliers in the winter and spring with up to +33% in future generation change (Figure S5 in Supporting Information S1). Though the trend in future summer generation is regionally dependent, all regions experience enhanced winter and spring generation.

For the GCM ensemble mean at the national scale, winter generation rises by nearly 9% into the future and spring generation rises by about 5%, while summer generation decreases by 3.4% and fall generation increases minutely (Figure 7h). Altogether, national hydropower generation increases by almost 3% in the future. The selection of GCMs is crucial in drawing conclusions for future seasonal and annual changes in hydropower generation, as

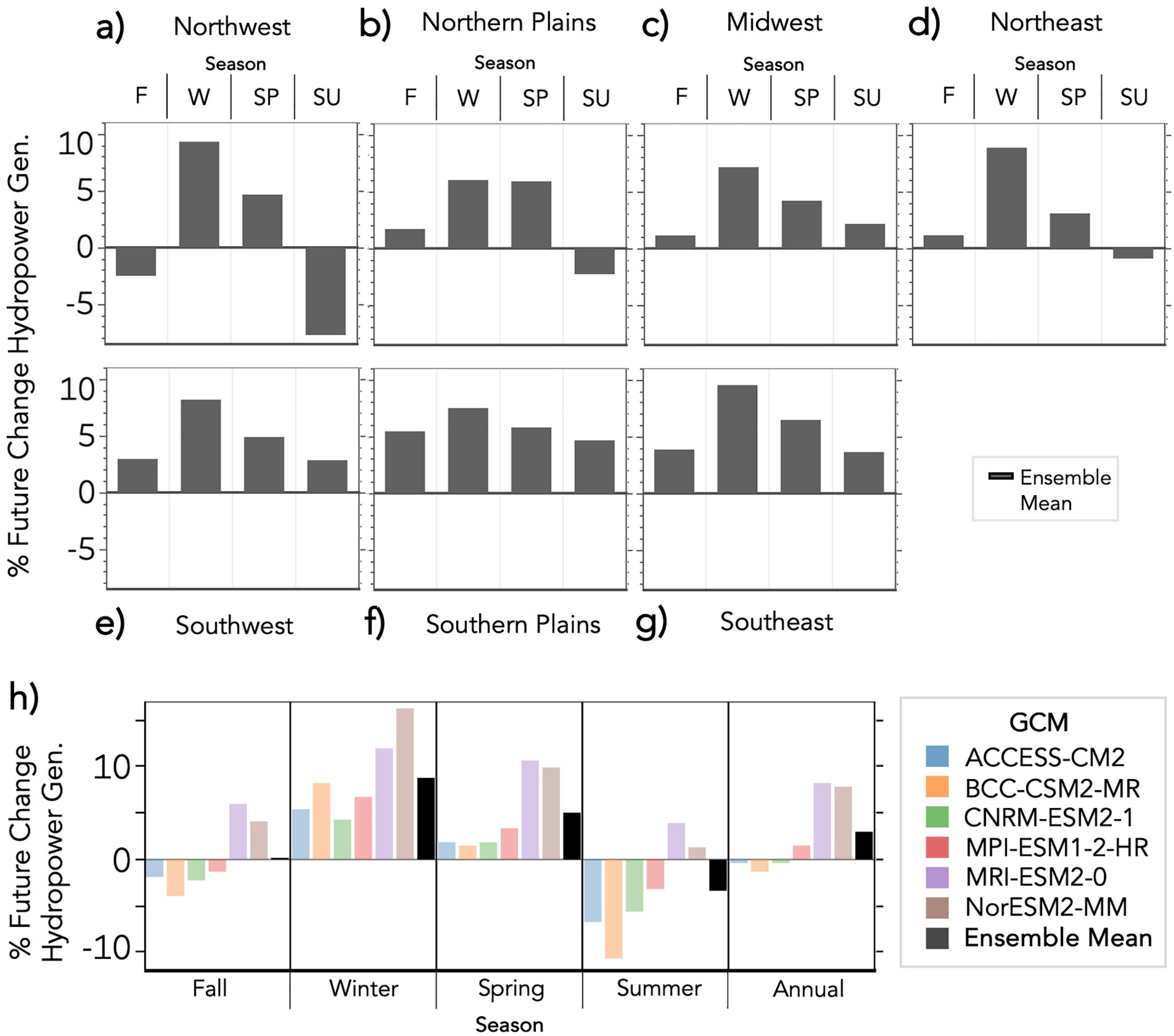

Figure 7. Multi-panel plots showing seasonal percent future change in hydropower generation for 326 dams, where change is calculated as the percent difference of 20-year mean discharge between historical (2000–2019) and future (2056–2075) periods. (a–g) Results for 7 National Climate Assessment regions for the General Circulation Model (GCM) ensemble mean, with seasons indicated by F (fall), W (winter), SP (spring), SU (summer). (h) Seasonal and annual summary of total national generation change for colored GCMs and the ensemble mean.

evident in the long-term variability among the GCMs. Winter and spring generation is increasing for all GCMs, though the magnitude is significantly greater for MRI-ESM2-0 and NorESM2-MM, while the projected summer and fall generations demonstrate strong disagreements among the GCMs. BCC-CSM2-MR produces the sharpest decline in summer and annual generation in the future, but strong increases for MRI-ESM2-0 and NorESM2-MM drive future annual generation for the ensemble mean firmly into the positive range.

The temporal effects of variabilities in climate inputs and hydrological outputs across the simulation timeline were examined for hydropower generation estimates (Figure 8). Relative changes in regional hydropower generation for the ensemble mean are expressed as percent changes in decade-averaged generation relative to the starting decade (1995–2005) (Figure 8a). Contrasting with the 20-year snapshots reported in previous figures, variability and trends in projected hydropower changes are appreciated in greater detail with this decadal representation, but the magnitudes of relative change differ from the longer-term snapshots.

Generation in the Northern Plains climbs into the mid-century far more than the remaining regions, peaking at 12% greater than the starting decade, before ending with a 4% change (Figure 8a). The Southern Plains experiences the least stability over the simulation timeline, with an immediate dip of 9% from the starting decade

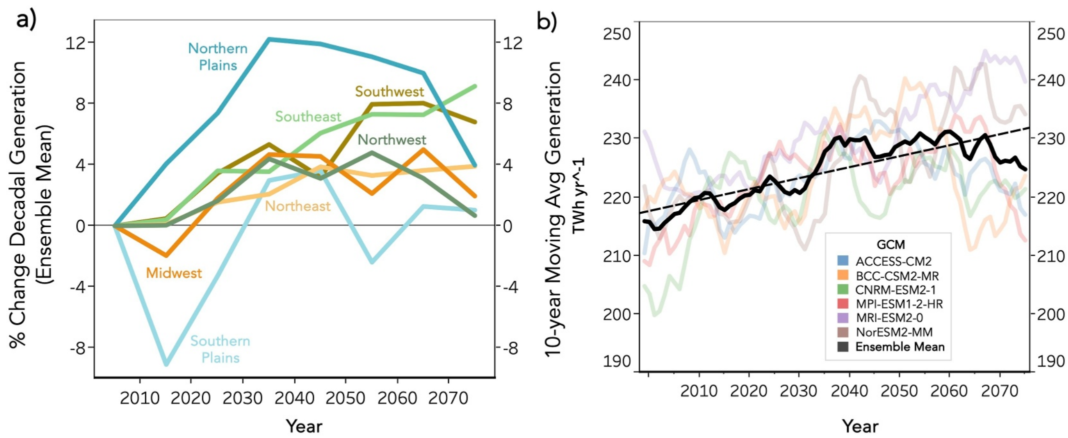

Figure 8. Plots of projected hydropower changes into the future. (a) Decade-averaged hydropower generation for the General Circulation Model (GCM) ensemble mean expressed as a percent change relative to the starting decade (1995–2005). (b) 10-year moving average of hydropower generation for colored GCMs, with a trend line shown for the ensemble mean.

followed by a peak of 3.6% and another dip, ending with a mere 1% change from the starting decade. The Southern Plains is the only region that sees decreased hydropower generation during the mid-century. The remaining regions exhibit relatively consistent increases in hydropower generation for most of the simulation timeline, but positive and negative changes in decade-to-decade generation in all regions reflect decade-scale climate variability. The Northwest and Midwest, which peak at 4.8% and 5% relative changes to the starting decade, end with 0.7% and 2%, respectively. The Southeast and Southwest see the largest relative increase in generation by the final decade, at 9.2% and 6.8%, respectively. The Northeast sees a 4% increase in generation by the final decade.

Total annual average generation for all simulated dams is presented in a 10-year moving average of the GCM ensemble mean along with the six GCMs (Figure 8b). The entire range of GCM variability across the simulation timeline amounts to 45 TWh per year (23% of the lowest value), with a maximum range for a single year of 27 TWh (13% of the lower value). The GCMS are in general agreement with respect to long term trends in generation up to 2060, even though decadal variability is apparent. Hydropower generation rises moderately but steadily for the ensemble mean, peaking in 2060 with 231 TWh per year. From 2060 onwards, the GCM trends diverge strongly, with 4 GCMS decreasing and 2 GCMs increasing. Despite the decadal variability among GCMs, the ensemble mean trend for the entire time series indicates an average projection of +188 GWh/year into the future.

4. Discussion and Conclusion

In this study, we present an integrated assessment of nationwide reservoir and hydropower operations in the U.S. using future climate projections from the CMIP6. We employ a new reservoir operations and parameterization scheme in a multi-model framework to develop insights for future water management and energy planning at the regional scale. Our study manages the multi-layered complexity of climate model variability and high-resolution hydrological modeling to project aggregate changes in water availability and assess the future viability of hydropower through the late 21st century.

4.1. Streamflow and Hydropower Projections

With notable exceptions in western regions, we simulate climate-driven increases in future annual streamflow at the locations of most U.S. reservoirs, amounting to a CONUS-wide 11% increase by dam median for the GCM ensemble mean. The incline in naturalized streamflow is primarily driven by winter streamflow increases, which are pronounced in three snowmelt-dominated regions - Northeast, Northern Plains, and Southwest. Changes to summer flows are regionally diverse, with prominent declines in the Northwest, Northern Plains, and Northeast and increases in the Midwest, Southern Plains, and Southeast. These findings support previous studies that have attributed amplified winter flows and consequent declined summer flows to early snowmelt induced by warming temperatures and changes in precipitation patterns (Barnett et al., 2005; Kao et al., 2022), with particular sensitivity in the western and northeastern U.S. (Hayhoe et al., 2007; Li et al., 2017; Rauscher et al., 2008; Stewart, 2009). See Kao et al. (2022) for detailed analysis of climate-driven seasonal dynamics in the selected GCMs. Comparisons of future streamflow with and without the mediation of reservoirs highlight their dampening of intra-annual streamflow changes, including the delivery of additional releases in the summer to mitigate declining streamflow in all regions. Future work could incorporate the climate and infrastructure impacts discussed here in a larger assessment of water security, which can address limitations of our study including water demand projections and groundwater pumping.

Hydropower generation is principally determined by the respective river discharge at the dam locations, more specifically by dam releases to hydro turbines, with storage levels playing an additional but lesser role. In addition, roughly a quarter of the simulated generation capacity is attributed to run-of-river dams that do not simulate the influence of reservoir operation or storage on plant generation. Therefore, projected changes in long-term discharge in the future generally correlate with those of hydropower generation. For the GCM ensemble mean, all regions benefit from moderate increases in annual generation, most notably the Southeast, while the Northwest experiences small change due to strong divergences among its relatively large hydropower dams. Significant relative increases in future generation in the winter (+9%) and spring (+5%) are met with declines in the summer (−3.4%), amounting to a temperate increase in annual generation (+3%) at a rolling decade-averaged rate of +188 GWh per year. While the long-term averaged results reported here capture the overall direction and magnitude of climate change impacts, our methodology can support analyses at finer scales with consideration of extreme cases.

National hydropower projections are consistent with those reported by Kao et al. (2022) and Broman et al. (2024), based on identical GCMs, but with slight differences in magnitude (+4% and +10% annual change, respectively). Accepting that several methodological differences prevent a direct comparison, including in the hydropower facilities simulated, our findings highlight strong variability in trend direction and magnitude throughout the simulation timeline. From 2050 to 2075, we simulate generation declining in the Northwest, Midwest, and Northern Plains and rising in the Southeast. Extending the simulation timeline ultimately constrains the larger mid-century projections reported by the comparative studies. This is consistent with the widespread reductions in hydropower usable capacity for 2040–2069 simulated by van Vliet et al. (2016).

4.2. Uncertainties in Western U.S. Projections

The ensemble mean projections of increased annual streamflow for most reservoirs in the western U.S. contrast with multiple simulation studies that predict an overall declining future trend (Das et al., 2011; Miller et al., 2021; Seager et al., 2013; Siirila-Woodburn et al., 2021). An important caveat for the general findings is variability among GCM inputs, which is understood to be a major cause of bias in forming conclusions around future projections and power risks. GCM uncertainty is embedded in all reported results, but we observe that projections in western regions are highly sensitive to GCM consideration. While long-term streamflow changes downstream of reservoirs are not comprehensive representations of regional streamflow and do not weigh the reservoir distributions by flow magnitude in our results, the influence of climate inputs is present, nonetheless. For example, simulations based only on the GCM BCC-CSM2-MR consistently project negative streamflow and electricity generation trends in the future western U.S.

A primary factor driving western streamflow change is declining snowpack, a phenomenon that is challenging to accurately capture in earth system models due to the simplification and underrepresentation of mountain hydrology (Pierce et al., 2022; Siirila-Woodburn et al., 2021). Kao et al. (2022) project intensified future hydrology in the western U.S. with significant increases in high runoff due to early snowmelt and decreases in low runoff during the summer. Concluding the sign and significance of annual streamflow change in snowmelt-dominated catchments is dependent on the spatiotemporal resolution and domain considered as well as statistical treatments used, with long-term regional averages indicating an aggregate signal that may obscure the influence of extreme values. For instance, Bartos and Chester (2015) simulated nominal changes in future annual hydroelectric power in the Northwest and the western U.S. overall, despite significant losses to summertime generation capacity that may pose a greater challenge to grid reliability. Broman et al. (2024) further discuss high uncertainty in southwestern hydropower projections that arise from the seasonal intensification driven by snowpack dynamics, exhibited by large ranges in the 5th and 95th percentiles of generation change. These findings support our analysis of the western U.S. having the greatest incoherence among the GCMs and the largest variability in reservoir flow

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projections, resulting in minute annual change but intensified seasonal change in Northwestern hydropower, for the ensemble mean. Strong variability among the climate projections reported at the regional and national scale recommend the use of a wider array of GCMs to form well-defined conclusions on regional sustainability.

Another important feature driving western streamflow change is evapotranspiration, including its role in snowpack decline, soil moisture, and drought severity (Friedrich et al., 2018). While increased evapotranspiration from warming trends is captured in the hydroclimate simulations (Kao et al., 2016, 2022), our reservoir operations do not currently account for additional evaporative losses of impounded water bodies as compared to naturalized stream conditions. In a recent study, Zhao et al. (2023) evaluated future projected evaporation loss from 678 major reservoirs in the U.S. using identical CMIP6-based hydroclimate projections processed by the VIC model. As such, the enhanced reservoir evaporation losses reported by Zhao et al. (2023) can reasonably illustrate expected impacts of its omission from our methodology. The study projects an average increase in reservoir evaporation loss of 0.06% per year into the mid-century, with reservoirs in the Southwest and Southern Plains seeing a 9% increase in loss by the mid-century. Evaporation loss is a small fraction of total reservoir outflow in most regions of the U.S. (<10%), with future annual streamflow generally increasing faster than evaporation loss. However, reservoirs in arid/semi-arid regions in the western U.S. are more sensitive to this effect, owing to high evaporation-to-outflow ratios. Future work can include additional evaporative losses in reservoirs to isolate this effect in comparison to naturalized stream evaporation. The magnitude of evaporative loss in summer months can also be compared to the increased water availability facilitated by reservoir operating rules.

4.3. Sustaining Hydropower in the Future

Aggregate power projections suggest that hydropower may continue to serve as a reliable and dispatchable source of electricity in the future renewable portfolio if adaptations are considered for expected geographic and sub-annual trends. Reservoir and hydropower operations are currently simulated with operating rules calibrated for a contemporary hydroclimate using dam and stream gauge records. This presents an opportunity to explore strategic operating rules, as well as the retrofitting of non-powered dams, to optimize generation for future climate conditions (van Vliet et al., 2016). Importantly, the geographic distribution of hydropower dams is strongly heterogeneous, with greater concentrations in the Northwest, Southeast, and Southwest. Hydropower dams in the Northwest alone account for 46% of the total generation capacity in the simulated CONUS domain. For this reason, conclusions on the future viability of the nation's hydropower are anchored in regional uncertainties, particularly those pertaining to the western U.S. as previously discussed. The increased prevalence and severity of future droughts, for example, is a major source of uncertainty in all regions that yields power risks not sufficiently captured by GCM ensemble trends or long-term projections (Broman et al., 2024).

The seasonal intensification of the nation's hydropower, characterized by increased generation in the winter and declines in the summer, presents an important challenge to meeting future energy demands. Warmer ambient temperatures are expected to elevate peak electricity loads during summer months, particularly for residential and commercial cooling needs, while at the same time stressing transmission infrastructure (Bartos et al., 2016; Dirks et al., 2015; Fant et al., 2020; McFarland et al., 2015). This creates a conflict in sub-annual power supply-demand timing, particularly for balancing authorities in the western U.S. that rely on hydropower for 20%–30% of electricity needs (Kao et al., 2022; Turner, Voisin, Nelson, & Tidwell, 2022). However, in the context of electricity markets supported by the increasing penetration of renewables, seasonal shifts in hydropower may counterbalance the problematic seasonal intermittencies of solar power (Gandhi et al., 2020; Yin et al., 2020). These findings motivate further assessment of grid stability in the regional U.S. for future hydropower and solar, accounting for tradeoffs in their sub-annual generation trends and land requirements and efficiencies (Fekete et al., 2023; Waldman et al., 2019). Future work could also incorporate integration strategies from emerging floating solar photovoltaics (Jin et al., 2023) and pumped hydropower storage (Koritarov et al., 2014; Uria-Martinez & Johnson, 2023).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The code supporting WBM simulations, including the ResOps module and reservoir-related parameters and the post-processing regression for hydropower simulations, and all data presented in this paper have been made available at the https://doi.org/10.5281/zenodo.14272679 (Bokhari et al., 2025).

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