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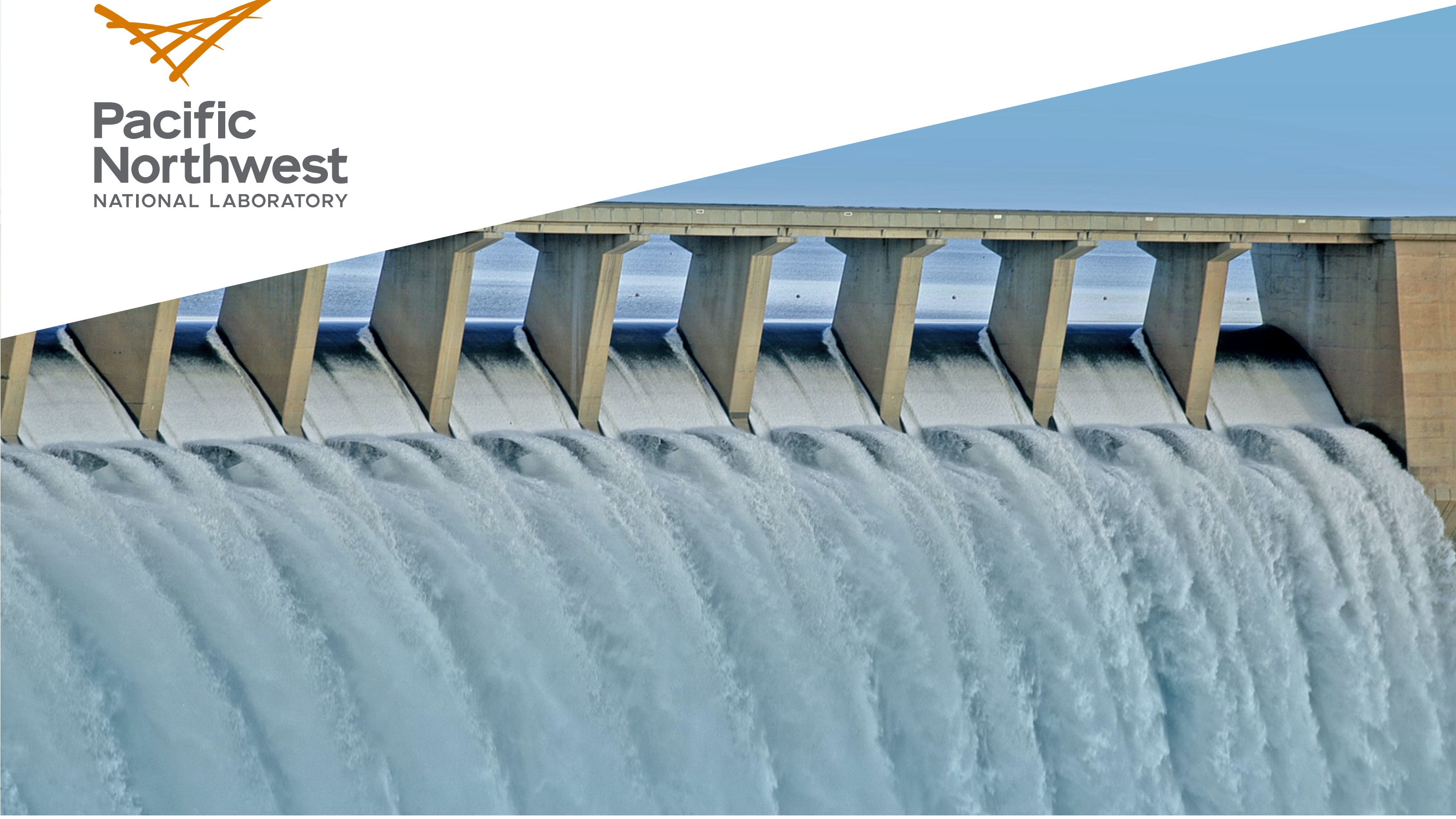

PNNL-33212

Drought Impacts on Hydroelectric Power Generation in the Western United States

A multiregional analysis of 21st century hydropower generation

September 2022

Sean W.D. Turner
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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Summary

The western United States (referred to as “the West” in this report) experiences large fluctuations in rain and snowfall from year to year, affecting river flows and reservoir levels. This interannual variability in water resources leaves a strong signature on total annual energy generated by the region’s fleet of hydroelectric dams. In a wet year, like 2011, hydropower can meet 30 percent of annual western electricity demand. That contribution can drop below 20 percent during severe drought years. Characterizing the contribution of hydroelectric power to the western generation portfolio during drought is crucial to understanding the resilience of the power grid to climate risk, both now and in the future. This report analyzes the impacts of historical western droughts on hydroelectric power by combining two decades’ worth of annual generation—recorded at more than 600 hydroelectric power plants—with historical climate data developed for distinct hydropower climate regions of the West.

The most extreme impacts of drought on hydroelectric power are found at individual dams where reservoir levels are so low that released water—and thus power generation—becomes severely restricted. These isolated cases often receive widespread attention in national media, leading to a possible misconception that hydroelectric power is an unreliable technology whose role and contribution will diminish over time if the western climate produces longer and more severe droughts. Yet, when aggregated to the scale of the West, the observational records of hydropower generation tell a different story. **Even during the most severe droughts experienced since the turn of the century, the western hydropower fleet sustained four-fifths or more of its typical annual generation**. This translates to approximately 140–150 TWh of renewable energy in a severe drought year, which is of similar magnitude to annual output from all other renewable electricity sources in the West combined (renewables excluding hydro contributed 140 TWh in 2020 and 159 TWh in 2021).

Drought in 2021 led to the worst year for hydropower generation in the West since 2001, with total generation approximately 16 percent below the 21st century average. The year 2021 was particularly severe in California (second worst hydro year of the last two decades, ~48 percent below average) and Oregon (worst hydro year of the last two decades, ~16 percent below average), while generation in Washington and Idaho was affected to a lesser degree (~12 percent below average for combined region). The year **2001 remains the year of lowest western hydropower generation of the 21st century so far**, owing to extreme drought in the Pacific Northwest, where about two-thirds of western hydropower capacity is located.

The main reason for the relative stability in total western annual hydropower generation is diversity of weather conditions across the region; **drought rarely impairs hydropower generation across all western river basins at the same time**. To support an analysis of drought impacts on hydroelectric generation that considers the West’s climatic diversity, this report introduces eight hydropower climate regions of the West, each unique in the drought conditions it experiences and in the water storage capacities and operations of its dam and reservoir fleet. The hydropower climate regions are Mid to Upper Columbia (accounting for 51 percent of western generation on average), South Cascades/California (18 percent), Snake River Basin (11 percent), North Cascades/Puget Sound (10 percent), Lower Colorado Projects (6 percent), Missouri Headwaters (2 percent), Colorado Rockies (1 percent), and Utah Wasatch Range (< 1 percent). **A multiregional analysis of drought impacts on total generation reveals six separate worst hydro drought years in the West during the 21st century**. These years are 2001 (worst hydro year overall in the West and worst year in the Mid to Upper Columbia, as well as Northern Cascades/Puget Sound region), 2002 (worst hydro year in

Missouri Headwaters), 2004 (worst hydro year in Utah Wasatch Range), 2013 (worst hydro year in Colorado Rockies), 2015 (worst year in Southern Cascades/California), and 2021 (worst hydro year in the Snake River Basin and Lower Colorado Projects).

Water-year rainfall totals correlate strongly with total annual hydropower generation in five of eight hydropower climate regions (including the four largest hydropower climate regions by generation). This allows for the use of statistical models—forced with historical precipitation data—to extrapolate western generation record back through the 20th century for each region. The extrapolated hydropower time series indicate that **a repeat of the historical western drought of 1976–1977 would cause a larger loss in annual hydropower generation than droughts experienced so far this century.** Unlike recent events, the 1976-77 drought affected the major hydropower generating regions of the Northwest and California simultaneously.

Total western hydropower generation in 2022 is likely to rebound from 2021, despite continuation of drought over much of the region. This projection is based on a forward extrapolation of hydropower generation informed by a seasonal precipitation outlook for the remainder of the current water year. The rebound in generation from 2021 levels has been driven by increased output in the Northwest regions (Mid to Upper Columbia, Snake River Basin, and Northern Cascades/Puget Sound), which experienced a relatively wet spring and held above-average snow levels going into summer dry months. Generation in California and in the Lower Colorado Projects will remain very low in 2022.

For some regions and plants, a combination of multi-year drought and reliance on large storage reservoirs can lead to non-linear loss in generation relative to water-year precipitation. Continual drawdown of reservoirs can cause sharp curtailments in powered releases as water levels drop below water management triggers or, in extreme cases, below turbine intakes. A well-documented example is Edward Hyatt power plant (second largest hydropower plant by capacity in California), which was shut down for the latter five months of 2021 as water levels in Lake Oroville dipped below intakes for the first time in more than fifty years. By analyzing the monthly net generation observations of 50 plants, we show that **sharp curtailments in hydroelectric production—which may be planned or unplanned—emerge in isolated cases in California following two or more years of continuous drought**. Lack of generation data at sub-annual timescales for the West overall means the number of plants vulnerable to shutdowns during severe drought remains unquantified. While there is little evidence for significant curtailments and shutdowns caused by drought in the West, risks of reservoir dead pool under more extreme drought conditions are not well understood and require further study. Hydropower dams with very large multi-year storage, such as the Lower Colorado Projects (Glen Canyon, Hoover) have sustained relatively stable generation through multi-year drought so far but are at risk of breaching critical reservoir thresholds within the next few years. Such risks are unique to the Lower Colorado Projects and do not reflect the status of western hydropower in general.

Acknowledgments

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The study relies on publicly available data provided by the U.S. Energy Information Administration (EIA), the U.S. Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), Oak Ridge National Laboratory, the U.S. Bureau of Reclamation (USBR), the U.S. Army Corps of Engineers (USACE), the California Data Exchange, the Northwest Alliance for Computational Science and Engineering, and the National Drought Mitigation Center.

Acronyms and Abbreviations

EIA	Energy Information Administration
ENSO	El Niño Southern Oscillation
NOAA	National Oceanic and Atmospheric Administration
PDSI	Palmer Drought Severity Index
PRISM	Parameter-elevation Regressions on Independent Slopes Model
U.S.	United States
USACE	U.S. Army Corp of Engineers
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey

Unit abbreviations

MCM	Million cubic meters
MW	Megawatt
MWh	Megawatt hours
TWh	Terawatt hours

Western state abbreviations

AZ	Arizona
CA	California
CO	Colorado
ID	Idaho
MT	Montana
NM	New Mexico
NV	Nevada
OR	Oregon
UT	Utah
WA	Washington
WY	Wyoming

Hydropower climate regions

COL	Mid to Upper Columbia River Basin
COR	Colorado Rockies
LCP	Lower Colorado Projects
MOH	Missouri Headwaters
NCP	Northern Cascades/Puget Sound
SCC	Southern Cascades/California
SRB	Snake River Basin
UTW	Utah Wasatch Range

Contents

Figures

Tables

1 Background, motivation, and approach

1.1 Hydropower droughts in the West

The western United States (herein "the West") is a region of extreme climate variability, subject to large year-to-year fluctuations in the rain and snow water required to fill reservoirs, drive turbines, and generate electricity. As a result, the region's hydroelectric power industry has been exposed to drought since its inception. The West's hydropower fleet is relatively new in geophysical timescales; few hydroelectric dams impounded western rivers during a period of frequent drought in the 1920s and early 1930s. But by the drought of 1977, most of the existing fleet was built and operational. This extreme drought caused widespread water resources depletion and significant impairment of hydropower generation across hundreds of plants throughout the region (Matthai, 1979). Such droughts are a reliably occurring feature of the western climate rather than an aberration (Diaz, 1983).

Hydroelectric dams contribute approximately one quarter of total western electricity generation, so losses in hydropower generation caused by drought are an important consideration in the planning and operation of a reliable and efficient electrical power grid. Recent drought conditions have been particularly concerning for the western electricity sector. In the southwest, single and multi-year droughts are occurring within an extreme multi-decadal climatic anomaly—the driest 22-year period in more than 1,200 years, as indicated by the paleo record (Williams et al., 2022). During the last two decades, the West's hydroclimate has been characterized by high volatility, with more frequent and intense periods of drought as compared to the 20th century (Figure 1). These conditions raise public concerns on the future of western hydropower and its role as a reliable contributor of renewable energy in a warming world.

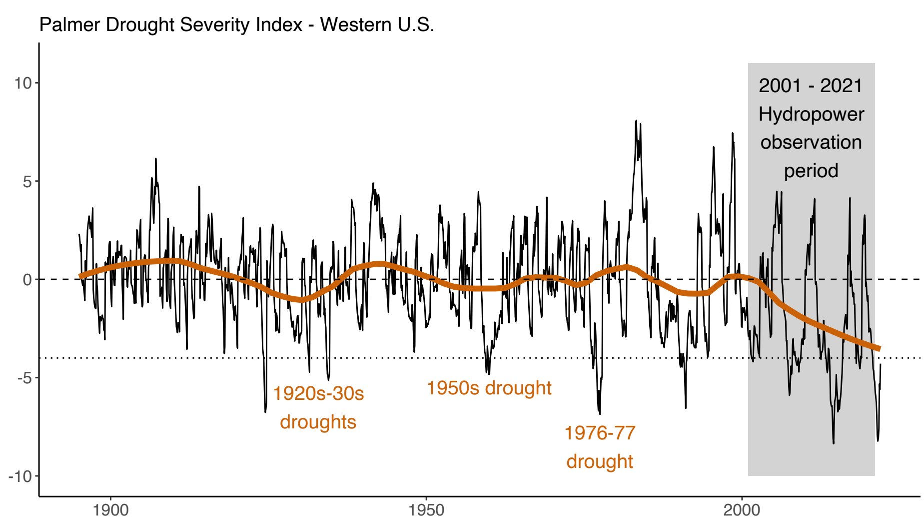


Figure 1. Western U.S. monthly Palmer Drought Severity Index (PDSI) over the last 120 years (orange line gives smoothed trend). PDSI is a meteorological drought index based on precipitation and temperature and is used to assess the severity of dry or wet spells of weather. PSDI < -4 is often interpreted as extreme drought. (Data source: NOAA Monthly U.S. Climate Divisional Database; method described in Vose et al. [2014].)

Despite recent alarming weather patterns, this report shows how and why the 21st century droughts (experienced so far) impose a lesser degree of impairment on total western hydropower generation than would a repeat of the most extreme 20th century western droughts. In this report, the West is defined as the 11-state region bounded on the east by (and including) Montana, Wyoming, Colorado, and New Mexico (consistent with the West census region and the U.S. area of the Western Interconnection power grid). More than 60 percent of U.S. hydropower capacity is in these 11 western states, and most of the contemporary western hydropower fleet has been in place for decades, with an increase of only ~1 percent generating capacity in the last 20 years. So far this century, the region has experienced three notable and distinct *hydropower droughts*—defined in this report as drought that causes a reduction in annual western hydropower generation of more than 10 percent relative to average. These are the 2001 drought in the Northwest, the 2013–2015 California drought, and the ongoing drought spanning from Oregon to California and the desert Southwest, which began in 2020 and has yet to break. The impact of these droughts on hydropower is apparent in both western and U.S. annual hydropower generation totals (Figure 2).

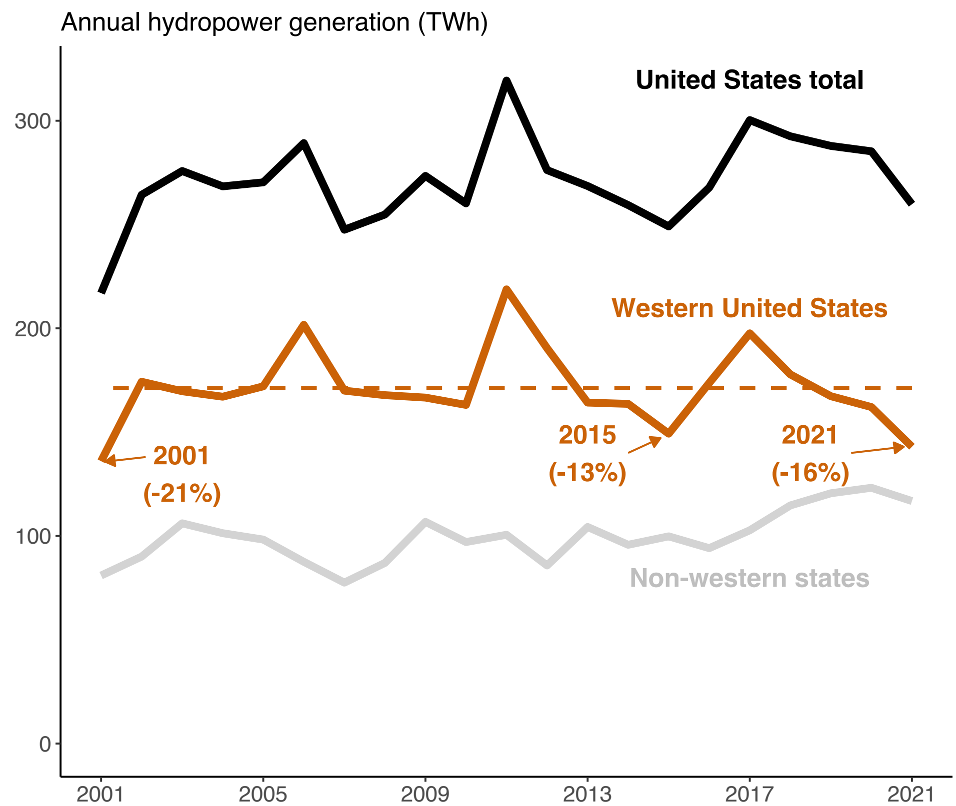


Figure 2. Total hydroelectric power generation in the United States. Western States are defined as WA, OR, CA, ID, MT, UT, CO, NV, AZ, WY, and NM. Percentage values in parentheses give deviation from mean annual western generation (dashed line). (Data source: EIA state-level generation reports.)

Each western drought is unique in its duration, intensity, and spatial extent (Figure 3). The worst of the 21st century hydropower droughts—as measured by impact on total western hydropower generation—was 2001. This drought began with exceptionally low precipitation and snow accumulation in the fall and winter of 2000 (Bumbaco and Mote, 2010), leading to near-record-low springtime flows in the Columbia River. The Columbia River Basin is home to approximately two-thirds of western hydropower generating capacity. Dry conditions in this basin, therefore, have an outsized effect on western hydropower generation. In 2001, this meant a reduction of just over one-fifth of average western hydropower generation. The significant loss of generating capacity in the Pacific Northwest led to reduction in electricity exports from the Northwest Power Pool into California, triggering what became known as the western electricity crisis (NWPCC).

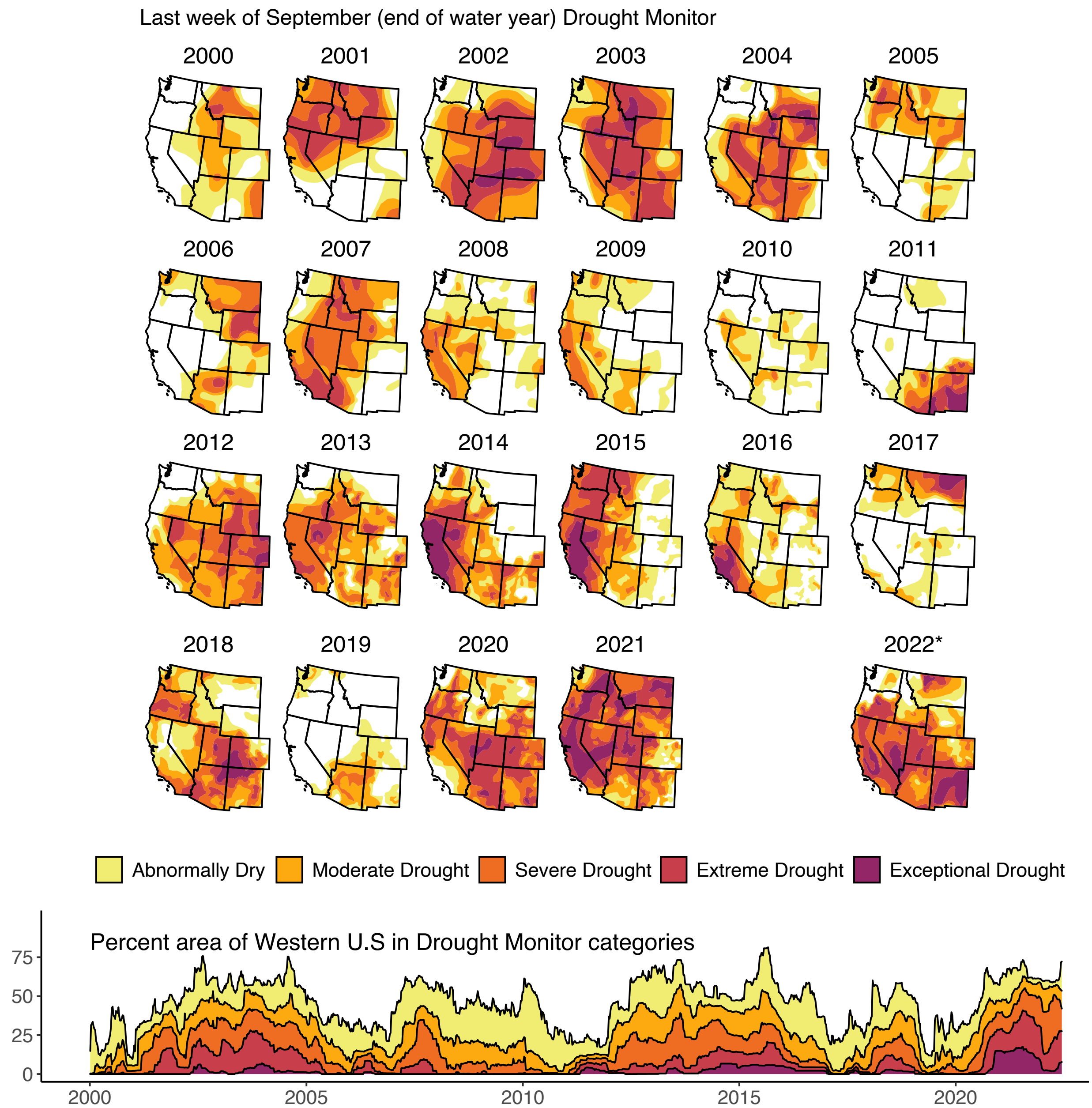


Figure 3. Upper panels—Western Region U.S. Drought Monitor maps for final week in September in each of the last 21 years (*mid-June 2022). Lower panel—Weekly U.S. Drought Monitor for Western United States this century. (Source: U.S. Drought Monitor.)

More recent hydropower drought years 2015 and 2021 differ markedly from 2001 in spatial extent, duration, and impact. These recent droughts were associated with annual generation reductions of 13 percent and 16 percent, respectively. The drought of 2013–2015 was a multi-year drought that reduced water resource availability throughout the state of California. Although California accommodates much less generating capacity that the Pacific Northwest, the region faces greater extremity in its dry years than any other region of the United States. Total annual precipitation in California can fluctuate 50 percent or more around the mean, and dry years often occur in sequence, leading to dried out soils, low river flows, and depleted reservoirs. Such conditions led to dramatic losses in hydropower in California in 2015 (more than 50 percent reduction relative to mean), causing the third worst western hydropower year of the 21st century, despite water conditions in the Northwest being close to average.

Like in 2015, the reduction in western hydropower experienced in 2021 followed an exceptionally dry year. The ongoing drought affecting much of the West began in 2020. Dry conditions intensified and expanded during 2021, such that, by late summer 2021, more than half of the West was categorized by the U.S. Drought Monitor as in “severe drought” or worse (Figure 3). Unlike in 2015, the 2021 drought affected generation in the Pacific Northwest, with generation in Washington and Idaho down ~12 percent relative to average in 2021. As a result, total western hydropower in calendar year 2021 was marginally worse than 2015, leading to an estimated 16 percent decline relative to average generation. This makes 2021 the second worst hydropower year of the 21st century.

1.2 Need for a multiregional, retrospective analysis

Much of the existing scientific knowledge of drought impacts on western hydropower derives from numerical simulation experiments. Coupled hydrological and power grid models deployed in these studies are powerful tools that have enabled scientists to explore the impacts of different droughts on hydroelectric power generation and on the performance and reliability of the Western Interconnect power grid. This rich vein of research has shown that impairment of hydropower in the West may manifest in heightened electricity supply vulnerability (Harto et al., 2012; Voisin et al., 2016; Voisin et al., 2018), increased system-wide operating costs (O’Connell et al., 2019; Cohen et al., 2022), and increased carbon emissions (Kern et al., 2020)—all of which are undesirable impacts that may be amplified in the presence of other drought-related effects, such as thermoelectric derating and heat waves (Turner et al., 2019; Dyreson et al., 2022). Drought can also alter sub-regional patterns of electricity import and export (Voisin et al., 2020), affecting electricity market dynamics (Hill et al., 2021). The advancement of coupled hydrological and grid simulation models that support such research depends on quantitative empirical studies to describe the behaviors of generating capacity under a range of conditions and at multiple scales, from river basin to plant and generating unit. Recent droughts in the West provide an excellent opportunity to explore the impacts of water shortage on the contemporary water-energy system through a retrospective analysis of generation.

The aim of this report is to analyze and explain drought impacts on observed generation across multiple subregions of the West. Prior retrospective analysis of historical climate and water availability has shown how different drought patterns could affect the West’s hydropower generating fleet; for example, severe sub-regional drought conditions coincident with large anomalies in the El Niño Southern Oscillation (ENSO) may be less threatening than milder, ENSO-neutral droughts that affect more river basins simultaneously (Voisin et al., 2018). Building on these insights, this report analyzes observed annual and monthly generation patterns across eight distinct western hydropower climate regions and 600 hydroelectric power plants, relying on meteorological data and reservoir information to link drought to impact. By analyzing historical generating patterns rather than water availability alone, the analysis captures important dam and reservoir operational effects, as well as changes in the infrastructural and institutional landscape over the last two decades.

This report does not address the impacts of drought on the ability of individual hydropower generators or groups of hydropower plants to respond to electricity price signals in real-time or to provide grid reserve and flexibility through ramping capabilities.

1.3 Data and approach

1.3.1 Hydropower generation data

Historical energy generation data for U.S. hydroelectric power plants are of inconsistent quality and resolution across plants and regions. Hourly or daily generation totals and sometimes powered flow (water released through turbines) time series are available for a selection of federally owned and operated plants in particular river basins. For example, the USACE Data Query platform provides multi-decadal, hourly generation data for 28 plants in the Northwest. Few regions or plants feature this level of data quality and availability. The most comprehensive data set of historical U.S. hydropower generation observations is provided by the Energy Information Administration through its survey Form EIA-923. EIA-923 provides monthly generation estimates for all grid-relevant western hydropower plants, covering the last two decades, from 2001 through 2021. The monthly generation totals provided through EIA-923 are unsuitable for use in a retrospective analysis, since approximately 90 percent of hydroelectric plants provide data with annual resolution only (for these plants, the EIA provides imputed rather than observed monthly generation estimates). Monthly hydropower generation data covering the period 1970 through 2000 are available via the Energy Information Administration but include approximately 150 fewer plants than in the later EIA-923 records.

This report adopts annual scale hydropower generation data for the years 2001–2021 from EIA-923, allowing for an authoritative study with full western coverage in a consistent and reliably informed approach. Higher resolution data are employed, where available, to enhance understanding and to corroborate key findings. These include plant-level generation and powered flows data with monthly, daily, and hourly resolution, and are used in this study to supplement key findings of the sub-regional analysis with corroborating evidence on an outlook for 2022 and impacts of drought on plant shutdowns. These data are gathered from multiple agencies, including the USACE, USBR, and California Data Exchange.

1.3.2 Hydropower climate regions of the West

Sub-regional analysis of western hydropower has been conducted in prior research by grouping plants into pre-existing spatial units, such as states (used in EIA state-level hydropower reports), river basins (e.g., USGS Hydrological Unit), or by regions of the power grid in which load and generation are balanced (known as Balancing Authority regions). A problem with these delineations is that they are often large enough to be influenced by very different weather patterns at the same time. The Bonneville Power Administration region, for example, includes large hydropower generating facilities on the Columbia River (e.g., Grand Coulee and downstream run-of-river facilities), as well as large run-of-river plants on the Snake River Basin. Drought conditions in the Upper Columbia do not necessarily coincide with drought conditions in the Snake. For example, 2013 was a dry year for the Snake but not in the Mid to Upper Columbia. Diversity of weather conditions across a hydropower portfolio can promote a resilient electricity supply service. But to attribute impacts of drought on hydropower generation, it is valuable to differentiate groups of plants according to the weather conditions they experience.

The analysis described in this report is conducted using annual hydropower totals aggregated from plants to eight newly defined hydropower climate regions of the West (Figure 4). These hydropower climate regions have been designed specifically for this drought impact study, drawing on clustering techniques to delineate groups of plants that are distinct in both the climate conditions they experience and in their reservoir characteristics (see Appendix B for clustering and delineation approach). These regions enable a clean analysis of each regional hydropower fleet's sensitivity to meteorological drought and create the opportunity to develop regional hydropower generation hindcasts (20th century) and outlooks (this year—2022) for the West.

The eight hydropower climate regions encapsulate 644 hydroelectric power plants, representing 97.3 percent of hydroelectric generating capacity and ~99 percent of hydropower generation of the West (Table 1). The largest hydropower climate region (by generation and capacity) is the Mid to Upper Columbia, accounting for just over half of western annual hydropower generation. Ninety percent of western generation is accounted for by the Mid to Upper Columbia in combination with the next three most important regions, namely South Cascades/California, Snake River Basin, and Northern Cascades/Puget Sound. The Lower Colorado Projects account for just over 5 percent of mean western generation. This region has the fewest plants of all regions (just 15), but it contributes more to western generation than all three of Missouri Headwaters (30 plants), Colorado Rockies (52 plants), and Utah Wasatch Range (58 plants) combined. This is due to two very large plants (Hoover and Glen Canyon) operating in the Lower Colorado Projects subregion that contribute most generation there and are among the top 10 largest hydropower facilities in the West overall.

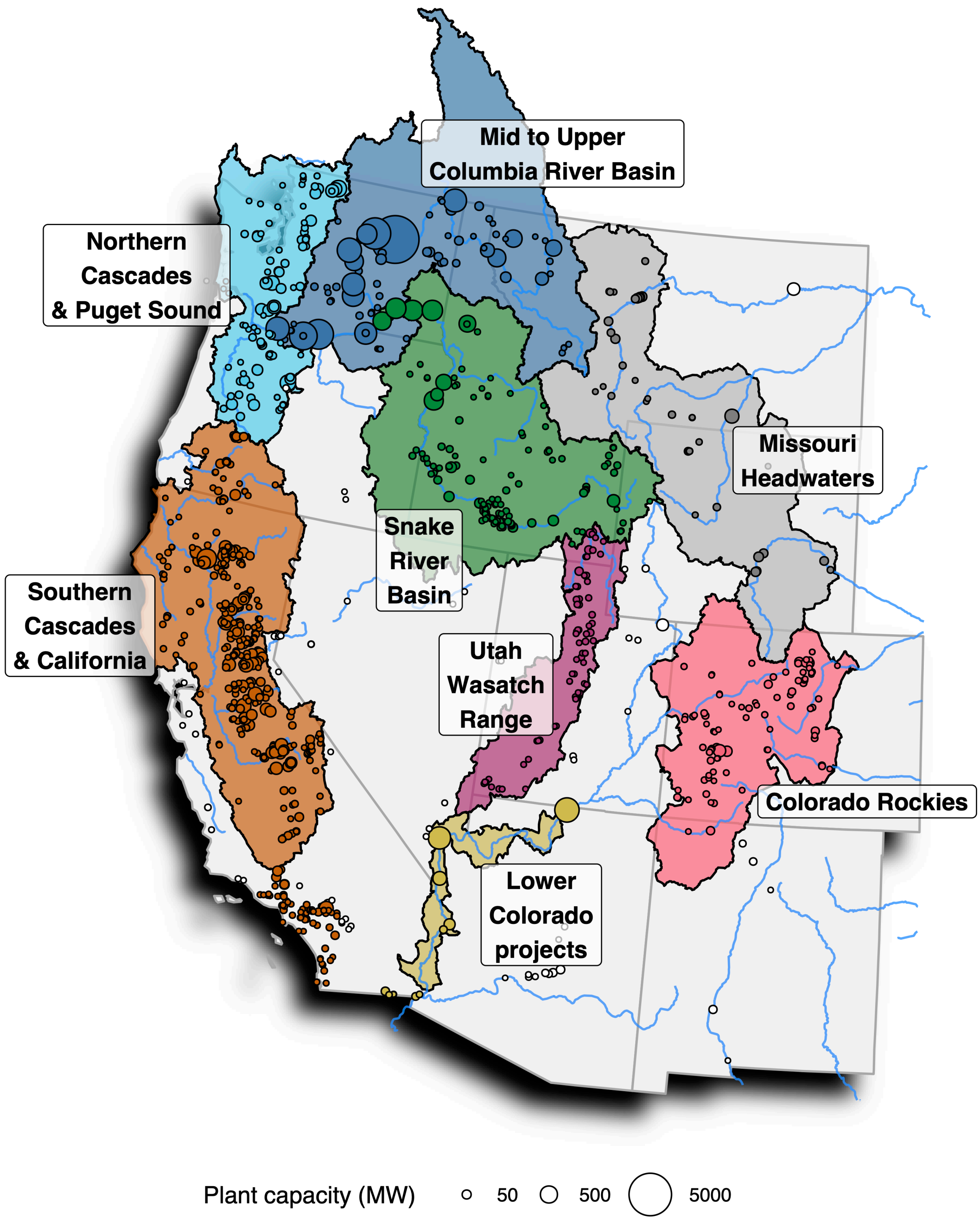


Figure 4. Eight hydropower climate regions of the West. Each point represents a hydroelectric plant (sized by plant capacity). Points matching region color but located beyond region boundaries (see Southern California) rely on water transferred from the relevant region (e.g., plants supplied by the All-American Canal from the Lower Colorado Projects).

Table 1. Hydropower climate regions of the West. The study includes only hydropower plants with a EIA unique identifier. Generation shares are based on 2001–2020 net generation annual observations.

Hydropower climate region	Share of western hydropower capacity	Share of western hydropower generation	Number of plants in study
1. Mid to Upper Columbia River Basin	44.8%	50.9%	55
2. South Cascades/California	19.0%	18.1%	280
3. Snake River Basin	11.7%	11.1%	81
4. Northern Cascades/Puget Sound	10.3%	10.0%	73
5. Lower Colorado Projects	7.6%	5.5%	15
6. Missouri Headwaters	2.0%	2.2%	30
7. Colorado Rockies	1.5%	1.0%	52
8. Utah Wasatch Range	0.4%	0.2%	58
Total	97.3%	99.0%	644

1.3.3 Climate data

Spatially distributed climate data are adopted in this study to link generation to climate conditions in each subregion. The climate data adopted are from the Parameter-elevation Regressions on Independent Slopes Model (PRISM), which provides 4-km resolution daily historical precipitation (PRISM Climate Group, 2022). These data are masked to each hydropower subregion delineation and then aggregated to water-year precipitation totals. One exception is the Lower Colorado Projects, for which the Upper Colorado Basin—upstream of Glen Canyon Dam—is adopted as the delineated climate region, since precipitation within the Lower Colorado region is of negligible importance relative to water generated in the upper basin. For all regions, the water-year is defined as October to September (e.g., water-year 2021: October 2020 to September 2021) and is useful in this context because western precipitation in fall and winter is accumulated as snowpack, to be released as snowmelt in the subsequent calendar year. The aggregated climate data are used to form relationships for hydropower climate region generation and water-year precipitation (snow plus rainfall), which then allow for a statistical extrapolation of the generation record back through the 20th century and forward through the end of calendar year 2022.

At the time of writing, precipitation data do not include the last two months of the water-year 2022. To estimate water-year precipitation for year 2022, precipitation totals for the water-year so far (October 2021 through July 2022) are added to precipitation estimates guided by the latest NOAA precipitation outlooks for each region. Precipitation estimates applied here are conservatively low to ensure 2022 hydropower is not overestimated in the outlook.

2 Drought impacts on generation across western hydropower climate regions

2.1 Regional diversity in interannual generating patters

Splitting total annual hydropower generation by hydropower climate region reveals significant diversity in annual hydropower patterns experienced across the West over the last two decades (Figure 5). While an aggregated western analysis suggests three significant drought years over the last two decades, the regional analysis identifies three additional years that are not immediately apparent in the West scale analysis but are the worst hydropower years in their respective hydropower climate regions. These years are 2013 (worst hydropower drought year in the Colorado Rockies; second worst in Snake River Basin), 2002 (worst in Missouri Headwaters), and 2004 (worst in Utah Wasatch Range).

Regional annual generation, 2001 - 2021 (% of total nameplate capacity)

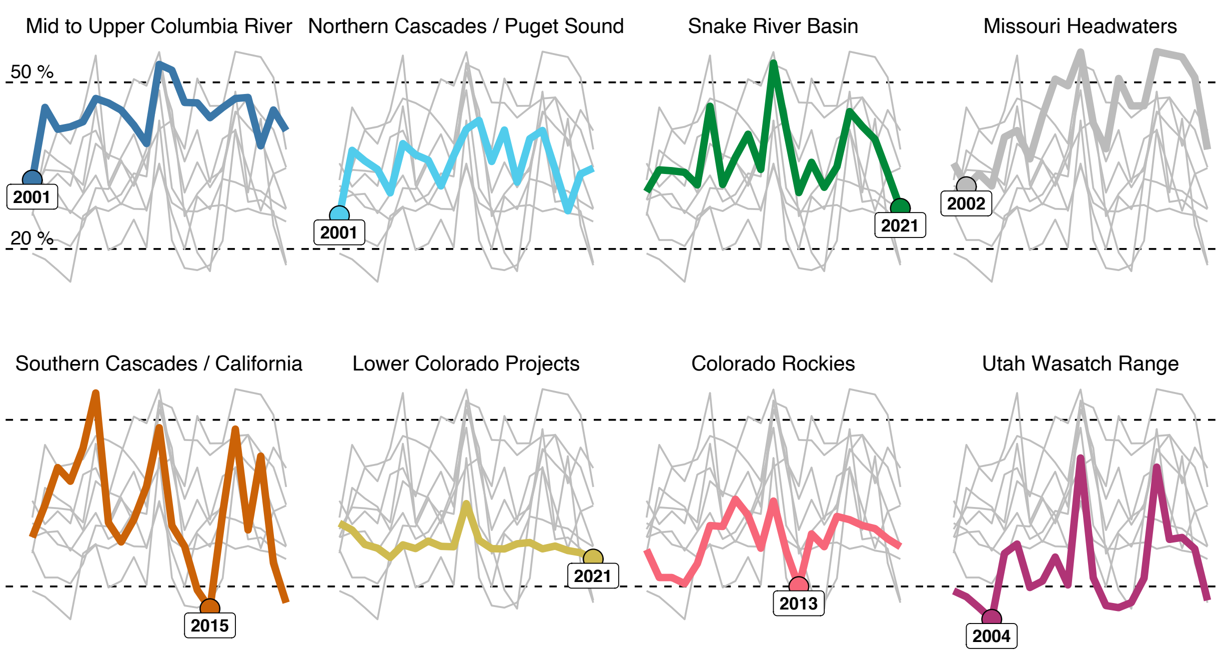


Figure 5. Diverse interannual variability of sub-regional hydropower generation. Each panel displays a subregion's average annual generation as % of nameplate capacity. Faded lines in each panel give the other seven subregions' data.

The Mid to Upper Columbia River (COL) region generates about half of western hydropower. And so predictably the worst hydro year in this subregion (2001) coincides with the worst hydropower year of the West, overall. The year 2001 is also the worst hydropower year in the neighboring Northern Cascades/Puget Sound (NCP) region. Unlike the COL region, where 2001 is an outlier, the NCP experienced significant hydropower impairment in other years, including 2019. The U.S. Drought Monitor shows that the NCP region can be drought-stricken while the remainder of the West is drought-free (e.g., 2019—second worst hydropower year in NCP this century)—and vice versa (e.g., 2012–2014; 2022) (Figure 3).

Generating patterns differ not only in timing of most severe hydropower drought years, but also in overall variability of hydropower generation. Large interannual variability of precipitation that characterizes the Southern Cascades/California (SCC) climate is evident in the region's hydropower output. Annual generation as a proportion of total nameplate capacity has ranged from ~55 percent in 2006 (exceeding the highest observed annual typical capacity factor of all other regions, including COL) to just 16 percent in 2015. The difference in generation between these two extreme years is approximately 35 TWh—or 112 percent of mean annual generation for the SCC region. The only region other than SCC experiencing capacity factor below 20 percent in the year 2015 is Utah Wasatch Range (UTW), which produced very low output relative to capacity through the entirety of the 2012–2015 drought, as well as in 2004, which was the worst hydro year in UTW while being a relatively good year for the SCC region. Annual generation relative to nameplate tends to be low in the Lower Colorado Projects (LCP) and Colorado Rockies (COR) regions (ranging 20 – 35 percent) and high in the Mid to Upper Columbia (COL), Snake River Basin (SRB), and Missouri Headwaters (MOH) regions (ranging 30 – 55 percent).

Both the Snake River Basin (SRB) and the Colorado Rockies (COR) regions experienced hydropower drought in 2013. This was the second year of a multi-year drought in the West, lasting 2012–2015. What separates these regions from the SCC region is the impact of 2014, which brought rainfall and, thus, temporary relief from drought conditions in the SRB and COR regions. Meanwhile, the SCC region experienced its driest year of the 21st century in 2014. Thus, hydropower generation declined in SCC through the 2012–2015 period, while generation in COR and SRB dipped then recovered.

The Missouri Headwaters (MOH) is the only region for which annual hydropower generation has increased over the last two decades, albeit recent drought has caused a sharp reversal in the apparent upward trend. This pattern has coincided with wetter conditions in the years leading up to 2020. Twenty years is a short time in geophysical scales, and natural variability within such a period can easily be mistaken for a longer-term pattern or trend. In the case of the MOH region, it appears that the earlier years of the 21st century were generally dry; precipitation in seven out of the eight years from 2000 to 2007 was below the 50-year average. In contrast, the subsequent years were relatively wet, with precipitation in 11 out of 13 years post 2007 above the 50-year average. This regime change is apparent in the region's total annual hydropower output but should not be expected to continue in future years without more detailed analysis of possible drivers of precipitation change, which may include anthropogenic warming.

Interannual hydropower generation from the Lower Colorado Projects (LCP) is characterized by relative stability, with generation rarely deviating more than 10 percent above or below the average output of ~9.5 TWh per year. The year 2011 was an exception, with generation up 25 percent relative to the two-decade average due to favorable snow conditions during the preceding winter. In the LCP region, hydroelectric power is generated primarily from two very large plants—Glen Canyon and Hoover. Each of these plants relies on huge reservoirs capable of storing multiple years' Colorado River flow (Lake Powell and Lake Mead, respectively). Water must be released from these reservoirs to fulfill the Colorado River Compact, which governs the allocation of water to various states relying on Colorado River water. As a result, generation has remained stable while reservoir levels have slowly declined over two decades. Continued reservoir drawdown may eventually lead to curtailments in powered water releases as water levels drop below turbine intakes. Action is already being taken to minimize storage decline, with increased releases from upstream (Flaming Gorge Dam) and reduction of annual total releases from Glen Canyon scheduled for 2022 (USBR, 2022).

In addition to revealing a range of different hydropower drought years, the regional interannual generation time series also highlights differences in the hydropower plant characteristics and operations across regions. For example, the Mid to Upper Columbia hydropower fleet is characterized by high generation relative to nameplate capacity. This is because, during spring months, large run-of-river plants dedicated to hydropower generation along the Columbia River operate at near full capacity for lengthy periods of time as flows rise with melting snow from the basin headwaters. In contrast, dams in the Colorado Rockies are operated primarily for irrigation and water supply purposes. Water releases are often constrained by the need to conserve water storage, resulting in a much lower proportion of nameplate capacity deployed in this region each year.

2.2 Correlation with water-year precipitation

Relationships between water-year precipitation and annual hydropower generation totals reveal further diversity across the eight hydropower climate regions (Figure 6). For five out of eight subregions, the total amount of sub-regional precipitation during water-year is the dominant driver of annual hydropower generation in a calendar year. Specifically, variability in annual generation in the Mid to Upper Columbia, Northern Cascades/Puget Sound, Snake River Basin, Southern Cascades/California, and Missouri Headwaters is explained primarily by water-year precipitation. The relationship between annual hydropower generation and water-year precipitation is weak for the more arid regions, including the Colorado Rockies and Utah Wasatch Range.

There are various factors that explain why water-year precipitation and annual generation are not perfectly correlated, and why the strength of these correlations varies across regions. Over-year water storage is a major reason. This includes both soil moisture in the watershed upstream of hydropower facilities, as well as reservoir storage at hydropower dams and upstream reservoirs. Over-year water storage effects are particularly important following dry years, since precipitation that might otherwise yield generation is captured by dry soils and through refilling of reservoirs rather than flowing through turbines. Storage effects explain results for the SCC region, for example, where average water years that follow dry years yield below average generation (e.g., 2016, which followed severe drought in 2015), and dry years that follow dry years (i.e., multi-year drought) result in very significant impairments to generation (e.g., 2015 and 2021 following 2014 and 2020, respectively). For these reasons, climate-based predictions of regional annual generation applied in this study are often best informed with both current and prior year water conditions (see section 3.1 on statistical models). Reservoir storage is also the primary reason for relative stability in generation in the Lower Colorado Projects, as discussed in section 2.1. In general, when precipitation is low relative to storage, factors other than annual precipitation influence annual generation.

Regulations on hydropower reservoir operations often change, causing variability in expected generation per unit water available. In the Northwest, many hydropower plants are subject to regulations that require a certain portion of outflow to be nonpowered spill. The 2019–2021 Flexible Spill Agreement increases nonpowered spills, resulting in less overall generation per unit water available in spring (although under this agreement increased operating flexibility improves hydropower sales as generators more effectively respond to price—see NWPCC, 2021). This may explain why, for example, year 2019 generation in the Mid to Upper Columbia falls below generation attained for similar levels of precipitation in prior years.

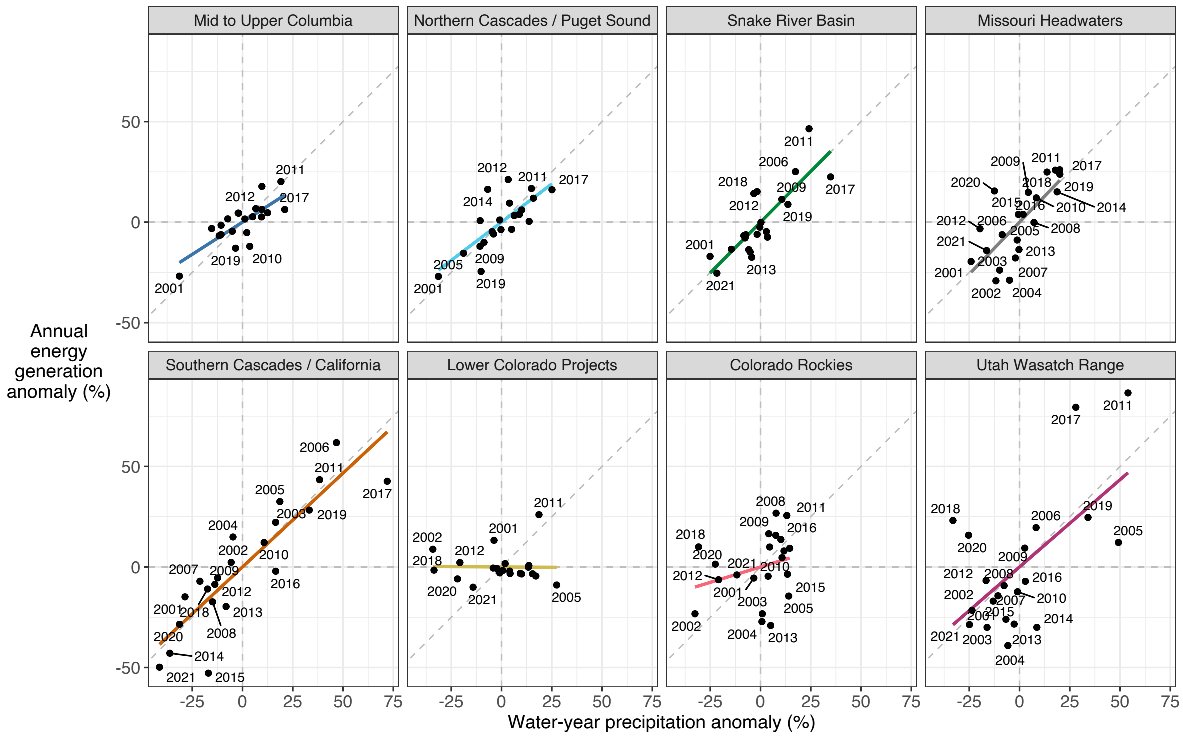


Figure 6. Water-year precipitation is a dominant driver of calendar year hydropower generation in five of eight hydropower climate regions. Water-year precipitation is based on PRISM data (PRISM, 2022) masked to each region's boundaries, except for the Lower Colorado Projects (area upstream of Lake Powell is used for the LCP hydropower climate region).

3 Hydropower droughts of the 21st century in historical perspective

3.1 Statistical models for hydropower climate region generation

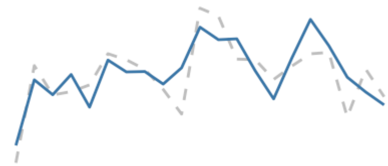
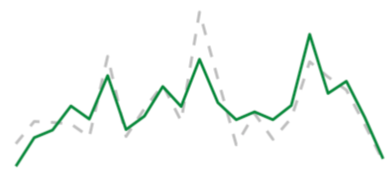
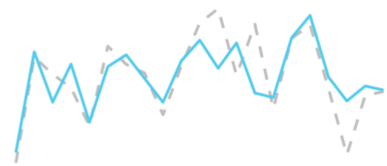
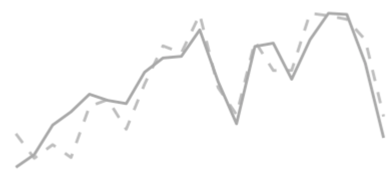
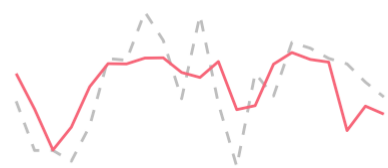
The strong relationships between climate and generation at annual timescales can be used to extrapolate the generation record back through the 20th century. The purpose of such a model is to estimate the impacts of 20th century droughts on today's hydropower fleet. This allows for 21st century hydropower droughts to be compared against historical events. Statistical models that predict annual regional generation from water-year precipitation have been derived for each region and are summarized in Table 2.

Model quality varies significantly by region. Most models include both current water year and prior water year as inputs, highlighting the relevance of over-year catchment and reservoir storage to hydropower generation. The Northern Cascades/Puget Sound is the only hydropower climate region that does not benefit from including prior-water precipitation. Also interesting is the failure of this region's model to capture 2019, highlighting either the impact of a recent hydropower dam operational change at certain facilities within the region or perhaps localized drought that affected a small number of key dams while much of the region received average precipitation. The South Cascades/California region's annual generation can be predicted to a high degree of accuracy using three inputs: water-year precipitation over the region, the prior water year's precipitation, and parameter *B*—a switch that determines whether the prior water year precipitation is applied in the prediction (becoming active if the prior year is sufficiently dry). This parameter, which is also applied in the Utah Wasatch Range model, is required to capture the extreme downshift in hydropower generation occurring after two or more drought years.

Both the Snake River Basin and Missouri Headwaters subregion models perform with a coefficient of determination (R^2) > 0.7. Spill regulations, as well as other operational changes within the last two decades, result in differing energy per unit volume of reservoir inflow and may, therefore, explain marginally lower performance attained for the Mid to Upper Columbia region (R^2 = 0.65). Same water-year precipitation over the Colorado Rockies region fails to capture the variability in generation within this region. Although precipitation totals from the prior two water years explain some variability, our ability to predict annual generation from precipitation in this region is hampered by significant nonpowered operations dictating the release of water from dams. This report finds no viable model of annual generation from upstream precipitation for the Lower Colorado Projects.

Further details of the statistical models are given in Appendix C.

Table 2. Summary of statistical models for predicting regional annual hydropower output (E) from water-year precipitation. Outlier wet year 2017 is dropped from the training sample in some instances to improve model performance in drought years.

Subregion	Model inputs	R^2	Notes	Obs. (- - -) vs pred. (—) MWh
Mid to Upper Columbia River Basin	$E_{yr} = f(P_{\widetilde{yr}}, P_{\widetilde{yr-1}})$	0.65	2017 dropped from training sample.	
South Cascades/ California	$E_{yr} = f(P_{\widetilde{yr}}, P_{\widetilde{yr-1}}, B)$	0.86	2017 dropped from training sample.	
Snake River Basin	$E_{yr} = f(P_{\widetilde{yr}}, P_{\widetilde{yr-1}})$	0.72		
Northern Cascades/ Puget Sound	$E_{yr} = f(P_{\widetilde{yr}})$	0.57	Low generation in 2019 not explained by regional precipitation.	
Missouri Headwaters	$E_{yr} = f(P_{\widetilde{yr}}, P_{\widetilde{yr-1}})$	0.83		
Colorado Rockies	$E_{yr} = f(P_{\widetilde{yr-1}}, P_{\widetilde{yr-2}})$	0.40	Weak model. Current year precipitation does not explain MWh.	
Utah Wasatch Range	$E_{yr} = f(P_{\widetilde{yr}}, P_{\widetilde{yr-1}}, B)$	0.54		
Lower Colorado Projects	N/A	N/A	No viable statistical model.	N/A

3.2 Out-of-record hydropower extrapolation

Results for the extrapolation of regional hydropower indicate that a repeat of the 1976–1977 drought event would cause more severe loss of hydropower than drought events experienced in the 21st century. A repeat of the 1976–1977 drought would be particularly severe because, unlike recent droughts, this event manifested in significantly reduced water availability across multiple important hydropower regions. As shown in Figure 7, the year 1977 represents the worst hydropower year for the SCC region and is among the worst eight years in each of the other major western hydropower generating regions (COL, SRB, NCP). A unique aspect of this event was that its dry conditions emerged in 1976 in California, then spread throughout much of the West in 1977. This meant 1977 was a two-year event in the SCC region (a region sensitive to multi-year drought) while being a one-year event in other major generating regions, including COL, NCP, and SRB.

Four different years during the period 1924–1931 are associated with significant loss of hydropower comparable to the worst events of the 21st century. Between this period and the 1977 drought is a comparatively drought-free era, with no hydropower drought with more than 10 percent western generation impairment relative to average. Although parts of the West experienced significant drought in the 1950s, the key hydropower subregions that contribute ~90 percent of western generation (COL, SRB, SCC, NCP) were largely unaffected by this event. The apparent temporal clustering of western hydropower droughts is further discussed in section 3.3.

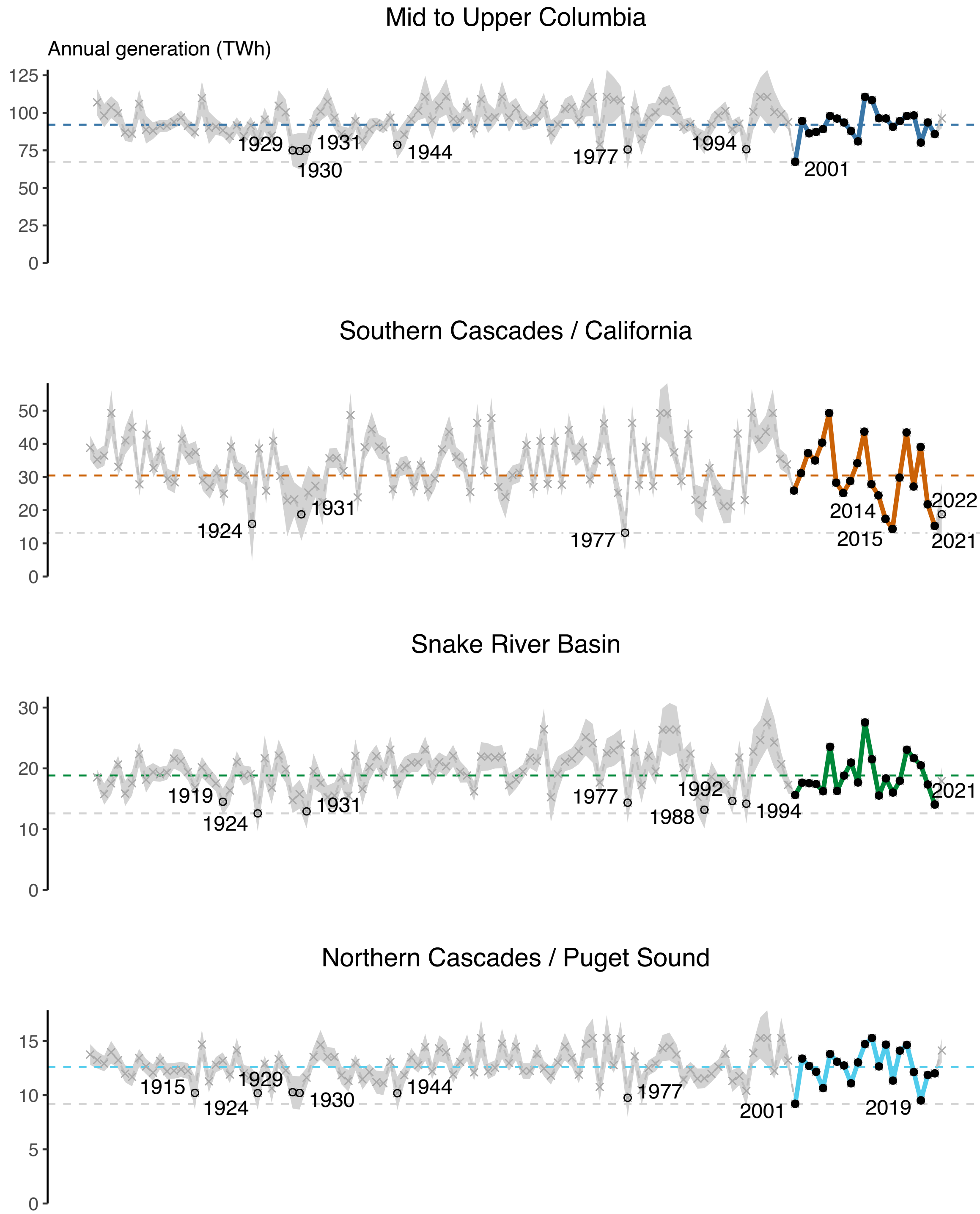


Figure 7. Annual generation time series extrapolated back to 1900 and forward into 2022. Grey ribbon gives standard error 99% confidence internal around estimated generation. Eight lowest points in each series are labeled. Horizontal broken lines give lowest annual generation (1900–2022) and observation period (2001–2021) mean.

3.2.1 Corroboration of 20th century extrapolated generation

EIA hydropower generation data for the period 1970 through 2000 include utility-owned power plants only and, thus, feature 100–200 fewer plants than post-2000 data (difference varying by year). However, since the hydropower subregions created for this report are designed such that most plants within a region face similar climate conditions, the incomplete data can be reasonably scaled for missing capacity in each region to create a capacity-adjusted, regional reconstruction of observed generation. These 20th century data can thus be used to corroborate and verify the precipitation-based statistical model.

The statistical model is found to perform well when compared to available observations for the 20th century (Figure 8). Analysis of reconstructed annual regional generation observations leads to similar conclusions on the worst hydropower years since 1970, with 2001 and 1977 associated with significantly lower generation than other drought years. The western drought of the late 1980s and early 1990s is evident in both observed and modeled annual hydropower generation, with SCC and SRB regions exhibiting significant losses of hydropower in 1988, 1992, and 1994 that contribute to Western scale hydropower generation impairments of 15–20 percent in these years relative to average.

A marginal bias is observed between the adjusted capacity observational data and the precipitation-based statistical model estimates. This may be caused by differences in conversion of precipitation to reservoir inflows, perhaps driven by warming temperatures over the last five decades. For this reason, the models identified may marginally underestimate the available generation through the 20th century. Since the statistical models neglect temperature effects, caution is advised for applying such models to estimate generation in future climates simulated by Global Climate Models. This report does not address possible impacts of climate change on hydropower generation.

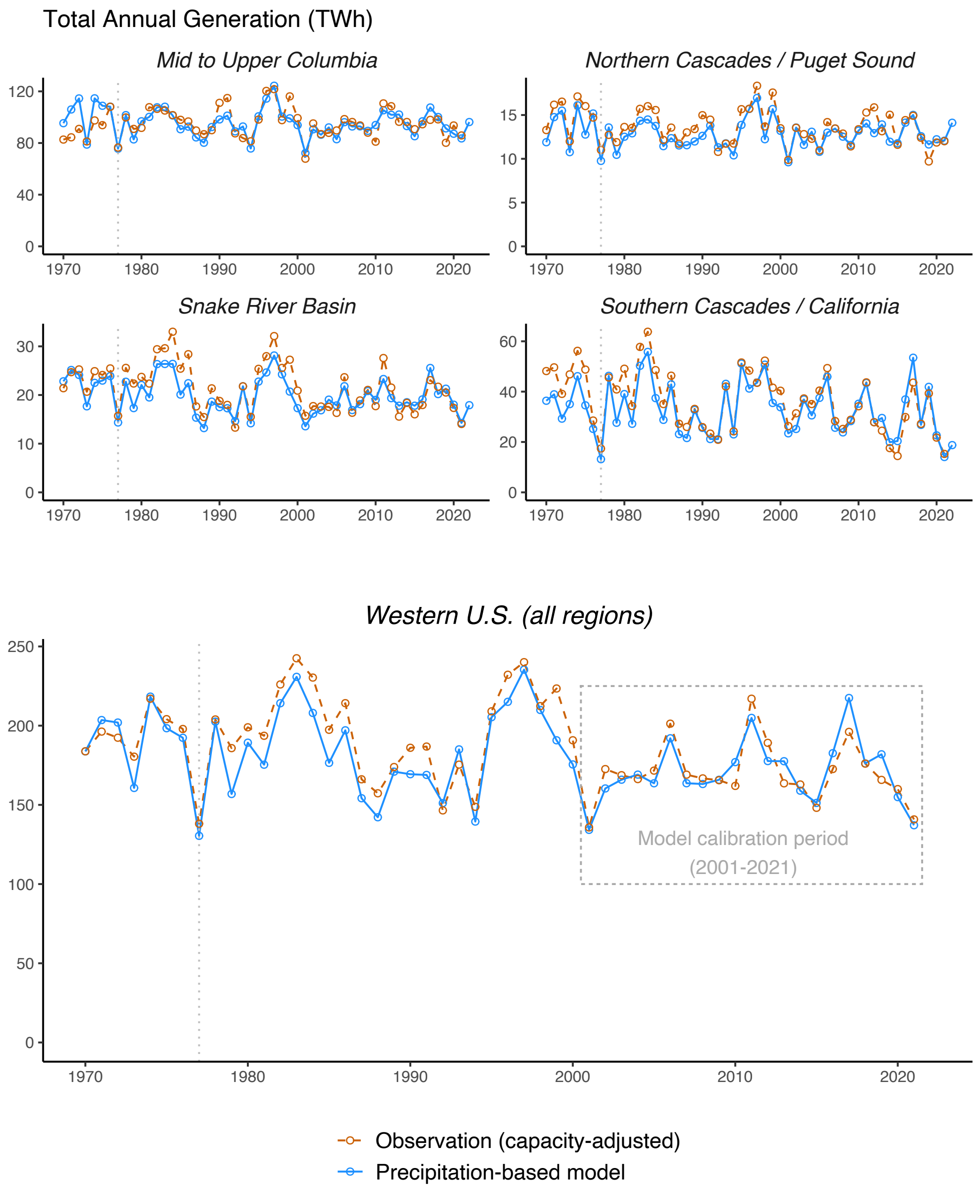


Figure 8. Comparison of precipitation-based model results against EIA-923 annual hydropower generation (utility plants only). To account for varying numbers of plants represented in each year of EIA-923 utility data, each region's observed hydropower is adjusted according to percent of capacity missing. The year 1977 is marked with a grey dotted vertical line within each panel.

3.3 Analysis of western hydropower droughts of the last 100 years

The statistical hydropower generation models can be used to rank and categorize droughts of the last 100 years according to their predicted impact on total western hydropower generation (Figure 9). Comparing regional generation impacts across these droughts reveals a range of drought types that lead to western hydropower drought (i.e., more than ten percent reduction in annual generation relative to average). For instance, the three most severe hydropower drought years differ markedly in sub-regional impacts. The 1977 drought year is particularly severe in SCC while also affecting COL, SRB, and NCP. The 1931 drought would impair SCC hydropower to a lesser degree than 1977 but is associated with a stronger impact on generation from the SRB region. Then 2001, which is similar to 1931 in overall western impact (reduction of 22 percent), is primarily a drought in the Northwest, impairing generation in COL and NCP more than in any other western hydropower drought year.

Most of the identified hydropower drought years are ENSO-neutral years. These include three of the most severe hydropower drought years, namely 1977, 2001, and 1924. Non-neutral warm (El Niño) and cool (La Niña) phases of ENSO bring differing extremities in western weather, meaning potentially dry conditions in some areas (e.g., dry winter in the Northwest associated with El Niño phase) coincident with wet in others (increased likelihood of flooding in California during an El Niño phase). In contrast, western hydropower drought results from dry conditions throughout the West, affecting both California and the Northwest. This finding agrees with prior western grid modeling research, which suggests increased risk of electricity supply disruption during ENSO-neutral years (Voisin et al., 2018).

There is a temporal clustering of western hydropower drought years. During the 21-year period 1924 – 1944 there are five western hydropower droughts. Between 1944 and 1977—a 33-year period—there are none. There was significant meteorological drought that affected parts of the West during this period, including the drought of 1950s (Figure 1). However, the 1950s event affected water availability primarily outside of the key hydropower generating regions of the West, in addition to Texas and in the mid-continent (Nace and Pluhowski, 1965). A major western meteorological or hydrological drought does not necessarily lead to western hydropower drought. The current cluster of hydropower drought years began 1987, representing a 35-year period (to date) that has featured six western hydropower droughts. These include the three drought years analyzed in this report (2001, 2015, 2021) as well as 1987, 1988, and 1994 drought years.

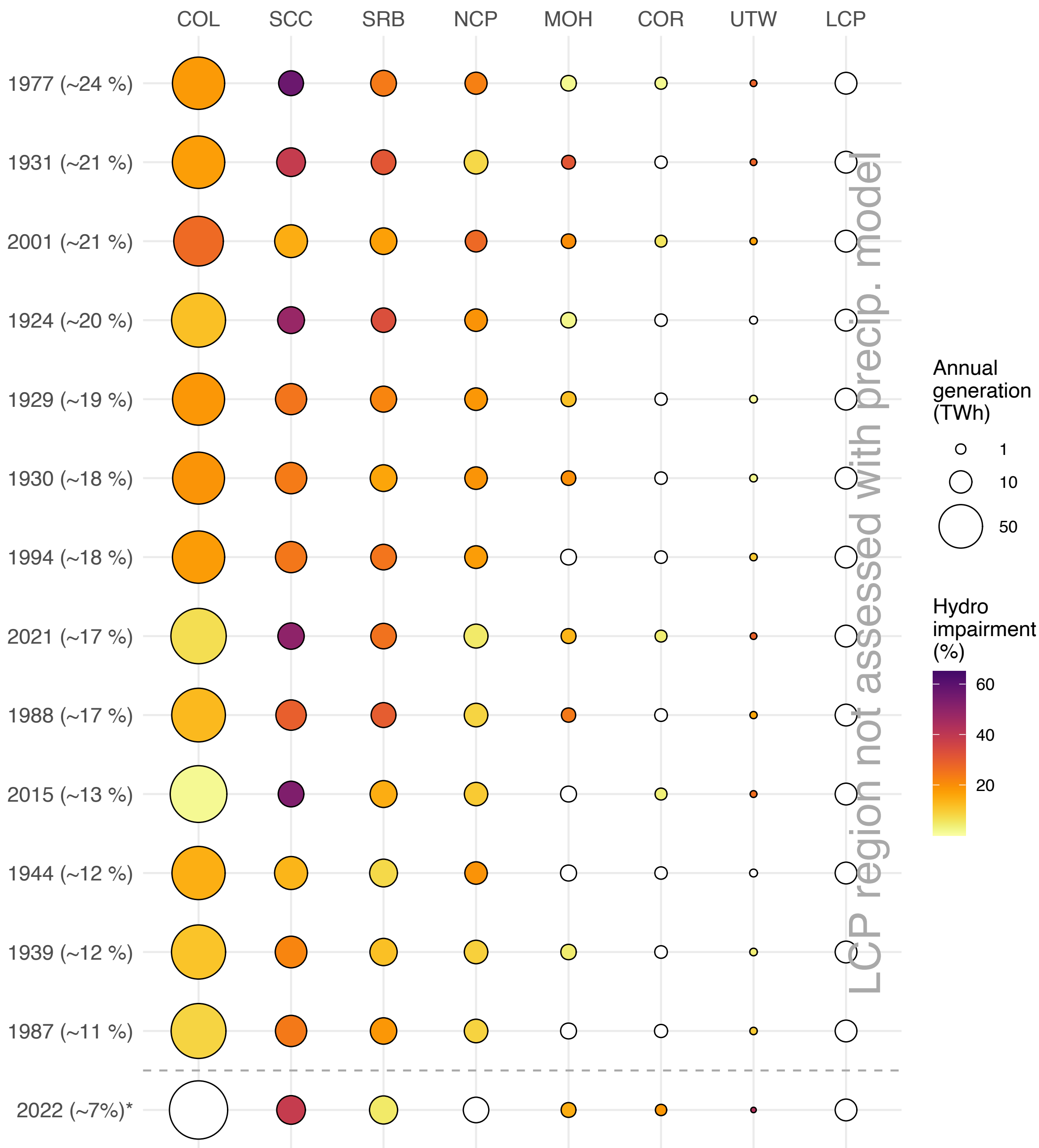


Figure 9. Drought years ranked by estimated impact on Western hydropower (contemporary infrastructure). Point size gives estimated annual regional generation extrapolated using the statistical model (observed for 2001–2021). Fill color indicates the % reduction from mean generation in each region (white fill indicates greater than average generation, except for LCP region, which is not evaluated). Years are ordered based on western U.S.-wide percent reduction from average hydropower generation (values given in parentheses after each year).

4 Outlook for the year 2022

4.1 A conservative estimate for generation in 2022

With the 2022 water-year just two months from completion at time of writing, a conservative estimate of regional 2022 water-year precipitation (and, thus, regional generation) is possible. Precipitation estimates for August and September are based on historical precipitation for each region, adjusted (conservatively) according to NOAA precipitation outlooks, which give probabilities of 2022 being above or below average conditions. At time of writing, the precipitation outlook for the end of the water-year does not indicate strong chances of less precipitation than normal for this time of year. Most of the West is categorized as "equal chances" of being normal for the time of year. A small portion of the NCP region is "leaning above," suggesting some limited evidence for wetter conditions. Parts of SCC, LCP, COR, SRB, and MOH regions are "leaning below." To be conservative, the following outlook assumes moderately drier conditions for all subregions (33rd percentile of the historical monthly precipitation for August and September). With the exception of COR, where August/September rainfall contributes about one-fifth annual precipitation on average, summer months contribute only a very small proportion of annual precipitation in western hydropower subregions (almost negligible in the SCC, NCP, and SRB regions). The following results are, therefore, robust to error in the precipitation outlook for the remainder of the water-year.

Overall, **the year 2022 is projected to be a below average hydropower year in the West, producing approximately <u>155–160 TWh</u>** (~7 percent below 21st century average). This represents a significant rebound from 2021 (~16 percent below average) and means that 2022 does not meet the criterion to be classified as a western hydropower drought year (10 percent reduction, as defined in this report). The 2022 rebound is driven primarily by conditions in the Northwest. The COL subregion generates half of western hydropower energy on an annual basis. This year, the **COL region is projected to generate approximately <u>95 TWh</u>**, which is slightly above average. The **NCP region is projected to generate approximately <u>14 TWh</u>**, which is 12 percent above average. Wet and cool conditions lasting late into spring 2022 have relieved drought conditions in the Pacific Northwest. Snowpack levels were above average and even continuing to accumulate in April and May, leading to very healthy streamflow through late spring and summer. Further improving conditions for hydropower, the state of Washington experienced the 7th wettest June since records began in 1895. Parts of the COL region in southeastern Washington experienced record high June streamflow, and most flow gage stations throughout the NCP region indicated flow conditions at 75th percentile or above (many > 90th percentile) (information from University of Washington Office of the Washington State Climatologist).

The **SRB is projected to generate approximately <u>18 TWh</u>**. This is approximately 5 percent below average for the region but remains a significant rebound from 2021 levels (~25 percent below average). For the other five regions, hydropower is projected to remain significantly below average and in line with or below generation reported for 2021. The SCC region remains afflicted by extreme and, in some areas, exceptional drought conditions. Catchment and reservoir water storage levels are depressed following two years of below-average precipitation. As a result, **the SCC region is projected to generate approximately 14–16 TWh in 2022.** This would be very similar to 2021 output and approximately 50 percent below average annual generation for the 21st century. Estimates for COR and UTW are subject to greater uncertainty than other regions due to relatively weak performance in their statistical models. Both are projected to generate marginally lower energy relative to 2021. **COR is projected to generate**

approximately <u>1.5 TWh</u> (~20 percent below average) while **UWT is projected to generate approximately <u>0.25 TWh</u>** (~50 percent below average).

The LCP region is not included in the statistical model, so this report does not offer any quantitative estimate of generation for 2022 in this region. Over the last two decades, LCP has produced a relatively stable output, owing to very large storage in Lake Powell and Lake Mead, which serve large Glen Canyon and Hoover hydropower plants, respectively. However, below-average water availability over a period of two decades has resulted in significant and widely reported storage decline in both reservoirs. This led to a marginal downshift in generation in 2021 that can be expected to continue into 2022, due to continuation of dry conditions and associated drought response actions that reduce releases from Lake Powell. This impact is discussed further in the following section with reference to some reservoir operations data for these plants.

4.2 Corroborating evidence for a rebound in 2022

At time of writing, EIA generation data for year 2022 cover only a small sample of western hydropower plants for just the first three months of the year. Other data sources are used here instead to assess whether results from the statistical model agree with generation experienced so far this year. For northwestern hydropower climate regions, up-to-date hourly generation observations are available for a selection of plants via USACE. These data include generation for 14 plants in the COL hydropower climate region, 5 plants in the SRB, and 8 plants in NCP. For the SCC region, generation data are unavailable but can be proxied with water release records. These data were obtained for eight of the largest hydropower dams in the SCC region via CDEC. Finally, powered flow (water released through turbines) information from the USBR are obtained and analyzed for two plants in COR and two plants in LCP.

As with the precipitation-driven results reported above, 2022 generation in COL and SRB regions is on track to rebound significantly from 2021 generation (Figure 10). COL region generation appears to have been consistently above 2021 generation for the first seven months of the calendar year 2022. For all three regions, the impact of healthy snowpack conditions and relatively wet spring is evident in above normal generation in May, June. July generation in observed COL plants is third highest of the last 20 years. Given the importance of the COL region to overall western generation, these data provide additional strong evidence for a western hydropower rebound in 2022.

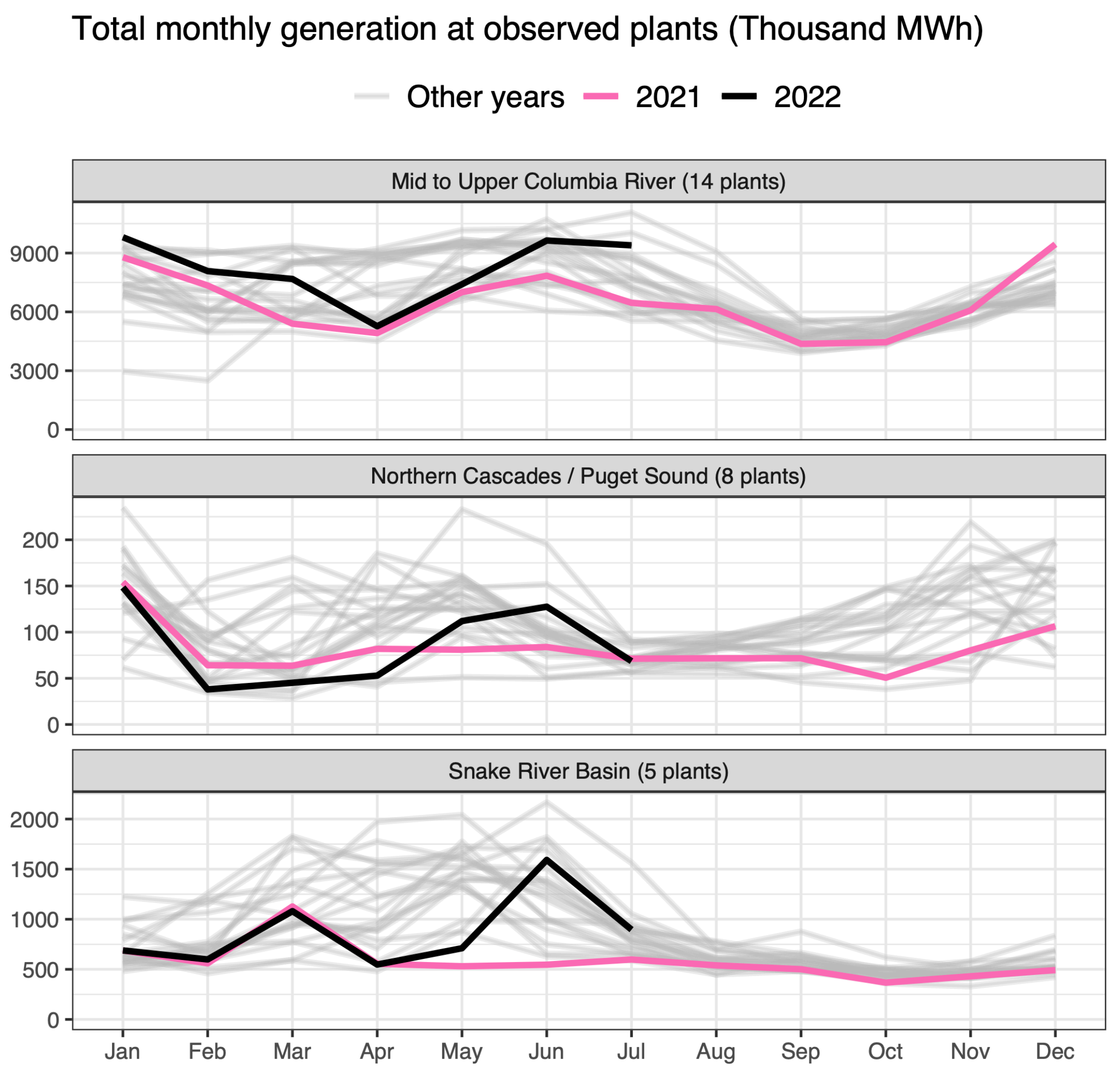


Figure 10. Monthly generation totals, summed across a selection of hydropower plants with generation data through May 2022 (source: USACE Data Query). "Other years" include 2003 through 2019. Observed plants are Albeni Falls, Grand Coulee, Hungry Horse, John Day, Priest Rapids, Rock Island, Rocky Reach, Wanapum. Wells, Bonneville, Chief Joseph, Libby, McNary, and The Dalles in the COL region, Big Cliff, Cougar, Detroit, Dexter, Foster, Green Peter, Hills Creek, and Lookout Point in the NCP region, and Dworshak, Ice Harbor, Little Goose, Lower Monument, and Lower Granite in the SRB region.

Water releases from key hydropower plants across the SCC region remain below average across most analyzed plants and some cases significantly below 2021 releases (Figure 11). These data provide further evidence for continuation of depressed hydropower generation in the SCC region in 2022. Limited evidence available for the COR and LCP regions suggest that year 2022 generation in these regions may decline further from 2021 levels (Figure 12). Powered flows from Glen Canyon are set to be the lowest on record in 2022.

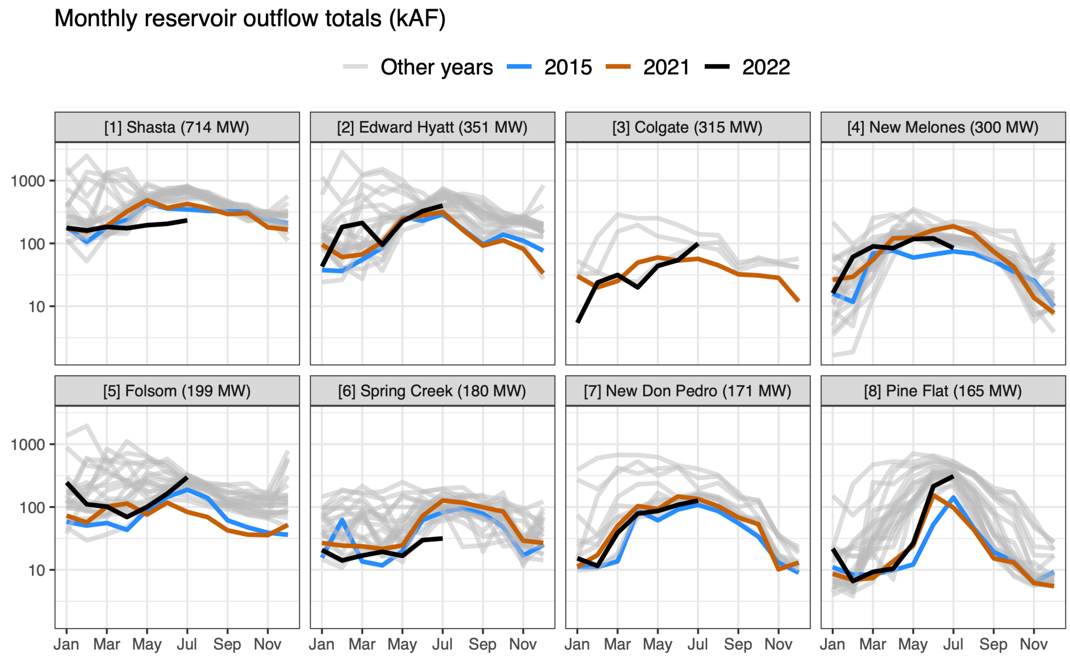


Figure 11. Monthly reservoir outflow totals at eight of the largest hydroelectric dams in the Southern Cascades/California hydropower region.

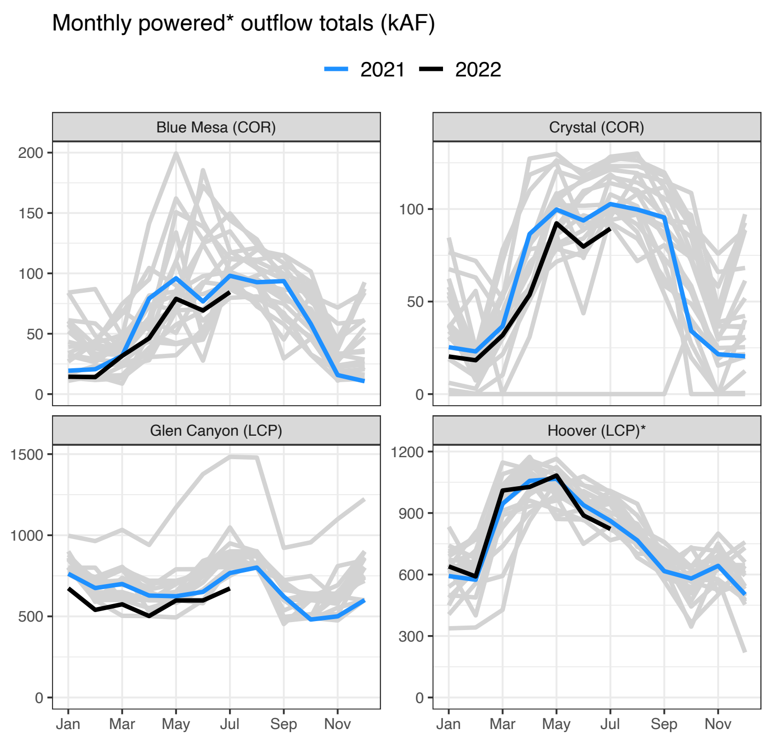


Figure 12. Monthly powered flow time series for two plants in the Colorado Rockies (COR) region and the two major Lower Colorado Projects (LCP). *Hoover flows are total outflows (rather than powered, which are unavailable).

5 Drought and plant shutdowns

5.1 Limited evidence for drought-caused plant shutdowns throughout most of the West in the 21st century

Drought may cause significant loss of generation at a plant if water releases through turbines are curtailed for a lengthy period. Substantial hydropower generation cutbacks may be required under the following circumstances:

- **Deadpool**. Reservoir levels are depleted below turbine intake and generation must cease until water levels recover. This occurred at Edward Hyatt (second largest plant in CA by capacity) in 2021 as water levels in Oroville Lake dropped below intakes. Deadpool is also a well-publicized threat for Glen Canyon Dam (LCP) as reservoir levels in Lake Powell reach new lows.
- **Flows out of operating range**. Releases from the reservoir are too low for the operational range of generating units. This has occurred recently at Pine Flat (SCC), prompting plans for a fourth generating unit to capture energy from low outflows.
- **Conservation**. Releases are reduced significantly to conserve water, occurring if the reservoir's primary purpose is to supply water for municipal, industrial, or agricultural purposes.
- **Maintenance/repair**. All or most generating units at the plant are out for maintenance, or the plant is shut down due to a structural or safety concern relating to the dam. These shutdowns are not typically caused by drought.

Assessing the impact of drought on plant shutdowns across the West is challenging due to lack of data. To assess shutdown frequency, generation data are required at sub-annual temporal resolution (ideally weekly or monthly), since plant shutdowns are unlikely to last more than a few weeks or months. Available data for the 21st century lack sub-annual resolution for approximately 90 percent of plants in the West. Available monthly data for a small selection of federally owned plants contain no evidence for significant curtailments or shutdowns in power generation. This should not be taken as conclusive evidence that shutdowns have not occurred; short-duration shutdowns of one month duration or less cannot be identified from calendar month hydropower generation totals. Moreover, hundreds more plants operate in these regions and must be analyzed to rule out the presence of drought-caused shutdowns in these regions.

Only in the SCC region do 21st century shutdowns appear in the available data. These are analyzed in the following section. Since earlier generation data for the period of 1970–2000 include monthly resolution across a wider sample of western plants, these earlier data are analyzed in section 5.3 for evidence of western shutdowns during the 1976–1977 drought.

5.2 Evidence for plant shutdowns and curtailments during severe drought in the SCC region

The SCC region experiences the largest year-to-year variability of all western hydropower climate regions, resulting in large deviations (± 50 percent relative to mean) in annual hydropower. When the region experiences dry years in sequence (i.e., multi-year drought) there is a nonlinear effect on hydropower, as dried out watersheds become less efficient in converting precipitation to river flows, contributing to reservoir level decline. As a result, annual hydropower generation in the year following a dry year tends to fall significantly below the precipitation power generation trendline. This effect was observed in 2015 following an extremely dry year in 2014 (Figure 13, upper-right panel) and is also evident in the provisional data available for 2021 (which follows a dry year in 2020).

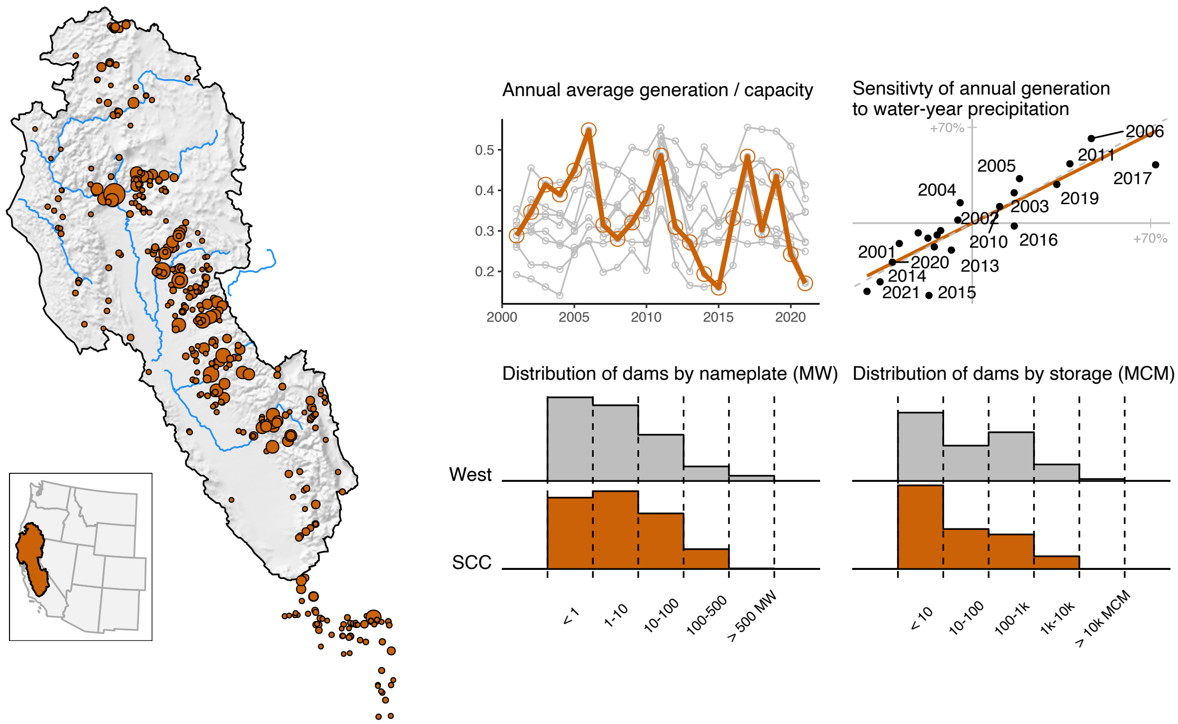


Figure 13. South Cascades/California subregion detail. Map shows hydropower plant locations, sized by nameplate capacity. Top-left of graphics panel: annual average generation (as proportion of total nameplate) with seven other regions in grey. Top-right: % change in water-year precipitation (horizontal axis) versus % change in annual power generation, relative to mean. Bottom-left: distribution of plant capacity for the West and SCC region. Bottom panels compare distributions of plants by size and reservoir storage capacity, as compared to the West, overall. See Appendix A for similar graphics for each region.

Hydropower generation data for California's largest two power plants exemplify the strong impact of multi-year drought on energy per unit precipitation received (Figure 14). Generation at Shasta powerplant was of similar magnitude in 2015 relative to 2014, despite 2015 being a significantly wetter year. This is likely caused by some combination of the following: reduced powered releases from Lake Shasta as water managers sought to conserve scarce water resources; reduced reservoir levels causing lower hydraulic head levels, thus, less power generation per unit water volume released; and reduced inflows to Lake Shasta per unit precipitation, due to dried out soil and vegetation in headwaters.

Another factor was at play at Edward Hyatt powerplant (Lake Oroville) in 2021. As a result of severe dry conditions in 2020, which continued into 2021, water storage levels in Lake Oroville dropped below turbine intakes, resulting in five months of plant shutdown between August 2021 and early January 2022. As a result, total 2021 generation from Edward Hyatt was more than 80 percent below average annual generation and significantly below expected generation given water-year precipitation. Given the large capacity of Edward Hyatt, this was a well-publicized case of drought-caused plant shutdown due to dead pool. The following section of this report aims to analyze available generating data across a larger sample of power plants to understand the extent of drought-caused plant shutdowns and severe curtailments in California.

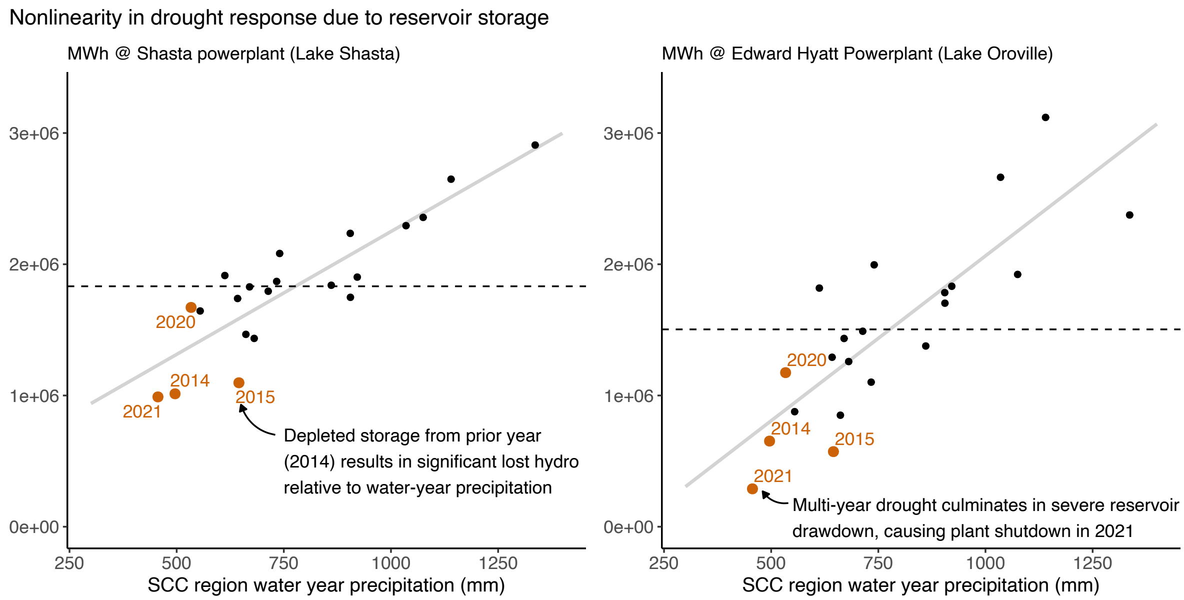


Figure 14. Total annual generation plotted against SCC water-year precipitation for Shasta and Edward Hyatt power plants.

5.2.1 Analysis of monthly generation data for California

Monthly generation data collected for 50 plants in California indicate that sharp curtailments and plant shutdowns are not confined to the Edward Hyatt case. These incidents become more frequent as drought progresses, suggesting they are caused by drought and are not solely maintenance/repair shutdowns (Figure 15). During April 2015, almost half of plants analyzed experienced generation reduction more than 80 percent below average generation for that month. Curtailment frequency dips during spring months (following a reservoir refill period driven by snowmelt) and rises in late summer.

Plants that experienced shutdown in these years include Edward Hyatt (already discussed with respect to reservoir dead pool), and a selection of plants in Fresno and Madera counties—adjacent counties in central California that have experienced “exceptional drought” across 90 percent or more of their land area over the last two years. Plants in these counties with month-long periods of zero power production in 2021 (as reported in EIA-923) include Pine Flat (165 MW), Pit 4 (103 MW), Big Creek 2A (110 MW nameplate), Big Creek 3 (175 MW), Big Creek 4 (100 MW), Kerckhoff (140 MW), and Haas (135 MW). Reasons for apparent loss of power in these particular plants are unconfirmed. Many of these plants have recorded periods of zero generation in non-drought years, suggesting that loss of output during certain months of the year relate to normal operations rather than being drought-related. An exception is Pine Flat, where extremely dry weather results in total loss of power as outflows drop below the design operating range of in-situ generators (KRCD, n.d.). Plans to install a fourth generating unit here show how significant loss of power can be mitigated in some circumstances through continued investment in hydropower infrastructure.

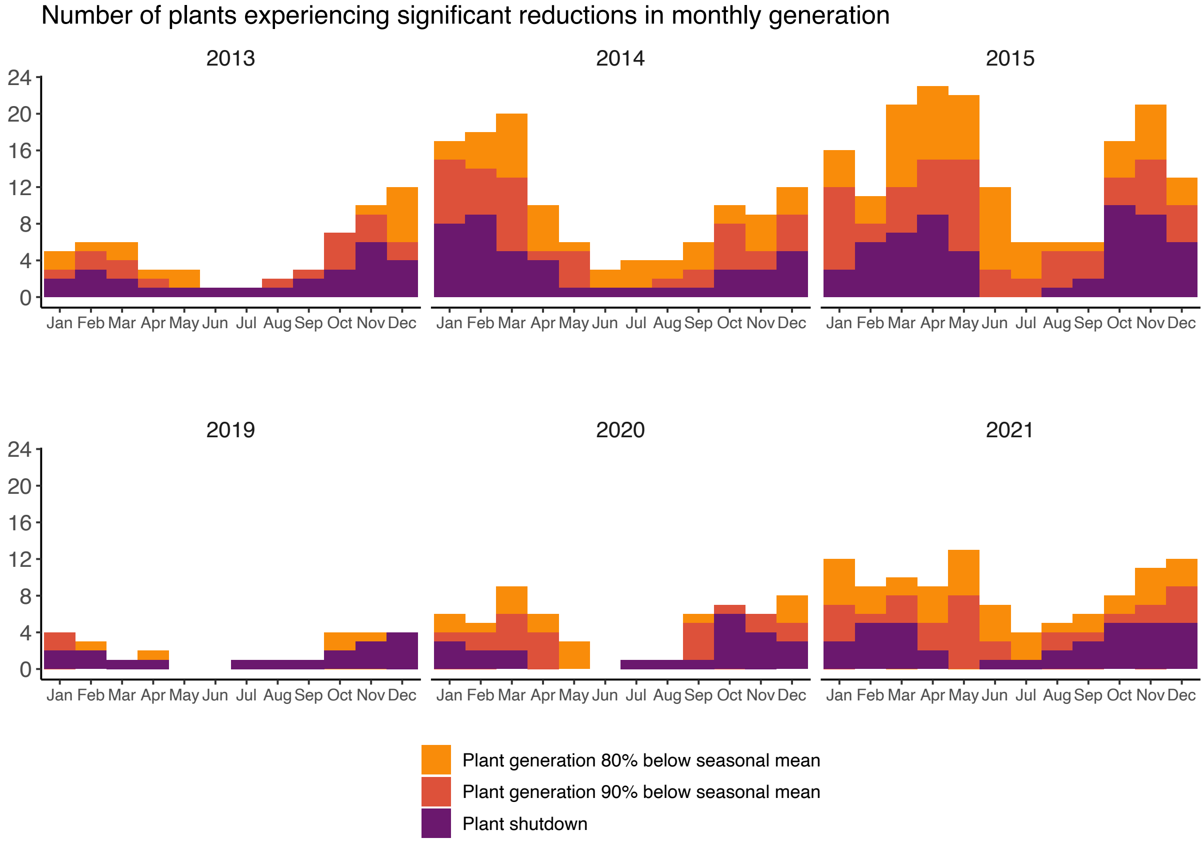


Figure 15. Based on analysis of 50 plants in California that report monthly generation to EIA-923. "Plant shutdown" denotes zero generation for the entire month.

5.3 Impact of the 1977 drought on plant shutdowns

Analysis of 21st century plant shutdowns is hampered by lack of sub-annual generation data across a wide sample of plants. Monthly generation data for the period of 2001–2021 are available for only 80–90 plants (depending on year). This is why much of the analysis reported in this study was conducted using annual resolution data (available for more 600 western plants). Generation data for the earlier period of 1970–2000 include fewer plants overall (approximately 400). All of these include generation data at a monthly resolution that can enable more comprehensive assessment of drought impacts on plant shutdowns.

These 20th century monthly generation data show that at least 123 plants were shut down or severely curtailed (here defined as generation of more than 99 percent below monthly average) for one month or longer in 1977. Up to half of these shutdowns/curtailments may have been caused by the drought, since non-drought years are associated with 63 (± ~15) plant shutdowns on average, perhaps due to seasonal operations or scheduled maintenance. Shutdowns in the 1977 event are concentrated in central California in the SCC region (Figure 16). The metric hydropower "capacity at risk" (Turner et al., 2021) may be used to indicate the impact of such shutdowns at regional scale and is computed the proportion of each region's generating capacity not producing power during drought. In the SCC region, hydropower capacity at risk in 1977 reaches 8 percent during February and March before dipping to approximately 2 percent in July (perhaps relieved by spring snowmelt), then returning to ~8 percent in the fall of 1977. The major generating regions of COL and SRB, as well as LCP, experience negligible capacity at risk in 1977, while the NCP region experiences close to 9 percent hydropower capacity at risk in February and March. The Missouri Headwaters has 4 percent capacity at risk in January, February, March, October, November, and December. This is not likely drought-caused, since similar values are found in non-drought years for this region.

The risk of hydropower plant shutdowns and severe curtailments during extreme drought across the West is not well understood, owing to a lack of publicly available sub-annual data across a widespread sample of western hydropower plants. Even if monthly data were available for all plants, this resolution would be insufficient for short-duration shutdowns lasting less than a few weeks. Additionally, the period over which current hydropower infrastructure has been operational is relatively short in hydrological terms—just a few decades for most plants. Understanding the risk of drought-caused generation curtailments and shutdowns requires analysis of plant performance under a fuller sample of hydrological conditions to represent the range of plausible droughts that could emerge in both present and future climates. This will require western-scale simulations of the hydrological system, including detailed reservoir operations, driven by the best available projections of 21^{st} century climate and associated weather patterns. Key plant and reservoir specifications to support such studies, including reservoir intake levels, generator operating ranges (for flow), maintenance schedules, and local flow and storage regulations are not widely reported. Further collection and publication of historical records of both reservoir and plant/unit operations, as well as creation of improved western-scale reservoir and hydropower modeling capabilities, will be essential to support an analysis of the impacts of drought on short-duration reservoir dead pool and associated western hydropower capacity at risk.

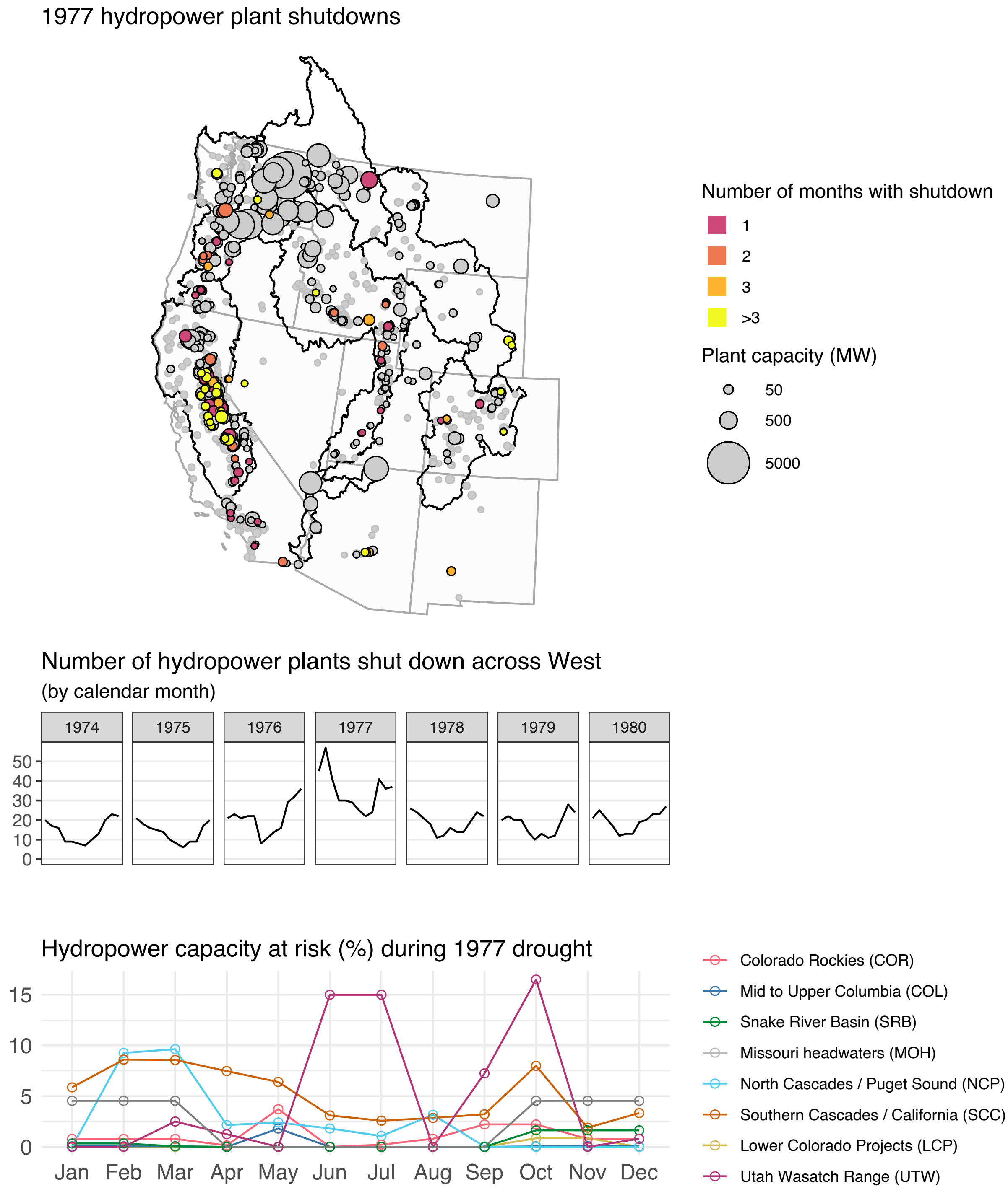


Figure 16. Plant shutdowns evident in 1977 monthly generation data. Outlined points show plants represented in the 1977 monthly EIA data (grey points with no outline have no data for this period).

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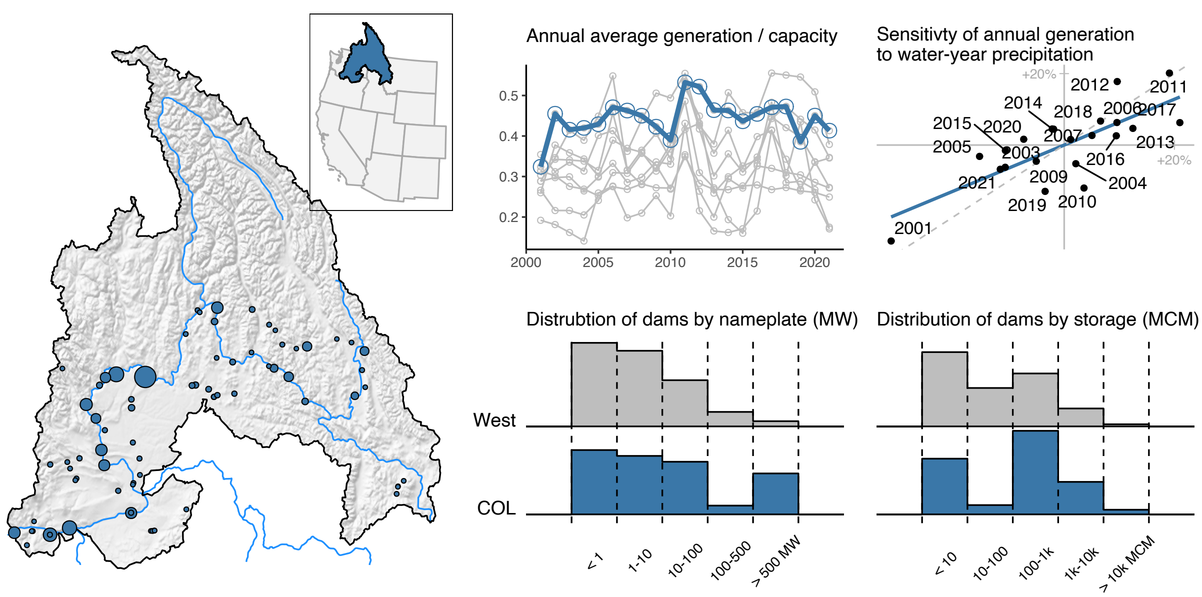
Appendix A – Hydropower Climate Region Detail

A.1 Mid to Upper Columbia River Basin (COL)

The COL hydropower climate region is defined as the Columbia River Basin excluding the Snake River Basin and excluding some tributaries in the lower reaches of the basin, namely the Willamette, Lewis, Cowlitz, and Deschutes rivers (featuring hydropower capacity assigned to the Northern Cascades/Puget Sound region). The region spans multiple climate classifications but is mainly a combination of Temperate Continental (Köppen classification *Dsb*)—characterized by significant temperature difference between summer and winter and relatively uniform precipitation across seasons—and Cold semi-arid (*BSk*)—typical of high elevations areas and characterized by warm dry summers and freezing winters with snowfall. Significant winter snow accumulation and springtime snowmelt results in a sharp increase in flows through spring, declining through summer.

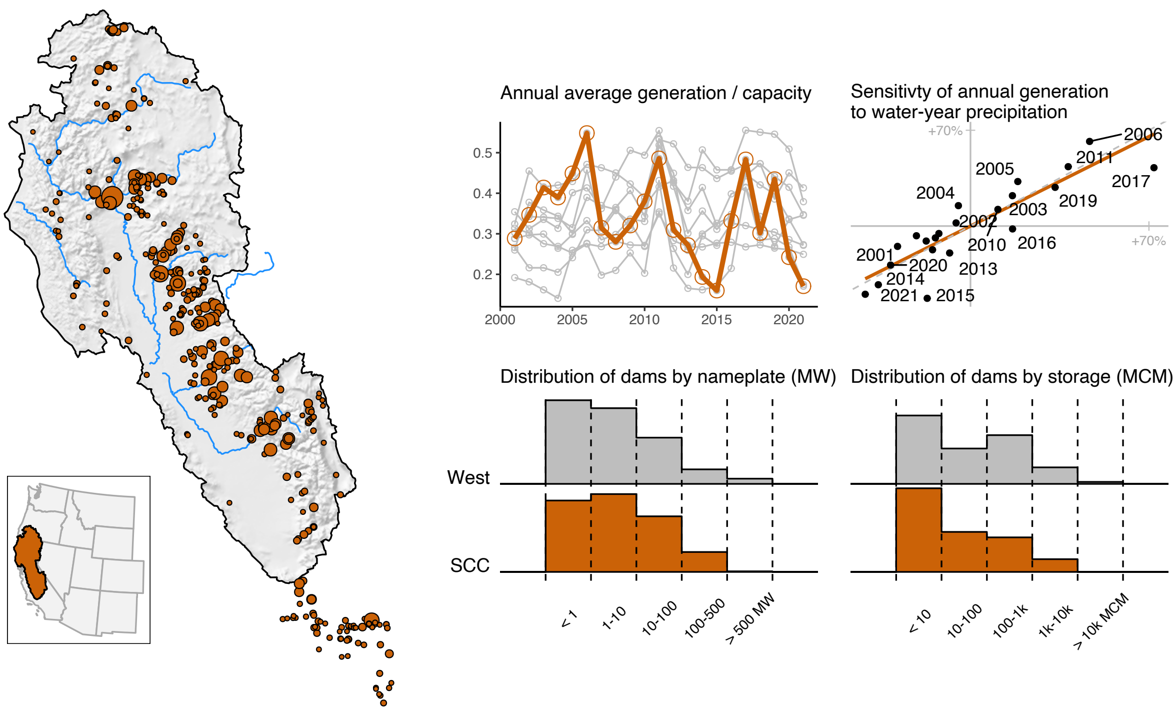
COL generates more hydroelectric power than all other hydropower climate regions combined. Most generation is from a dozen or so very large plants (> 500 MW), which include Grand Coulee (largest power plant in the United States by nameplate capacity, ~6,000 MW) and a cascade of run-of-river plants with very large capacity and generation supported by the huge flows of the Columbia River. Dams in this region are primarily owned and operated by federal agencies Bonneville Power Administration and U.S. Army Corps of Engineers, as well as various public utility districts. Power generating operations are highly constrained by spill requirements to support salmon and other fish populations. Significant hydropower facilities in the Canadian portion of the Columbia River Basin operated by B.C. Hydro are not analyzed in this study.



A.2 Southern Cascades/California (SCC)

The SCC hydropower climate region includes the southern tip of Oregon and nearly all of Northern and Central California, encompassing the Klamath River Basin in the Southern Cascades and Sacramento and San Joaquin River Basins that drain Sierran Nevada Mountains on the eastern side of California. The SCC experiences Warm (*Csa*) and Temperate Mediterranean (*Csb*) climates, characterized by hot, dry summers and mild, wet winters that bring snow to the region's mountainous east, where the region's hydropower dams are located. Interannual variability of precipitation is larger than elsewhere in the West, with total water-year precipitation ranging up ~50% below average on dry years and 70% above average on wet years. The climate generates severe and frequent multi-year droughts, including two experienced in the last decade (2013–2015, 2020–present).

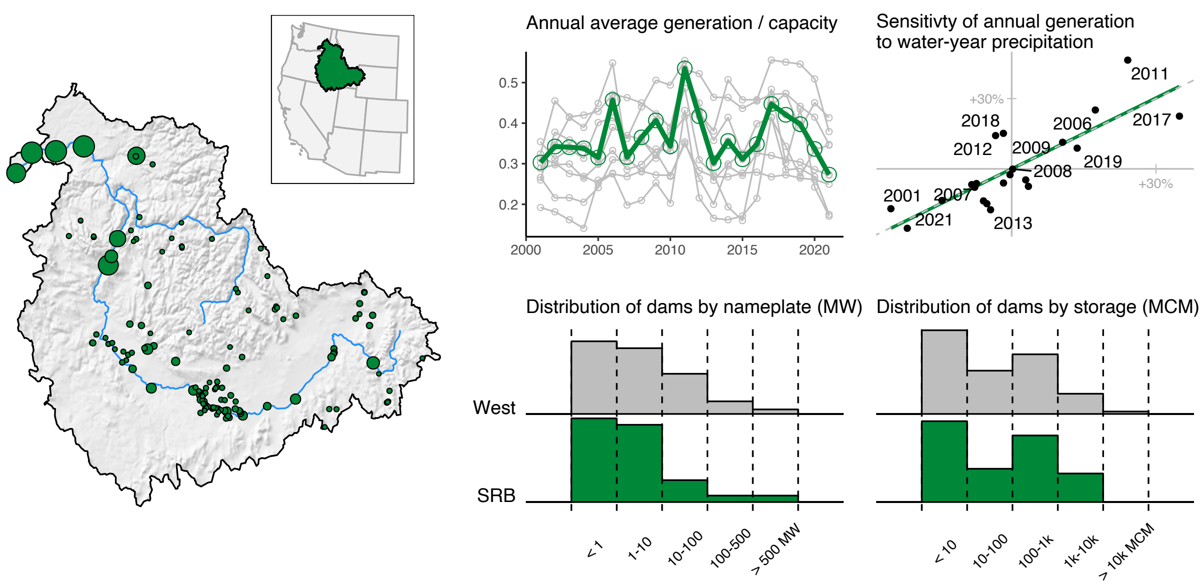
SCC features a mix of storage and run-of-river facilities and 57 medium-to-large capacity plants (> 50 MW). The largest plants by capacity are Shasta (714 MW) and Edward C Hyatt (351 MW). Some large plants, such as Shasta, are federally owned and operated. Most plants are non-federal and owned by a large number of different utilities, including Pacific Gas & Electric, Southern California Edison, as well as the state of California Department of Water Resources.



A.3 Snake River Basin (SRB)

The SRB hydropower climate region includes the entire Snake River Basin upstream of the Snake's confluence with the Columbia River. The climate is predominantly classified as Cold Semi-arid (*BSk*). Although part of the larger Columbia River Basin, the Snake may often exhibit significantly different water availability conditions relative to the Upper Columbia, leading to a significantly different record of annual hydropower output.

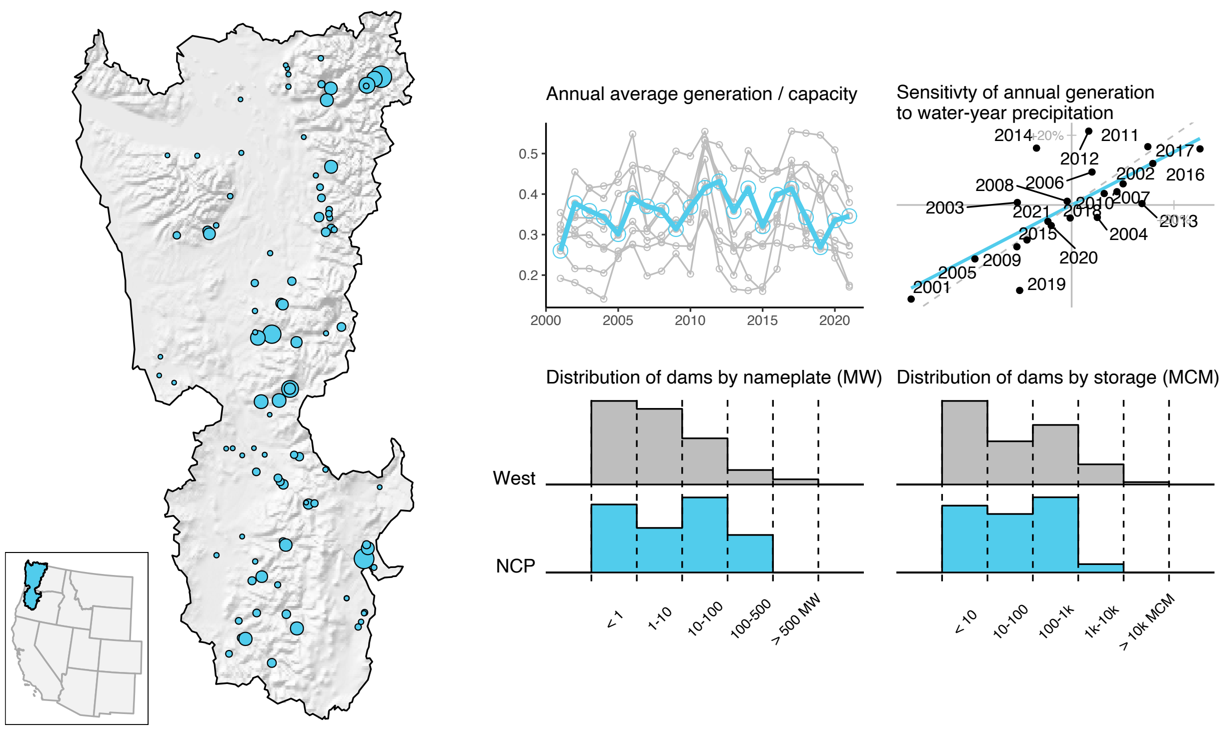
The four largest plants by nameplate capacity are the run-of-river facilities at the outlet of the Snake River to the north (average plant capacity ~800 MW). Significant storage projects include Brownlee (675 MW), Dworshak (465 MW), and Hell's Canyon (392 MW). Although this small number of plants accounts for most of the region's generation, SRB has a large proportion of very small (< 1 MW) and small (< 10 MW) facilities relative to other regions. Dams in SRB are owned primarily by the U.S. Army Corps of Engineers and Idaho Power Company, with the Bureau of Reclamation owning a selection of small capacity projects.



A.4 Northern Cascades/Puget Sound (NCP)

The NCP hydropower climate region straddles western Oregon and western Washington, dissected by the outlet of Columbia River as it drains into the Pacific Ocean. In addition to representing rivers that drain directly to the Puget Sound and Pacific Ocean, NCP includes hydropower facilities on rivers that are tributaries to the Columbia River. The region has a Temperate Mediterranean Climate (Koppen classification Csb) characterized by dry summers and mild, wet winters. Reservoirs located throughout the Cascades are filled annually with spring flows driven by melting of mountain snow that accumulates through winter and early spring. Notable low-generation years include 2001 and 2019, the latter being a dry year in the NCP region only.

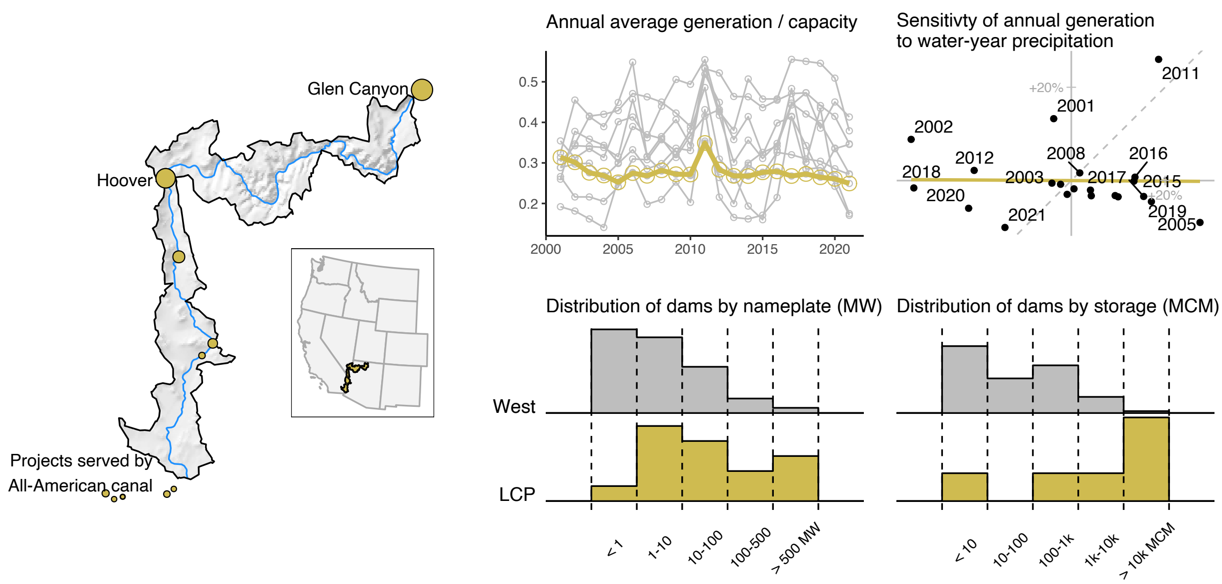
The NCP fleet of hydropower dams includes a substantial proportion of medium-to-large storage projects in the 100–500 MW range spread across the region in different rivers cascades. These include the Skagit River projects in the north (featuring Ross, Gorge, and Diablo dams in cascade), the Cowlitz River projects (including Mossyrock and Mayfield), the Lewis River projects (Swift 1, Yale, Mayfield), and projects on the Deschutes River, Oregon (Round Butte, Pelton). Major hydropower-plant-owning utilities in this region include Seattle City Light, Tacoma Power, PacifiCorp, Portland General Electric, and Puget Sound Energy, as well as the U.S. Army Corps of Engineers and various public utility districts and small utilities.



A.5 Lower Colorado Projects (LCP)

The LCP hydropower climate region is unique in several important respects. The relevant climate for this region is not the highlighted region south of Glen Canyon Dam, but rather the Upper Colorado River Basin (upstream of Glen Canyon). Interannual generation records from plants in the Upper Colorado bear little similarity to those in the LCP, owing to the effects of the enormous storage capacity in both Lake Powell (upstream of Glen Canyon) and Lake Mead (upstream of Hoover dam).

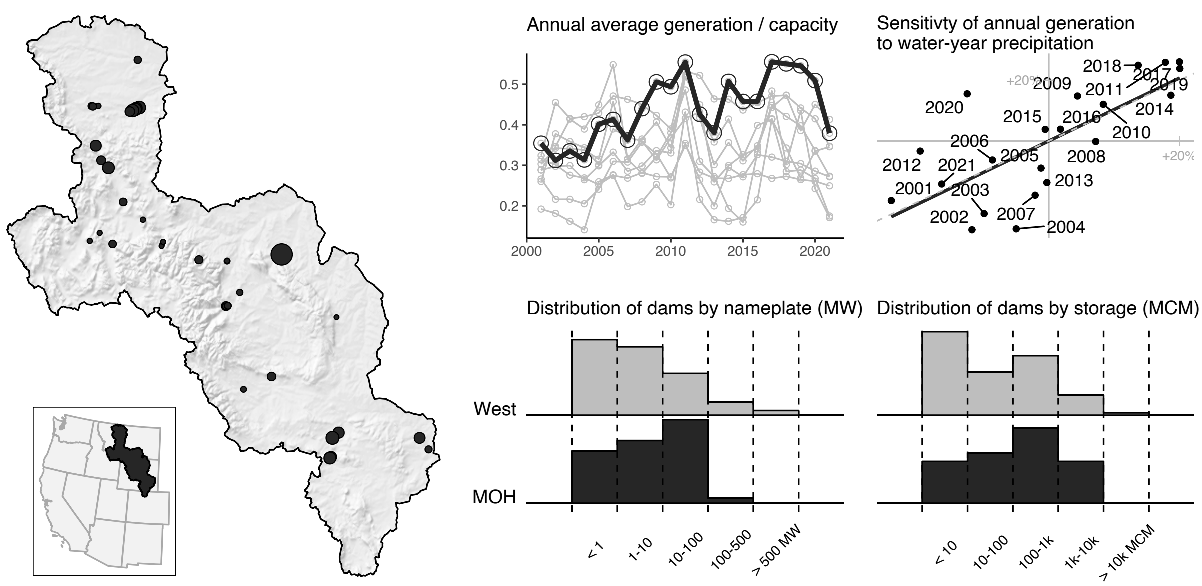
The major plants in LCP are federally owned Hoover (represented as two plants for the Nevada and Arizona generators, respectively, with combined capacity of 2078 MW), Glen Canyon (1312 MW), David (255 MW), and Parker (255 MW). These are all Bureau of Reclamation owned and operated. The significant water storage (equal to multiple years' annual flow volume) and requirements to release water to meet the Colorado River Compact have enabled a relatively stable annual hydropower time series over the last two decades. A number of small plants (< 20 MW) owned by Imperial irrigation District are served from the Colorado River via the All-American Canal.



A.6 Missouri Headwaters (MOH)

The MOH hydropower climate region spans the western side of Montana and through most of Wyoming, featuring 32 small to moderate capacity hydropower projects located across various major tributaries to the Missouri. These include (working from north to south) the upper reaches of the Missouri River, the Yellowstone River, and the North Platte River. The climate is predominantly Temperate Continental/Humid Continental (Dfb), characterized by well distributed precipitation year-round.

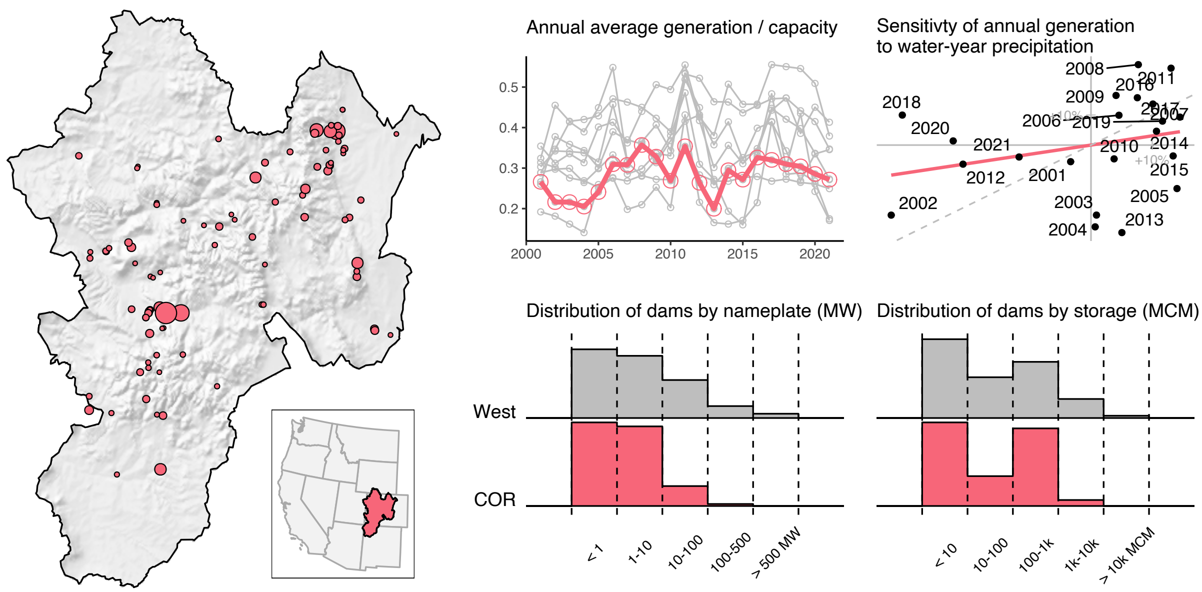
Most capacity in the region is owned and operated by the Bureau of Reclamation, including the largest plants by capacity—namely, Yellowtail (269 MW), Fremont Canyon. The Northwestern Corporation owns and most other capacity, including moderately sized Morony (63 MW), Cochrane (60 MW), and Rainbow (59 MW). A moderate to large plant in eastern Montana (Fort Peck, ~180 MW) is excluded from this region, owing to a significantly different interannual generating profile (perhaps due to very large storage in Fort Peck).



A.7 Colorado Rockies (COR)

The COR hydropower climate region spans western and mountainous (central) Colorado, covering both the northeast, mountainous headwaters of the Colorado River Basin, as well as the eastern side of the Continental divide in the headwaters of the South Platte. The region's mountainous nature leads to a complex myriad of climate classifications.

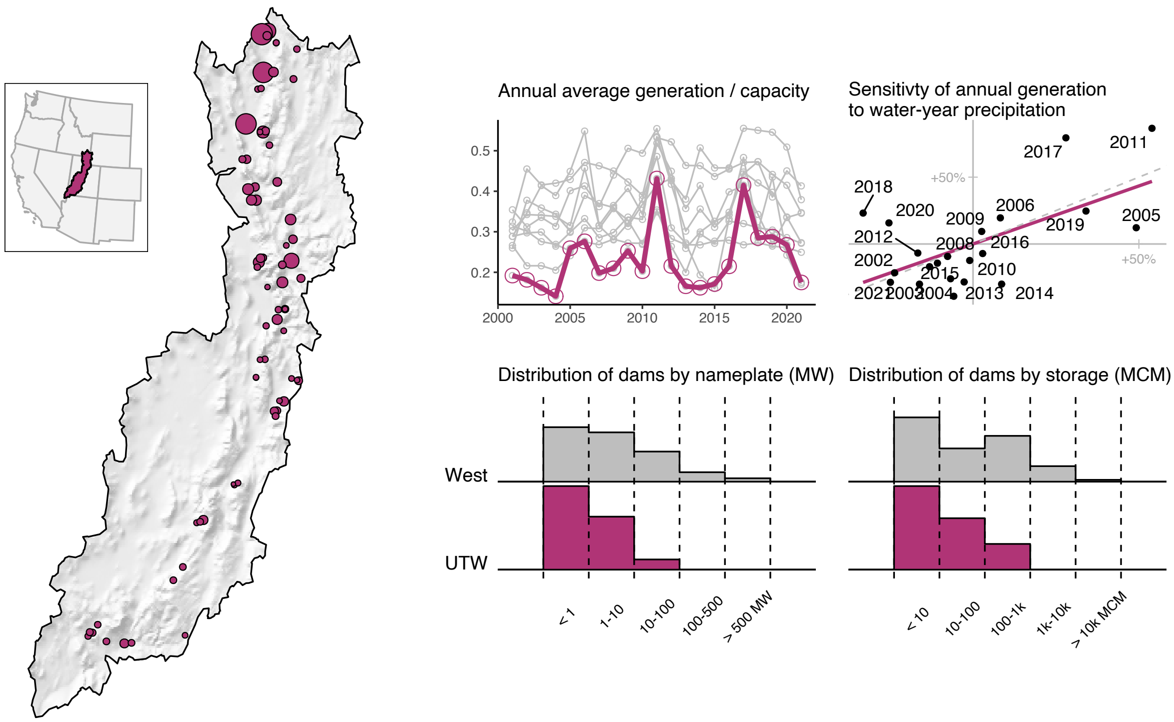
The distribution of reservoir storages in COR does not differ markedly from other regions. Dry conditions and upstream position of key dams means flows are low relative to storage, allowing for a greater degree of control in reservoir operations, resulting in a weaker relationship between water-year precipitation and annual generation. The Bureau of Reclamation owns all of the plants in this region with > 30 MW capacity, including Morrow Point (176 MW), Blue Mesa (86 MW), Flatiron (86 MW), Estes (45 MW), and Pole Hill (38 MW).



A.8 Utah Wasatch Range (UTW)

The UTW hydropower climate region includes the Wasatch Range in northern Utah, as well as more southerly Pahvant Range and Tushar Mountains. The region has a Warm-summer Mediterranean continental climate (Dsb), with wet winters.

Dams and hydropower facilities throughout UWR are relatively small-scale in both water storage capacity and generating capacity. PacifiCorp owns and operates the largest four, namely Grace (33 MW), Oneida (30 MW), and Soda (30 MW) on the Bear River, which flows to Great Salt Lake.



Appendix B – Approach for identifying hydropower climate regions

The hydropower climate regions developed for this report are designed to separate hydropower plants into different groups according to their interannual generating patterns over the last 20 years. This enables a clean analysis of regional drought impacts on generation (section 2.1), creates the opportunity to develop regional climate-generation statistical models (section 3.1), and enables scaling of capacity by region to apply 20th century generation records (section 3.2.1). The hydropower climate regions were created with the aid of an unsupervised learning algorithm that clusters plants into dissimilar groups. The overall approach was as follows:

1. Data standardization. Time series clustering algorithms use measures of distance between different sequences to determine the dissimilarity of all possible pairs of time series. To avoid clustering generation data by its magnitude and instead cluster by shape and pattern over 20 years, data must be standardized to anomalies. In this study, annual time series of generation (2001–2020) were standardized by subtracting the mean of annual generation and then dividing by standard deviation. The resulting anomalies of annual generation were then applied in various clustering experiments.

2. Clustering experimentation. Annual generation anomalies for 645 hydropower plants in the West were used in various clustering experiments to understand regions with similar interannual generation time series. Experimentation involved adjustments to the clustering algorithm parameters, number of clusters, spatial extent, and number of plants considered. For example, an initial experiment involved use of all data (n = 645) and just three clusters (Figure B.1.). Although imperfect, this experiment revealed a clear distinction between the Snake and Columbia portions of the Columbia River Basin, as well between northern and southern portions of the Cascades. Results for other regions were unclear, indicating a possible need for allowance of more clusters. Initial analyses at the scale of the West were used to identify smaller regions to further isolate and perform new clustering experiments to identify distinct spatial regions containing a majority of plants within the same cluster.

To identify clusters of time series for any of these experiments, there are two distinct steps. First is to compute a dissimilarity matrix, which contains distances between all pairs of items (in this case each plant's standardized time series of annual generation). Various measures can be applied to determine distances in this matrix. This study adopted an algorithm that computes an adaptive dissimilarity index between two time series that covers both dissimilarity on the standardized annual generation values and dissimilarity in the temporal correlation behaviors of those data (Chouakria and Nagabhushan, 2007). Computation is performed using the "TSclust" R library (Montero and Vilar, 2014). With a dissimilarity matrix created, clustering of plants was performed using the "Partitioning Around Mediods" (PAM) method (Reynolds et al., 1992; Schubert and Rousseeuw, 2019; Schubert and Rousseeuw, 2021).

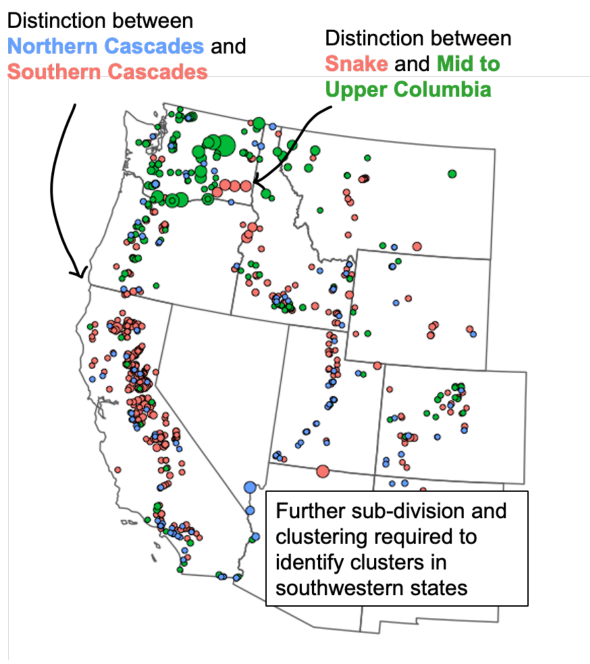


Figure B.1. Result of initial clustering experiment, with just three clusters assigned and using the entire western hydropower fleet.

3. Delineation of climate regions. The clustering approach described above does not automatically generate a clean and unambiguous set of hydropower climate regions. Rather, the clustering experiments provide a visual guide to defining climate regions through human judgment. Alternative versions of the hydropower climate regions are possible and may be more appropriate for other forms of study. For this report, existing USGS watershed delineations named Hydrologic Unit Codes (HUCs) were used to define clean boundaries for each group of hydropower plants deemed to belong to the same cluster. Use of hydrological boundaries also ensures that precipitation totals applied in the statistical models are representative of the full upstream area of hydropower reservoirs. Details of HUCs used to define each region are given in Table B.1.

References for clustering approach

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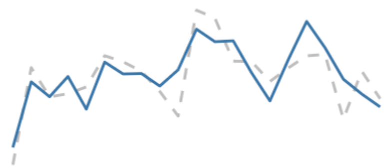
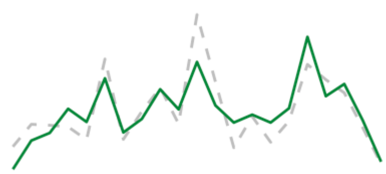
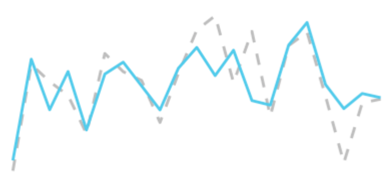
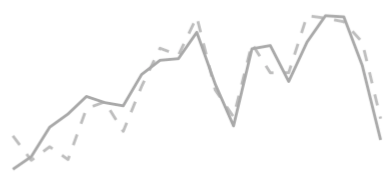
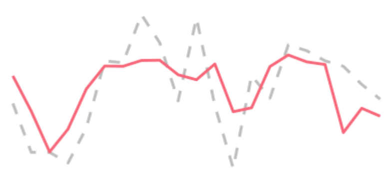
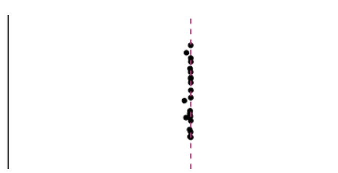
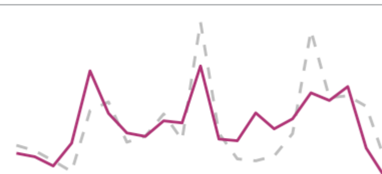
Table B.1. Definitions of hydropower climate regions by Hydrologic Unit Code.

Hydropower climate region	HUC 2	HUC 4	HUC 6	HUC 8
Mid to Upper Columbia River Basin (COL)		1701, 1702, 1703	170701.	
South Cascades/California (SCC)		1801, 1803, 1802, 1804, 1808	180901.	17100309, 17100308, 17100307, 17100301, 17100302.
Snake River Basin (SRB)		1704, 1705, 1706		
Northern Cascades/Puget Sound (NCP)		1711, 1709	171001, 170800	17070301, 17070302, 17070306, 17080004, 17080002, 17080001, 17080005
Lower Colorado Projects (LCP) (climate basis)	14			
Lower Colorado Projects (LCP) (area in visualization)				15010001, 15010002, 15010005, 15030101, 15030104
Missouri Headwaters		1002, 1003, 1007, 1008		10180008, 10180011, 10180003, 10180004, 10180005, 10180006, 10180007, 10180002, 10180001, 10180010, 10090101, 10090201, 10090202, 10090203, 10090204, 10090206, 10090205
Colorado Rockies		1405, 1401, 1402	140801	14030002, 14030003, 10190007, 10190006, 10190005, 10190004, 10190002, 10190001, 10190003, 11020001,11020002, 11020003, 11020004, 13010001, 13010004
Utah Wasatch Range			160201, 160202, 160102, 160101, 160300	15010008, 15010010

Appendix C – Regional precipitation – generation statistical models

Table C.1. Statistical model details including analysis of model robustness to one year being dropped from the training sample.

Model region	Model	Model robustness to one year being dropped from the training sample. R^2 (0 – 1) on horizonal axis	Obs. (- - -) vs pred. (—) MWh
COL *R^2 = 0.65*	$E_{yr} = f(P_{\widetilde{yr}}, P_{\widetilde{yr-1}})$		
SCC *R^2 = 0.86*	$E_{yr} = f(P_{\widetilde{yr}}, P_{\widetilde{yr-1}}, B)$		
SRB *R^2 = 0.72*	$E_{yr} = f(P_{\widetilde{yr}}, P_{\widetilde{yr-1}})$		
NCP *R^2 = 0.57*	$E_{yr} = f(P_{\widetilde{yr}})$		
MOH *R^2 = 0.83*	$E_{yr} = f(P_{\widetilde{yr}}, P_{\widetilde{yr-1}})$		
COR *R^2 = 0.40*	$E_{yr} = f(P_{\widetilde{yr-1}}, P_{\widetilde{yr-2}})$		
UTW *R^2 = 0.54*	$E_{yr} = f(P_{\widetilde{yr}}, P_{\widetilde{yr-1}}, B)$		

The *B* parameter applied in SCC and UTW hydropower climate regions is introduced and trained as follows. A binary variable is defined for each year to distinguish whether the year is considered to be severe drought. For SCC, the threshold is set at 650 mm for average annual two-year precipitation. This results in 2015 and 2021 as well as 2002, 2008, and 2014 being assigned “dry”. For UTW, the threshold is set as 418mm for two-year average annual precipitation. This results in 2001 – 2004, 2008, 2009, 2013, 2018, and 2021 being assigned “dry”. In each case, a lower threshold would result in fewer dry years identified and would improve calibrated model fit during the most severe drought years, like 2021. However, these models would likely be overfitted for those drought years, reducing robustness and making the models less reliable in the 20th century extrapolation of generation. Once set, the binary variable is an input, “B”, to the statistical model. Since B = 0 in non-dry years, this essentially acts as a switch that adds nuance to the statistical model to capture dry year behavior distinctly.

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