U.S. DEPARTMENT OF ENERGY

Effects of Climate Change on Federal Hydropower

The Third Report to Congress

December 2023

United States Department of Energy
Washington, DC 20585

Message from the Secretary

The Department of Energy is responding to Section 9505 of the SECURE Water Act of 2009 (Omnibus Public Lands Act, Pub. L. No 111-11, Subtitle F), which requested that the Department assess the effects of, and risks from, global climate change associated with water supplies for Federal hydroelectric power generation and marketing practice. In response, the Department conducted a nationwide assessment using the best available scientific models and data. The assessment was done in consultation with the United States Geological Survey, the National Oceanic and Atmospheric Administration, and the appropriate Federal and state water resource agencies.

This third assessment report summarizes the updated findings from the most recent studies, as well as proposed operational responses to the predicted impacts from each Federal Power Marketing Administration.

Pursuant to statutory requirements, this report is being provided to the following Members of Congress:

- **The Honorable Joe Manchin**
  Chairman, Senate Committee on Energy and Natural Resources

- **The Honorable John Barrasso**
  Ranking Member, Senate Committee on Energy and Natural Resources

- **The Honorable Cathy McMorris Rodgers**
  Chair, House Committee on Energy and Commerce

- **The Honorable Frank Pallone, Jr.**
  Ranking Member, House Committee on Energy and Commerce

If you have any further questions, please contact me or Ms. Becca Ward, Deputy Assistant Secretary for Senate Affairs, or Ms. Janie Thompson, Deputy Assistant Secretary of House Affairs, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Jennifer Granholm

Executive Summary

Understanding the future changes in projected freshwater water supply is a vital objective for Federal hydropower facilities tasked with providing low-cost, reliable electricity across the nation. Hydropower facilities face a growing customer base and changing electricity market structures that include more dynamic and diverse supply and demand mixes than the past several decades. *The Third Assessment of the Effects of Climate Change on Federal Hydropower*, directed by Section 9505 of the SECURE Water Act of 2009 (SWA), is the third report on evaluating the effects of climate change on hydroelectric energy generated from 132 U.S. Federal hydropower plants marketed by four Power Marketing Administrations (PMAs). The assessment method, technical findings, along with the PMA Administrators' recommendations, are described in this report.

Leveraging the latest global climate projections from the international Coupled Model Intercomparison Project Phase 6 effort, a multi-model framework is used for this assessment to understand the long-term effects of climate change on federally generated hydropower at the regional scale for each of the four PMAs. The results show that maintaining operational flexibility remains a key challenge for Federal hydropower reservoirs that are projected to experience seasonal supply and demand changes. Although the long-term average annual runoff and hydropower generation are projected to slightly increase across the continental United States (CONUS, lower 48 states), reduction of seasonal runoff and generation in some regions can be expected. Specifically, summer runoff is projected to decrease across much of the CONUS by mid-21st century, which will likely affect hydropower generation in regions where the generation is provided largely through run-of-river facilities that have smaller storage capacity and operational flexibility. In terms of potential risks, the intensification of extreme events (both floods and droughts) is found to be a critical issue that challenges the resilience of future water and energy systems. At present, most of the western U.S. is experiencing a decades-long megadrought that resulted in an unprecedented disruption to water supply and hydropower generation. Increasing operational and marketing flexibilities would be highly valuable for all PMAs, if operational directives allow.

The recommendations from the PMA Administrators are included as part of this Report to Congress. Maintaining a large storage capacity, enabling more flexible operational policies, and joining other electricity markets are possible long-term strategies to better manage the effects of hydrologic uncertainty and extremes while maintaining affordable, reliable electricity for their customers. It is important to note that given the high uncertainty of climate modeling, the results shown in this study only represent a few possible future scenarios. For example, other published literatures on the Colorado River Basin show that climate change will reduce water availability and hence, on average produce less hydropower. This difference highlights the importance of further basin-specific studies using operational models, forced by up-to-date hydroclimate projections, and close collaboration with local stakeholders and experts, to assist PMAs in better evaluating risks and identifying potential mitigation actions for long-term water and energy infrastructure resilience.

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I. Legislative Language

This report responds to legislative language set forth in Section 9505 of the SECURE Water Act (SWA) of 2009 (Omnibus Public Lands Act, Pub. L. No. 111-11, Subtitle F), codified at 42 U.S.C. 10365, wherein it is stated:

"(a) Duty of Secretary of Energy—The Secretary of Energy, in consultation with the Administrator of each Federal Power Marketing Administration, shall assess each effect of, and risk resulting from, global climate change with respect to water supplies that are required for the generation of hydroelectric power at each Federal water project that is applicable to a Federal Power Marketing Administration.

(b) Access to Appropriate Data—

(1) IN GENERAL—In carrying out each assessment under subsection (a), the Secretary of Energy shall consult with the United States Geological Survey, the National Oceanic and Atmospheric Administration, the program, and each appropriate State water resource agency, to ensure that the Secretary of Energy has access to the best available scientific information with respect to presently observed impacts and projected future impacts of global climate change on water supplies that are used to produce hydroelectric power.

(2) ACCESS TO DATA FOR CERTAIN ASSESSMENTS—In carrying out each assessment under subsection (a), with respect to the Bonneville Power Administration and the Western Area Power Administration, the Secretary of Energy shall consult with the Commissioner to access data and other information that--

(A) is collected by the Commissioner; and

(B) the Secretary of Energy determines to be necessary for the conduct of the assessment.

(c) Report—Not later than 2 years after the date of enactment of this Act, and every 5 years thereafter, the Secretary of Energy shall submit to the appropriate committees of Congress a report that describes--

(1) each effect of, and risk resulting from, global climate change with respect to--

(A) water supplies used for hydroelectric power generation; and

(B) power supplies marketed by each Federal Power Marketing Administration, pursuant to—

(i) long-term power contracts;

(ii) contingent capacity contracts; and

(iii) short-term sales; and

(2) each recommendation of the Administrator of each Federal Power Marketing Administration relating to any change in any operation or contracting practice of each Federal Power Marketing Administration to address each effect and risk described in paragraph (1), including the use of purchased power to meet long-term commitments of each Federal Power Marketing Administration."

II. Assessment Approach

U.S. Federal hydropower

Hydropower is a key contributor to the U.S. renewable energy portfolio because of its established development history and the diverse benefits it provides to the electric power system. Ensuring the sustainable operation of existing hydropower facilities is of great importance to the U.S. renewable energy portfolio and the reliability of the electricity grid. As of 2019, there were 2,270 conventional hydropower plants in the United States with a total of 80.25 GW of generating capacity producing 6.6 percent of all electricity and 38 percent of electricity from renewables.[1] Additionally, there were 43 pumped storage hydropower plants with a total of 21.9 GW of generating capacity providing 94 percent of utility-scale, installed storage capacity.

Among these hydropower plants, around 40 percent of the generating capacity (42.5 GW) was provided by Federal projects and built and/or operated by one of four agencies: U.S. Army Corps of Engineers (USACE), U.S. Bureau of Reclamation (Reclamation), Tennessee Valley Authority (TVA), and International Boundary and Water Commission (IBWC). For the non-Federal assets comprising the other 60 percent, they are mostly regulated by the Federal Energy Regulatory Commission (FERC) under the authority of the Federal Power Act and owned and/or operated by investor-owned utilities, publicly owned utilities, state agencies, and non-utilities.[2] Although there are fewer Federal hydropower plants than non-Federal plants, the Federal plants have, on average, more than ten times generating capacity per plant.[3]

For Federal hydropower, the Power Marketing Administrations (PMA) market the hydroelectric energy generated from 132 federally owned/operated hydropower plants (Appendix A) to repay the government's investment in these projects. By statute, the PMAs prioritize access to their Federal hydropower resources for their preference customers—mostly municipalities, political subdivisions, and cooperatives—over for-profit entities.[3] The preference clauses, introduced in several pieces of legislation in the early 1900s, were designed to ensure that the operation of the Federal hydropower assets benefited the public, contributed to the economic development of rural areas, and avoided a monopoly in the nascent electric industry.[4] Each of the four PMAs is a distinct, self-contained entity within Department of Energy (DOE). The four PMAs include Bonneville Power Administration (BPA), Western Area Power Administration (WAPA), Southwestern Power Administration (SWPA), and Southeastern Power Administration (SEPA).

Most of these Federal hydropower plants are located at multipurpose reservoirs that also provide nonpower services, such as flood control; navigation; water supply for municipalities, industries, agriculture, and recreation; and protection of environmental resources, including water quality, fish, and wildlife. Since many nonpower services have higher priority than hydropower, generating Federal hydropower is under a variety of competing constraints and may not be as flexible, despite the large water storage capacity in Federal reservoirs.

Scope and objectives

Natural and extreme variability in the future water supply directly impacts the PMA's ability to continue serving their customer base with affordable and reliable electricity. A long-term perspective of this variability is vital to maintaining the services provided by Federal hydropower. Additionally, a more-precise understanding of the hydrologic and generation patterns may help improve marketing plan objectives, timing, and revenue from energy sales, and provide insight into updated operational regimes for Federal hydropower operators that considers possible hydrologic future states. This third assessment report, *Effects of Climate Change on Federal Hydropower: The Third Report to Congress*, was prepared by the DOE Water Power Technologies Office (WPTO), which engaged Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (PNNL) to prepare a technical assessment[3] to evaluate the potential future climate change effects on Federal hydropower (herein referred to as the "9505 assessment") as defined by the SWA Section 9505. This is expected to be the final assessment report required through the SWA, which will expire in 2023.

Given the specific legislative language of SWA, the assessment focuses on the 132 U.S. Federal hydropower plants marketed by four PMAs. Based on river basin hydrology and power systems, the 132 Federal hydropower plants are grouped into 18 assessment areas, labeled as BPA-1–4, WAPA-1–6, SWPA-1–4, and SEPA-1–4 (Figure 1; Appendix B). USACE has the most hydropower plants, followed by Reclamation, and then IBWC. The 75 PMA-marketed USACE hydropower plants are in 16 states across the U.S. Reclamation owns 76 Federal hydropower plants, 53 of which it operates in 11 western states, with 58 hydropower plants marketed through PMAs. IBWC owns and operates two small hydropower projects on the Rio Grande River. The 30 TVA hydropower plants are not included in this assessment because TVA is not a PMA. The hydropower generated from the TVA facilities is also not marketed by a PMA. Similarly, the assessment does not include USACE St. Mary's Falls (Michigan) or St. Stephen (South Carolina) because the electricity generated from these two hydropower plants is not marketed through the PMAs.

Data

To support model development and verification at various stages of the assessment, a variety of data and observations were collected from several agencies and research institutes, including the USACE and U.S. Geological Survey (USGS; Appendix C). These data include meteorological and hydrologic observations, other land surface characteristics, hydropower project characteristics and historical power generation data, reservoir evaporation storage and area, PMA electricity sales and revenue, and other income/electricity usage information. The meteorological observations (precipitation, temperature, and wind speed) were collected from several publicly available sources to represent the observed historical climatology. Land surface data (vegetation, soil, and elevation) were used for hydrologic model parameterization. Historic runoff, streamflow, snowpack, and generation data were used for the hydrologic and hydropower model calibration and validation. The historical reservoir storage and area data were used to estimate the water evaporation from the Federal reservoirs. All data assembled for this study are organized in an integrated, public database for possible use in further site-specific assessments.

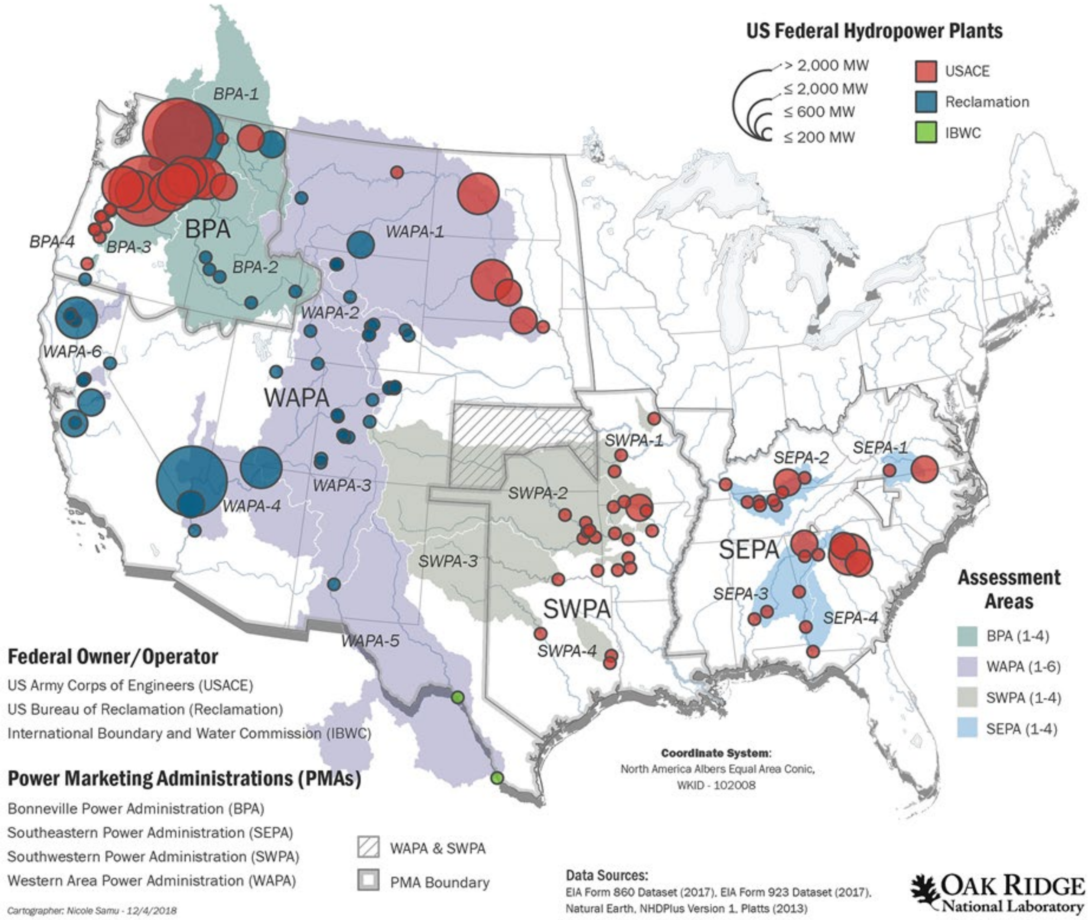

Figure 1. Federal hydropower facilities and Federal power marketing regions in the United States. Note that part of Kansas is supplied by both WAPA and SWPA.

Modeling and analysis

To date, global climate model (GCM) simulation remains the most science-informed approach to understand the Earth system response to the increase in greenhouse gas (GHG) emission. Evaluating the large-scale, climate change effects on all Federal hydropower plants across the U.S. requires a series of models and methods to translate the global climate dynamics down to regional, watershed-scale hydrologic and hydropower dynamics. A multi-model framework (Figure 2) is proposed to better understand how the choice of modeling and analytical approaches may affect the projections of future hydroclimate conditions and hydropower generation. This framework builds upon the first two 9505 assessments and leverages the latest GCM projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6).[5] This multi-model framework includes six selected GCMs under Shared Socioeconomic Pathways (SSPs) emission scenario, two downscaling methods, two meteorological observations, two hydrologic models, and two hydropower models to simulate the ensemble meteorological, hydrologic, and hydropower projections in the near-term (2020–2039) and mid-term (2040–

2059) future periods. The future timeframes are selected to support the evaluation of potential risks in long-term sales contracts.

Six CMIP6 GCMs are selected through an objective GCM evaluation and selection process that factors in the relative model skills, uniqueness, data availability, and computational resources. CMIP6 is a collaborative framework to archive and share the latest international global climate modeling efforts and includes more than 50 GCMs with newly defined greenhouse gas emission scenarios that are a combination of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). Following the same consideration with the previous 9505 assessment, the GHG emission scenario that is closer to the currently observed trajectory of global GHG emissions was selected (i.e., the high-end SSP858 scenario).

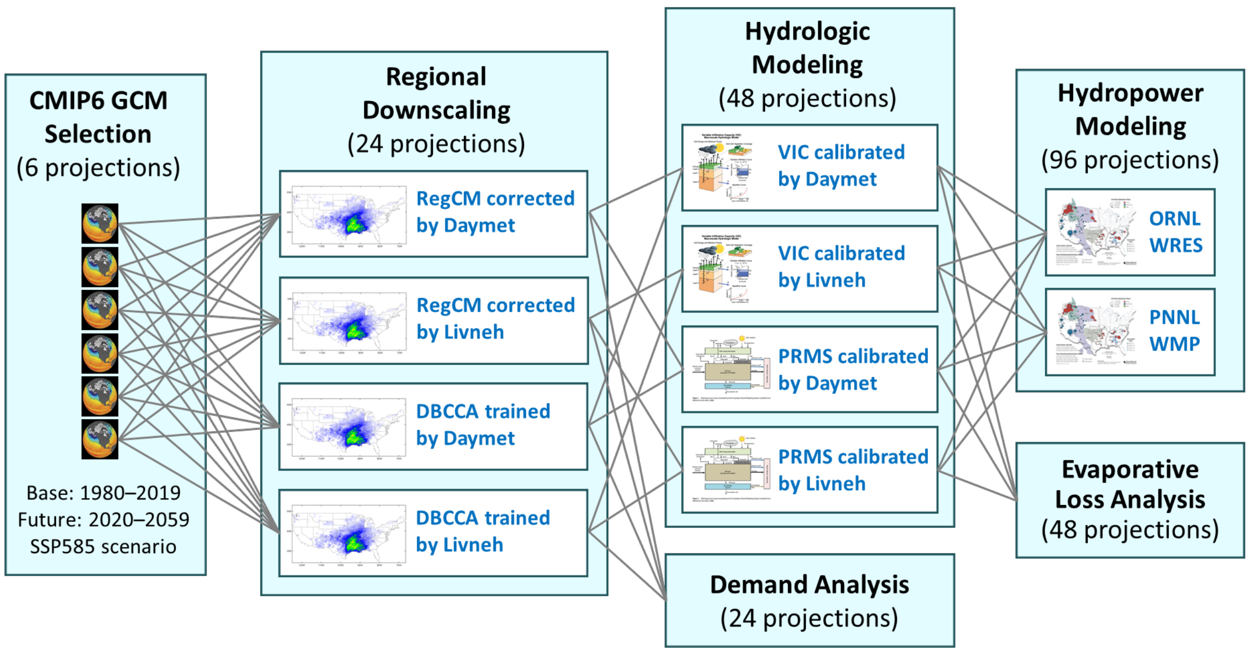

Figure 2. Multi-model assessment framework.

Dynamical and statistical downscaling represent two very different, but widely used, approaches for estimating regional climate from GCMs. To capture variation between the two approaches, both were applied to the six selected CMIP6 GCMs. Additionally, two reference meteorological observation datasets (Daymet and Livneh) are used in the training and/or correction of downscaled projections to account for the uncertainties resulting from the choice of different reference observations. Two regional hydropower models, Watershed Runoff-Energy Storage (WRES) and Water Management Hydropower model (WMP), are then applied to examine how the choice of the hydropower models may influence future hydropower projections. This multi-model assessment framework (Figure 2) results in 96 sets of projected future hydropower generation. Collectively, this multi-model assessment framework may capture variabilities related to GCM selection, downscaling methods, hydrologic model, and hydropower model.

Interagency consultation and review

The accuracy and applicability of the third 9505 assessment benefited greatly from extensive consultation with other Federal agencies, as directed by Congress in the SWA, and from a thorough technical review that was consistent with Office of Management and Budget policies on information quality. The DOE team conducted the third 9505 assessment closely with technical staff from the PMAs, Reclamation, and USACE to ensure the consistency of the methods and data. A technical assessment report was prepared and comprehensively reviewed by over 20 subject matter experts in late 2021. The results of that review are summarized in the full third 9505 technical assessment report.[Error! Bookmark not defined.]

Progression of the 9505 assessments

The first 9505 assessment[6] was conducted from 2010–2012, and the second assessment[7] was conducted from 2013–2017. A series of numerical models and analytical methods with different spatial resolutions were used to downscale the most current GCM findings at that time (i.e., CMIP Phase 3 for the first 9505 assessment and CMIP Phase 5 for the second 9505 assessment). The technical findings were used to support the two previous DOE Reports to Congress, respectively (DOE, 2013, 2017). Overall, the progression of the key components across the three 9505 assessments is summarized in Appendix D. The assessment presented in this third assessment report is the final assessment through the SWA, which will expire in 2023.

Unlike the third 9505 assessment, the previous assessments did not use a multi-model assessment framework and therefore only considered GCMs as the sole source of uncertainty. Results in the previous assessments were also derived from only one downscaling method, one reference meteorological observation, one hydrologic model, and one hydropower model. Although these models were calibrated based on the best available observations, there was no clear approach to discern whether a projected change was caused by the original GCM or by another factor. This lack of clarity could lower the confidence of the assessment findings and lead to a biased interpretation of climate change–induced risks to future Federal hydropower generation. Based on extensive consultation with several Federal hydropower stakeholder groups, a multi-model assessment framework was hence designed for this study which utilizes an ensemble of projections. Although the ensemble-based approach may provide more enriched insights, it still does not represent the full range of uncertainties related to all possible modeling choices. The ensemble-based approach adopted in this study serves as an initial example for a systematic analysis of broader uncertainties.

III. Summary of Findings

Climate projections

Overall, the selection of emission scenario has a clear influence on the projected change of temperature, however the projected change of precipitation is less obvious. Figure 3 compares a total of 98 CMIP6 GCM projections under four emission scenarios (from low to high: SSP126, SSP245, SSP370, SSP585) from which six were selected for this study. In general, SSP126 has the lowest temperature increase, while SSP585 has the highest (Figure 3). For temperature, all

CMIP6 projections showed a consistent increase, ranging from 1°F to 6°F across all seasons. For precipitation, except for parts of summer and fall, a consistent increase is projected (especially in winter), resulting in a net annual precipitation increase across most of the projections (−2 percent to 8 percent). The changes in terms of extreme temperature and precipitation quantiles are more complicated and involve stronger geographical differences. Of the 98 CMIP GCM projections, six were selected and although these six selected GCMs do not cover the full range of CMIP6 models and emission scenarios, they spread around the median of all models, suggesting that they are not biased toward any one direction.

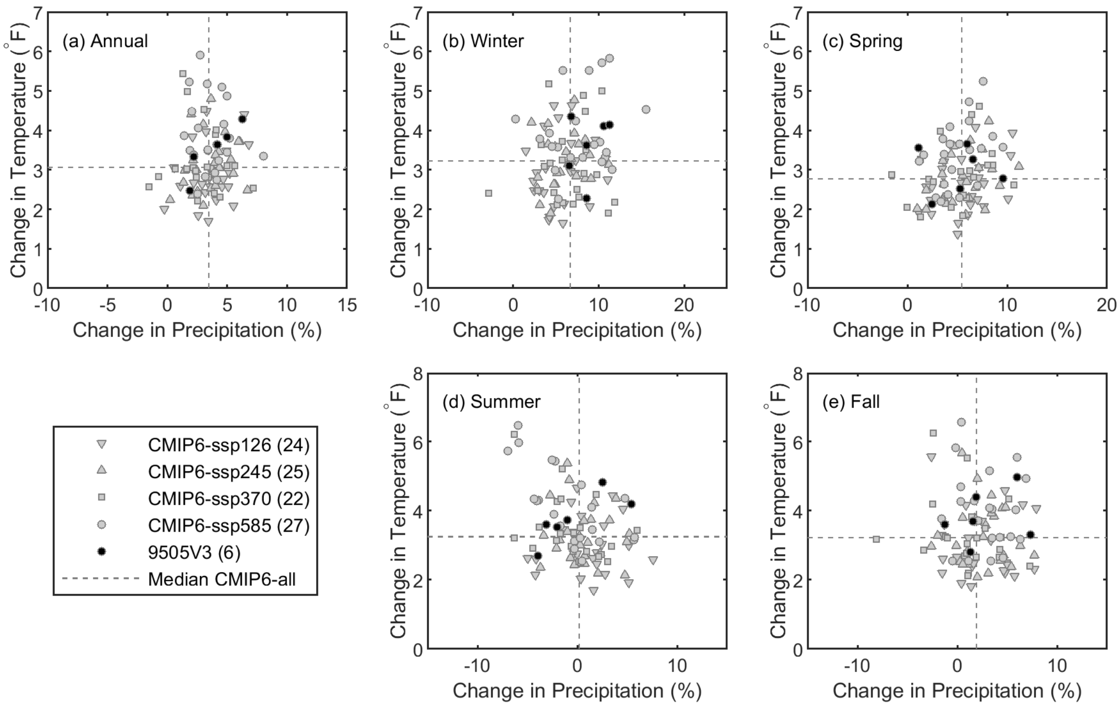

Figure 3. Annual and seasonal CONUS temperature and precipitation changes for 98 CMIP6 GCM projections under the four emission scenarios (from low to high: SSP126, SSP245, SSP370, and SSP585). Of the 98 CMIP6 GCM projections, six were selected for this study (shown in black). For each GCM projection, the average changes are calculated from the 1980–2019 baseline to the 2020–2059 future period.

Water availability for hydropower

Overall, the changes in runoff were inconsistent across PMA regions due to the strong precipitation inter-annual variability and differences in regional hydrology. Changes in precipitation and runoff more directly impact the expected hydropower production for the rainfall-dominated PMAs, SEPA and SWPA, which contain run-of-river facilities or possess relatively smaller storage capabilities. Changes in runoff for BPA and WAPA are more directly controlled by climate-induced changes in snowmelt, but large reservoir storages lessen impacts on hydropower production.

The annual total runoff is generally projected to increase across the CONUS (blue) in the near-term (2020–2039) and mid-term (2040–2059) future periods with respect to the baseline (1980–2019) period as shown in Figure 4. High runoff (95th percentile) is projected to increase in most CONUS watersheds (blue); however, low runoff (5th percentile of 7-day average) is projected to decrease in the eastern/central and western coastal areas of the CONUS (orange/red). The regions experiencing an increase in high runoff and decrease in low runoff will likely see more intensified hydrologic changes under future climate conditions. At the seasonal scale, winter and spring runoff are generally projected to increase across the CONUS. However, the summer runoff is projected to decrease for many parts of the CONUS, especially in the western and southern United States, indicating a shift in the timing and seasonality of the water availability.

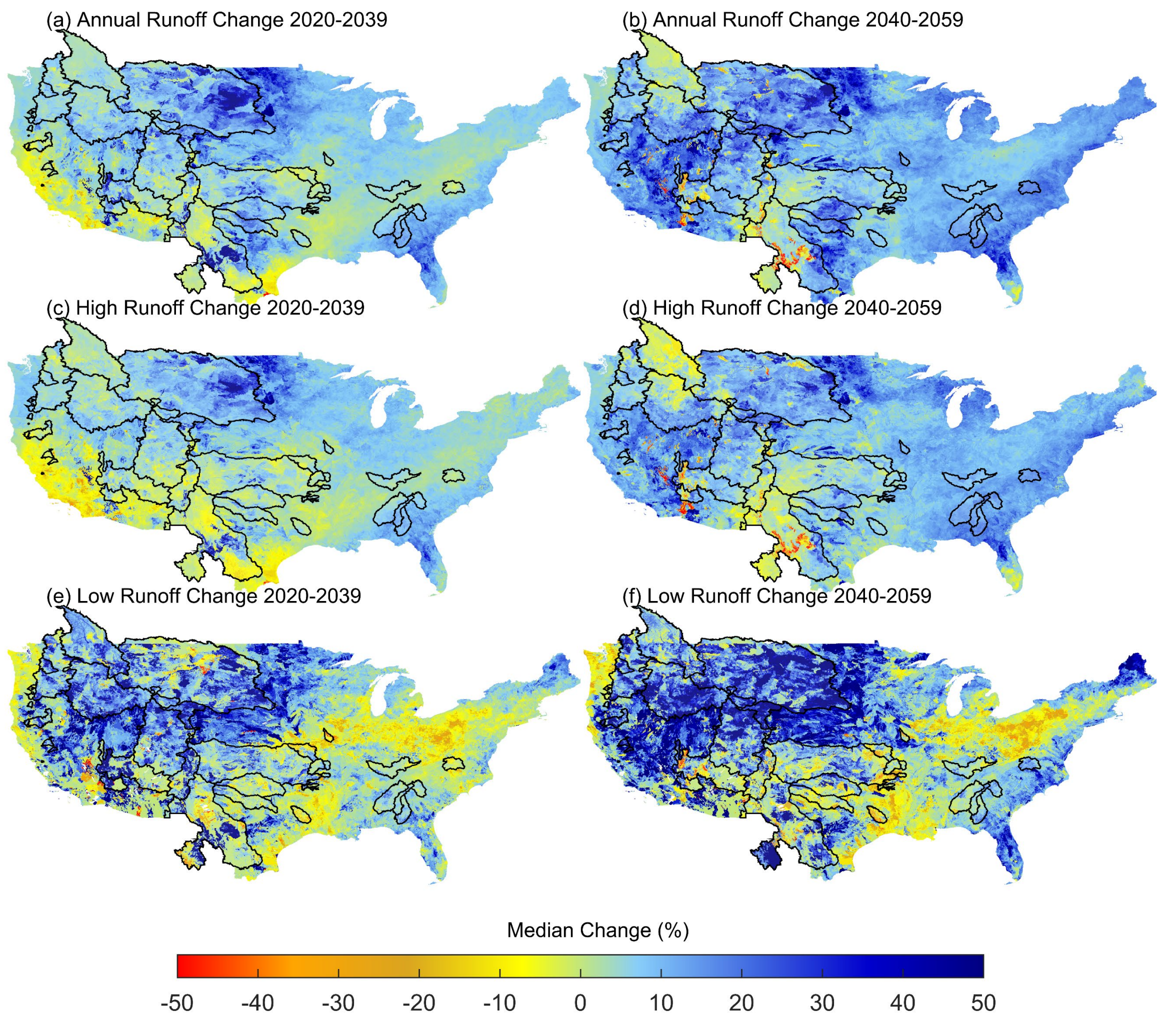

Figure 4. Projected change in annual total, high, and low runoff across the CONUS for the near term (2020–2039) and mid-term (2040–2059) future periods compared with the baseline historical period (1980–2019).

It is important to note that water availability projections shown in Figure 4 only represent results from six CMIP6 GCMs (shown in Figure 3). Given the large variation across all CMIP6 GCMs, future projections have large uncertainty that should be clearly acknowledged. Additionally, limitations in the model's ability to capture extremes means water availability may actually be less than what is projected in this study. For instance, an empirical study[8] examined the relationship between precipitation and runoff in the Upper Colorado River, suggesting that the recent droughts have been amplified by warmer temperatures. These warmer temperatures exacerbate the effects of relatively modest precipitation deficits. A recent study[9] also suggested that the current "megadrought" in the southwestern U.S. is a function of climate change, and a similar soil moisture drying signal can be seen in all CMIP6 models. Lastly, another research study[10] concluded that the continued business-as-usual warming will drive temperature-induced declines in river flow throughout the end of the century. Findings from these studies suggest that there is a high uncertainty and a knowledge gap in future water availability projections.

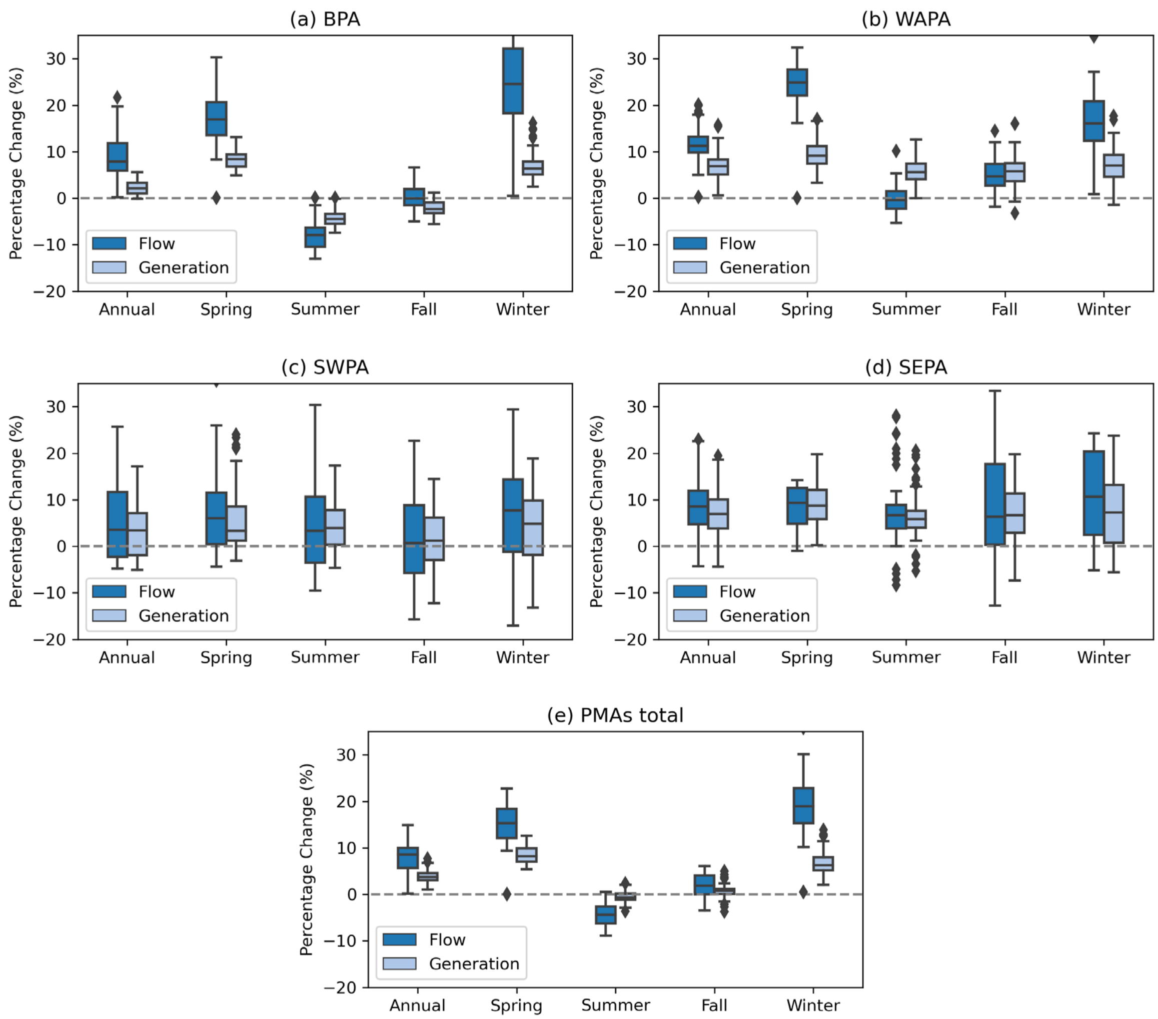

Figure 5. Projection of annual and seasonal flow and hydropower generation by PMA.

Climate change effects on generation

As a result of the projected increase in annual runoff (5-10 percent from 25th to 75th percentiles), hydropower generation is also projected to increase by 3-5 percent annually (Figure 5). Changes in reservoir inflow and hydropower generation vary by PMA. Overall, the projected annual changes (from 25th to 75th percentiles) at each PMA are:

- BPA: 5–12 percent increase in annual inflow and 1–3 percent increase in annual generation
- WAPA: 10–14 percent increase in annual inflow and 5–8 percent increase in annual generation
- SWPA: -3–12 percent increase in annual inflow and -2–7 percent increase in annual generation
- SEPA: 5-12 percent increase in annual inflow and 4-10 percent increase in annual generation

As stated previously, these increases in annual inflow and generation only represent the projections from six GCMs, so large uncertainty, either due to GCM selection or model limitations, may exist. It should also be noted that other studies of the western U.S. predict lower inflows based on region-specific modeling assumptions.[11] Additionally, the increase of inflows will not be steady and will likely accompany more extreme hydrologic events (i.e., both floods and droughts). Parts of the WAPA regions (e.g., Colorado River Basin) are experiencing an over 20-year drought that is interrupting regional water supply and hydropower generation. The results shown in Figure 5 are long-term averages computed over 40 years and do not capture extreme hydrologic events, sub-seasonal variations, or complex even hydrologic processes over mountainous terrain which dominate water availability and hydropower generation in the Western U.S.

Seasonally, increased median inflow and hydropower changes are projected in many seasons and regions, except for summer and fall in BPA. The spreads of annual and seasonal relative changes in both reservoir inflow and hydropower are generally smaller in BPA and WAPA than in SWPA and SEPA. As noted earlier, SEPA and SWPA generation is mainly provided by run-of-river facilities, whereas WAPA and BPA generation is provided by reservoirs with larger storage capacity relative to inflow. These differences are influenced by the different reservoir features in those PMA regions.

Climate change impacts on Federal power marketing

To understand the potential climate change impacts on Federal hydropower marketing, it is important to note the different power marketing rules, operational practices, and contract structures unique to each PMA.[7,12]

BACKGROUND ON UNIQUE PMAs RULES, PRACTICES, & STRUCTURES
Each PMA has unique power marketing rules, operational practices, and contract structures that must be considered alongside climate change impacts on hydropower generation.[7,12] • BPA provides hydroelectric power to its customers under long-term contracts, along with selling excess generation to the wholesale market. BPA is required to meet a customer's demand if requested. • WAPA offers contracts corresponding to various time lengths and product services (i.e., energy versus capacity) at rates that also vary by hydropower project. WAPA provides only a portion of its customers' wholesale power requirements and is not obligated to meet its customers load growth needs with Federal hydropower. • SWPA markets most of its hydropower as interconnected system peaking power allocations (1,200 hours of energy per kilowatt of capacity contracted per year), as many of the projects have limited storage capacity and several are low-head, run-of-river facilities. • SEPA typically uses long-term contracts, selling peaking power with a specified amount of energy per kilowatt of capacity.

Since BPA is the only PMA required to meet demand from its preference customers, we present a demand analysis for BPA in Figure 6. To understand how climate change may affect the customers' future demand, we evaluate the future trends in the demand for Federal hydropower given projected temperature levels. This information is crucial for meeting long-term market planning objectives and potentially shorter-term operational constraints. Annual heating degree days (HDDs) and cooling degree days (CDDs) are computed as the cumulative deviations of daily temperature from a reference balancing load point (BLP). This analysis uses sales data from the PMA preference customers selling to their end-users to estimate a demand-temperature relationship. The analysis for BPA customers is showed in Figure 6.

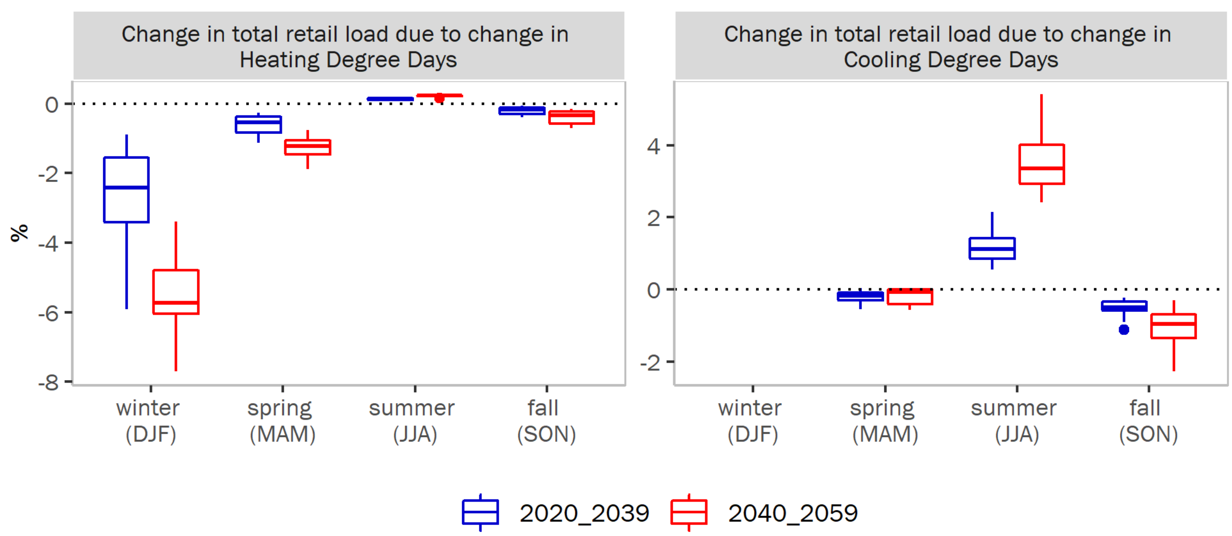

Figure 6. Estimated changes in seasonal load relative to baseline period due to projected changes in degree days for BPA preference customers with no large irrigation loads.

Due to a projected increase in the average temperature, there is a projected decrease in electricity sales of the BPA customers to their end-users in the winter and increased sales during summer. That is, the increased average temperature yields a lower number of heating degree days (HDDs) in the winter months (less demand for heating), and a higher number of cooling degree days (CDDs) in the summer months requiring air conditioning. This raises questions about what capacity and flexibility is available within BPA's region to meet increased summer demand as the operational flexibilities of Federal hydropower in BPA's system continue to be constrained.

Winter hydropower generation is expected to increase for all PMAs. The combination of the decreased heating load and increased hydropower generation (due to excess winter/spring runoff) suggests that Federal hydropower surpluses are likely during the winter months. The projected increase in cooling loads will be accompanied by decreased summer generation. Differences in the magnitude of the changes across the PMA marketing regions are due to many factors, including their geographic location, which influences the baseline values of HDDs and CDDs, and the load mix served by the preference customers in each region. Preference customers with large shares of residential loads tend to have the largest response of sales to temperature.

Despite the generally larger storage of Federal reservoirs, given a variety of legislative and operational constraints, the flexibility that currently exists in the PMA operational and marketing practices is limited. Climate-driven changes in total annual generation, seasonality of generation, and the frequency of extreme events (floods and droughts) might impact the competitiveness of Federal hydropower. Consistent and available generation from non-controllable generation assets (wind and solar) may also add constraints on hydropower scheduling that may or may not correlate well with the PMA customers' preferences. Two of the three PMAs that also operate load balancing authority areas (BPA and WAPA) are developing strategies for minimizing the cost of integrating variable renewables and co-evolving their hydropower assets with the other renewable resources. SWPA, though it operates a load balancing authority area, is considering how to maximize the value of their hydropower resources in external markets. The longevity of Federal hydropower is intrinsically linked to the need for flexibility in the operational rules and constraints set for the multi-purpose reservoirs, as climate-induced changes in the environment persist.

Reservoir evaporative loss

More severe reservoir evaporation losses are projected in the future providing new insight into water availability for future Federal hydropower production not shown in the two previous assessments. Although the amount may be relatively small when compared with the total runoff volume in some PMA regions (e.g., BPA), it may present a challenge for reservoirs in arid regions (e.g., WAPA). More specifically, the evaporation loss growth rate in the arid/semi-arid western United States is much higher than that in the eastern United States, which is expected to worsen the hydrological drought conditions in the future. In the near-term future period, the reservoirs with the largest changes are mainly in the south-central CONUS (mainly southern Missouri, western Arkansas–White–Red, and western Texas-Gulf hydrologic regions), whereas the rate of increase will be low in most of the eastern and western CONUS. In the mid-term future period, evaporation loss growth rates in the south-central United States will remain the largest. In addition, the changes of evaporation loss in the western United States are also significant (6 percent on average). The evaporation loss growth rate in the eastern United States (especially in the Southeast) will be relatively low in comparison.

Overview of potential risks

Overall, several potential risks that may impact the resilience of future Federal hydropower generation were identified. They include:

- ***Hydrologic extremes***: The intensification of future hydrologic cycle and extreme events is found to be one of the most critical issues threatening the resilience of power systems and infrastructure as suggested by the projected high/low precipitation and runoff. This is consistent with findings in other scientific literature. Both historical observations and model projections suggest that the intensity, frequency, and magnitude of extreme rainfall events will continue to increase, which will likely challenge conventional reservoir management practices. Although the reservoirs have been traditionally designed using relatively conservative rainfall estimates (i.e., probable maximum precipitation [PMP]), recent extreme events, such as the 2017 Hurricane Harvey near Houston, Texas, demonstrated that such an extremely large PMP estimate can still be exceeded[13], suggesting the potential need for more comprehensive evaluations.

  On the other hand, the duration and severity of extreme drought events are also projected to increase in many parts of the U.S. Although the annual precipitation and runoff are generally projected to increase in a warming environment, the distribution is not uniform in space and time. In 2021, Reclamation conducted a comprehensive drought assessment for the western U.S. using historical streamflow observations, future projections, and paleohydrology. [14] The results suggested that the severity of the drought events may not be sufficiently captured, based on limited historical streamflow observations. The ongoing severe drought in the western states resulted in an unprecedent disruption to the water supply and hydropower generation, demonstrating the dire impacts of drought.

- ***Conflicting timing of supply/demand changes***: Similar to the two previous assessments, temperature-driven early snowmelt is projected in most of the western U.S., suggesting that the bulk of runoff may arrive earlier in spring. However, as informed by the demand analysis, more temperature-driven water and energy demand is expected to shift from winter to summer, and hence creates a conflict. While ideally one may expect to mitigate this conflict through reservoir management, the intensified hydrologic extremes combined with all other competing water management objectives limit the ability and flexibility in storing more water resources to meet the peak demand. Furthermore, in arid regions, the enhanced reservoir evaporation may result in a sizable storage reduction and further exacerbate the nexus of electricity demand and water availability.

Assessment limitations

While this assessment utilizes state-of-the-art data and models, assessment limitations remain. They include:

- ***Interpretation of future projections***: Although GCM-driven dynamical/statistical downscaling may provide the most scientifically defensible regional-scale climate projections, it should not be considered an absolute, day-to-day weather prediction. The main purpose of climate modeling is to simulate how general climate statistics may evolve with respect to the specified future emission scenarios—not to provide an exact prediction of future weather and hydrology. Also, a simulation is only one of the tools that one may use to evaluate the potential impacts and system vulnerabilities. Other observation-based assessment approaches are equally valuable and should not be omitted for a more holistic understanding.

- ***Broader characterization of uncertainty***: While the multi-model framework provides a more comprehensive projection of future U.S. Federal hydropower generation, the multi-model projections still do not represent the full range of uncertainties related to all possible modeling choices. The extent of warmer temperatures causing increasingly drier soils and greater evapotranspiration is a significant additional uncertainty. Even in the case of higher average precipitation, drier soils and greater evapotranspiration will lead to reductions in water availability and lower average generation. The true uncertainties are more comprehensive and may not be fully captured because of limited knowledge, tools, and resources. The ensemble-based approach adopted in this study can serve as an initial example for the systematic analysis of broader uncertainties.

- ***Progression of climate science***: Although the capabilities of GCMs have continuously improved through the years, many ongoing challenges have not been resolved. For instance, although human activities play an important role in the Earth system environment, many of the GCM simulations were conducted without considering the potential human influence on land use, land cover change, and surface hydrologic alterations. Therefore, recurring climate impact assessments based on the best available climate science remain necessary.

- ***Regional assessment focus***: Overall, this study focuses on 18 PMA assessment areas rather than individual reservoirs or power plants. Impacts on site-specific features, such as reservoir operation rules, water withdrawal/return, environmental flow requirements, and energy generation, were not explicitly modeled at each power plant. In other words, this study means to provide a first-order assessment to identify areas with the highest risk under projected climate conditions. If a concern is identified for a specific region (e.g., change of streamflow seasonality), a regionally focused study can then be conducted. The assessment itself does not replace the existing site-specific models and tools used by the PMA's water and energy resource managers.

Future study needs

Through the series of 9505 assessments, a quantitative modeling framework has been established to gradually downscale the latest CMIP findings into regional, watershed-scale hydrologic and hydropower projections to support the understanding of risks for Federal hydropower generation and marketing. Although this framework has successfully achieved the anticipated SWA objectives, the climate change impacts are much broader and complex. Moving forward, additional studies and data support should be beneficial to the broader U.S. hydropower community, they include:

- ***Need to conduct basin-specific studies****:* Considering the varying geographical and socioeconomical challenges in different river basins, reservoir-specific studies may be required for basins with high water and energy interests. Studies using operational models forced by up-to-date hydroclimate projections, such as the recent RMJOC assessments[15,16], are one way to evaluate the risks and identify possible mitigation actions.

- ***Need to better understand the characteristics and impacts of future drought conditions***: As reported[9], 2000–2021 was the driest 22-year period in the southwest U.S. in the past 1,200 years. This prolonged megadrought highlights the need to better understand the characteristics (e.g., severity, timing, duration) and impacts of droughts for the resilience of U.S. long-term energy and water supply. In particular, efforts should focus on improving the understanding, modeling and analytics associated with future drought events.

- ***Need actionable, climate-informed data support***: Since hydroclimate modeling is not within a utility's original mission space, a utility may not have sufficient resources or dedicated in-house expertise to evaluate the risks due to long-term climate change. To reduce a utility's burden in conducting a full-scale hydroclimate study (i.e., from GCM selection all the way to river management simulation), it will be beneficial to provide actionable, climate-informed data support to the broader energy and water communities. The capabilities established through this Federal 9505 assessment may serve as a starting point.

- ***Need to address the broader risks***: Further disruptions due to wildfire, environmental requirements, and reduced operational flexibilities should be jointly considered. Additionally, the issue of aging infrastructure may reduce the system's ability to mitigate runoff variability and increase the difficulty of future operation. While these issues were not within the scope of this assessment, they should be further investigated in future studies.

VI. Recommendations from Administrators

Bonneville Power Administration (BPA)

BPA has been studying and considering climate change impacts on its operations for well over a decade. BPA analysis[17] shows that over the last several decades increasing temperatures throughout the Columbia River basin (inclusive of Canada) have contributed to increasing winter and early spring flows, with peak spring runoff shifting to several days earlier in the 20th century and decreasing summer flows. The third 9505 assessment and the recently completed River Management Joint Operating Committee (RMJOC-II) reports indicate that in the coming decades these trends will likely continue, along with the following climate change risks:

- Increasing temperatures;
- Wetter winters;
- Longer summer dry periods;
- Snowpacks melting earlier each year, or snowpacks that unreliably cycle between building and melting over winter seasons;
- Higher average fall and winter flows;
- Earlier peak spring runoff;
- Longer periods of low summer flows; and
- Longer, more severe wildfire seasons.

These projected changes in climate have implications for many facets of BPA's operations: hydropower generation, changes in demand, capacity and reliability of transmission lines, effectiveness of fish and wildlife mitigation programs, and vulnerability of infrastructure to sea level rise, flooding, and other natural disasters made worse by climate change.

Based on the best-available science and emerging trends, BPA is taking active but prudent steps to better align its planning functions with emerging climate change trends in the Pacific Northwest.

- BPA has updated its load forecasting assumptions to a more recent, 15-year period of record to reflect the increasing temperatures and corresponding impacts on electricity demand in the region.
- BPA is considering a significant update to its long-term hydropower generation assumptions for routine resource planning activities. Planning has historically been informed by streamflow data dating back to 1929, which includes runoff patterns that are becoming less likely as a result of climate change. BPA believes using the most recent 30 years of streamflow data will better enable BPA and other users of hydropower to plan for likely streamflow and generation conditions over the next several years as climate change continues to intensify. BPA held a public process in spring 2022 to discuss this change, and BPA will make a decision following public input.
- The 2020 Columbia River System Operations Environmental Impact Statement[18] included specific climate change scenarios, providing decision-makers with a reasonable range for total, bulk generation across the system under four climate change scenarios for different operating alternatives.

While the flexibility of the hydropower system is one critical tool to help BPA respond to the effects of climate change, environmental constraints have and are likely to continue to erode the operational flexibility of the system into the future. However, evolving regional markets and resource adequacy programs could help BPA tap into a more diverse pool of resources, helping address some of the climate change driven and other risks BPA faces in meeting its load obligations. This is one of the many reasons that BPA joined the Western Energy Imbalance Market on May 3, 2022; currently it is evaluating whether to join the Western Resource Adequacy Program (WRAP).

Collectively, these changes are helping BPA prepare for the effects of climate change and maintain a reliable, resilient Federal hydropower system into the future.

Western Area Power Administration (WAPA)

WAPA's response to climate change is framed within the context of their mission and authorities to safely provide reliable, cost-based hydropower and transmission to their customers and the communities they serve. In fulfilling that mission, WAPA markets and delivers cost-based hydroelectric power consistent with our existing statutory authority to more than 700 customers through over 17,000 miles of transmission lines. The process of developing and implementing marketing plans allows WAPA to evaluate energy and capacity allocations in response to observed and projected changes to generation over time, while preserving flexibility to meet power customers' needs.

While the third 9505 assessment provides regional forecasts for the very long term (40 years), WAPA's power marketing decisions are mostly based on shorter-term, plant specific information and analysis conducted by Reclamation and USACE. Both agencies use short-term (5-10 years) modeling and make reservoir releases based on the output of these models, of which hydropower generation is produced accordingly. WAPA's power marketing plans range between 30 and 50 years depending on the project being marketed. Each region evaluates many factors that go into the plan including future resource availability based on the above-mentioned modeling to ensure the most wide-spread use of the Federal hydropower resource.

WAPA will continue to evaluate new information regarding the impacts of climate change recognizing the need to honor existing contractual commitments and comply with existing marketing plans and applicable statutory authority. To prepare for continued uncertainty caused by climate change, WAPA, consistent within the above-described framework, has initiated:

- More flexible contract terms to allow for adjustments in commitments of energy delivery due to changes in hydrology.
- Developing modeling processes with assistance from the National Renewable Electricity Lab (NREL) and Argonne National Lab (ANL) to address drought conditions in the Lower Colorado River to assist the operation and planning for WAPA's DSW Region.
- Reviewing methods and strategies for purchasing firming power to improve reliability and retain ability to deliver firm power during period of drought and to facilitate hydroelectric generation sales during periods of surplus.

In addition to the current changes in its programs, WAPA continues to:

- Partner, as applicable, with existing customers and stakeholders to research methods to integrate hydropower with existing and new renewable generation, thereby improving the value of the hydropower, as well as potentially mitigate the impacts of climate-change induced drought.

- Partner with generating agencies and WAPA's existing customers to develop and implement ways to improve the value of hydropower through new scheduling procedures, services, or programs.
- Position WAPA for regional energy market participation by effectively managing industry changes surrounding WAPA's footprint while ensuring system reliability and alignment with WAPA's cost-effectiveness principles. Doing so allows WAPA to realize the added value and benefit to hydropower brought by electricity markets, while supporting their partner generating agencies' ability to meet water management objectives. WAPA DSW signed an implement agreement with CAISO in 2021 to join the Western Energy Imbalance Market (EIM) in 2023 (Western Area Power Administration, 2023).

Southwestern Power Administration (SWPA)

Consistent with comments provided in prior assessment reports, the effects of climate change on Federal hydropower in the southwest are specific to the hydrological and topographical attributes of the region. SWPA's river systems do not have large water storage capacity, either through the project reservoirs or natural snowpack found in other regions of the country and must rely directly on rainfall for hydropower generation. The third 9505 assessment demonstrates that SWPA's region already encounters significant variability in annual runoff, with the near-term period impact from climate change largely within that experienced range. Differing from the first 9505 assessment, which pointed to a potential increased frequency of drought conditions, this third 9505 assessment, like the second 9505 assessment, reveals strong indicators for increased runoff, particularly in the winter and spring seasons, although the threat of severe drought still exists.

All hydropower projects in the SWPA region are multipurpose projects, providing not only hydropower, but also flood control, water supply, navigation, fish and wildlife, both in-lake and downstream recreation, and tourism benefits. Changes in project operations or water storage to accommodate other beneficiaries can have significant impacts on hydropower generation and value. SWPA continues active participation on committees, work groups, studies and communications concerning the water availability and balance among the water resource uses. In addition, SWPA was instrumental in the 2016 establishment of the Federal Hydropower Council which brings PMA, USACE and Reclamation senior leaders together biannually to discuss these and other issues impacting Federal hydropower. SWPA continues strong engagement in this ongoing effort, which also includes interagency working groups addressing complex challenges facing the programs. SWPA remains continually aware of, and proactively responsive to, competing use demands on project storage and climate and hydrologic conditions that impact inflows in the SWPA region.

The wide variation in rainfall, runoff, and generation historically experienced in SWPA's region has resulted in the development of a marketing plan that maximizes the value of the Federal hydropower product with flexibility, contingencies, and the ability to purchase replacement energy when necessary to firm the hydropower resources. Purchases are blended with the available Federal hydropower to make a more beneficial and reliable product while assuring the repayment of the Federal investment with interest. SWPA uses a number of factors and computer models to determine when to purchase replacement power: a non-hydro guide curve (developed using period-of-record system simulations) in combination with inflow trends, storage remaining, long-term weather forecasts, the Palmer Drought Severity Index, season of the year, availability and price of power, impacts on competing users, and anticipated electrical loads. Annual funding authority levels for replacement power have been constrained since FY 2018. This elevates the potential for SWPA to utilize an emergency funding mechanism known as the Continuing Fund during a multi-year drought. Although all Federal hydropower program costs are recovered through power rates over a cycle of business, replacement energy purchased through the Continuing Fund requires cost recovery within a single year (since 2012) which would lead to rates spikes for regional customers during already difficult economic circumstances. SWPA has, and continues to pursue, solutions to ensure funding availability for replacement power purchase needs during times of drought, allowing for better planning and purchasing efficiencies, and ultimately more stable rates. In addition to SWPA's ability to purchase power, SWPA has a contract remedy in its Uncontrollable Forces provision, which relates to "failure of water supply," such as the result of a severe, long-term drought. If circumstances prevail such that it becomes imminently unlikely that SWPA can meet contractual power obligations due to a severe water shortage, the Uncontrollable Forces provision can be used.

Even though this assessment indicates a reduction in the probability of dry years (drought) and increased potential for significant runoff (flood events), purchases remain necessary during those events, and for competing use impacts, to meet contractual obligations. Additionally, similar purchasing flexibilities are needed during significant flood events when hydropower operations become constrained due to release restrictions for reducing downstream flooding and loss of unit capability from either too great or too low hydropower head conditions. It should be noted that planning for and responding to severe multi-year drought continues to be one of SWPA's largest operational and financial risks given constraints with current funding authorities.

SWPA will continue to review and monitor the findings identified in the third 9505 assessment and incorporate those with other issues impacting Federal hydropower production capability. SWPA will also continue strengthened coordination with customers, stakeholders and Federal partners during various extreme weather events and remain active in pursuit of solutions and opportunities to retain and improve the Federal hydropower resource value into the future.

Southeastern Power Administration (SEPA)

SEPA is not a full-requirements power supplier and makes up only a small percentage of its customers' electric power resource requirements. Under the current marketing strategy and marketing policies, SEPA has maintained effective operations through increasingly severe droughts. The hydrologic variability described in the third 9505 assessment did not exceed the variances already incorporated into SEPA's market strategy. SEPA participates in hydrologic studies, modeling groups, and other stakeholder activities concerning the operation of the

Federal projects. SEPA and USACE routinely communicate and adjust project operations to optimize water use and power production.

All the capacity and energy produced at USACE projects and marketed by SEPA is allocated to customers through long-term contractual arrangements. SEPA does not currently have any provisions for short-term sales. SEPA's long-term contracts specify the amount of capacity and energy available to each customer. Each contract has provisions to disperse power in excess of the contractual obligation and mechanisms to purchase replacement power if project operations cannot support the minimum requirements.

Replacement energy and pump energy purchases enable SEPA to provide energy to customers when hydrologic conditions are insufficient to meet contractual requirements. SEPA and USACE routinely communicate hydrologic forecasts. These forecasts provide information to SEPA concerning expected inflow and the potential for shortfalls in generation. SEPA can then make a proactive decision to purchase replacement power and conserve project storage for a time when replacement power would be more expensive or seasonal operations restrict the delivery of replacement power.

SEPA utilizes customer or alternative funding agreements to provide for replacement and refurbishment of generating equipment that has failed or is nearing life expectancy. Customer funding allows these capital infrastructure investments to occur rather than risk loss or remain out of service while awaiting congressional appropriations. Customer funding expedites the rehabilitation of generating equipment, which increases power production, enhances equipment reliability, and maximizes the availability of renewable generation.

SEPA's implementation of the aforementioned processes, along with the continuance of strategic operational reviews and routine power rate assessments, addresses the report's climate change forecast. SEPA is committed to monitoring the issues set forth in this study while preserving carbon free generation and sustaining the Federal Power Program.

V. Conclusion

This third 9505 assessment builds from the previous two assessments by analyzing the effects of climate change on annual and seasonal Federal hydropower generation and other related risks. A spatially consistent assessment approach was designed to evaluate hydropower generation from 132 Federal hydropower plants that are marketed by four PMAs. The assessment incorporates a new multi-model framework that examined to what extent the methodological choices may influence the full range of projected hydropower generation in the near-term (2020–2039) and mid-term (2040–2059) future periods.

In support of the two previous assessments, the results show that maintaining operational flexibility remains one key challenge for Federal hydropower reservoirs that are projected to experience seasonal supply and demand changes. Overall, while the annual runoff, streamflow, and hydropower generation are projected to slightly increase across the CONUS, a reduction can be expected in some seasons and regions. Winter and spring runoff is projected to increase in most PMA regions, and summer runoff is projected to decrease across much of the CONUS. This will affect the projection of seasonal hydropower generation, although the changes may be partially mitigated through the operation of Federal multipurpose reservoirs. On the other hand, the intensification of future hydrologic cycle and extreme events (including both floods and droughts) can be one of the most critical issues threatening the resilience of the Nation's infrastructure systems. Increasing operational and marketing flexibilities would be highly valuable for all PMAs, but this is beyond the operational directives of many Federal multipurpose reservoirs.

The recommendations from the PMA Administrators as to how they can respond to the effects of climate change are included as part of this Report to Congress. Generally, maintaining large storage capacity, more flexible operational policies, and joining other electricity markets are possible long-term strategies to better manage the effects of hydrologic uncertainty and extremes and maintain affordable, reliable electricity for their customers. Further basin-specific studies using operational models, forced by up-to-date hydroclimate projections, can be one of the ways to evaluate the risks and identify potential mitigation actions for long-term water and energy infrastructure resilience.

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APPENDIX A. *LIST OF FEDERAL HYDROPOWER PLANTS MARKETED THROUGH POWER MARKETING ADMINISTRATIONS*

N	Power plant name	Power system	Owner	Generation type	Capacity (MW)	1980–2019 average annual generation (GWh/year)
BPA-1 Upper Columbia						
1	Grand Coulee	Federal Columbia River Power System (FCRPS)	Reclamation	Conventional Hydro	6,495	20,160.6
				Pumped Storage	314	
2	Hungry Horse		Reclamation	Conventional Hydro	428	920.6
3	Albeni Falls		USACE	Conventional Hydro	42	210.8
4	Libby		USACE	Conventional Hydro	525	2,075.3
BPA-2 Snake River						
5	Anderson Ranch	Federal Columbia River Power System (FCRPS)	Reclamation	Conventional Hydro	40	129.4
6	Black Canyon		Reclamation	Conventional Hydro	10.2	60.2
7	Boise R Diversion		Reclamation	Conventional Hydro	3.3	4.3
8	Minidoka		Reclamation	Conventional Hydro	27.7	94.4
9	Palisades		Reclamation	Conventional Hydro	176.4	623.8
10	Dworshak		USACE	Conventional Hydro	465	1,744.2
11	Ice Harbor		USACE	Conventional Hydro	603	1,995.9
12	Little Goose		USACE	Conventional Hydro	810	2,452.1
13	Lower Granite		USACE	Conventional Hydro	810	2,492.2
14	Lower Monumental		USACE	Conventional Hydro	810	2,438.7
BPA-3 Mid-Lower Columbia						
15	Chandler	Federal Columbia River Power System (FCRPS)	Reclamation	Conventional Hydro	12	47.7
16	Roza		Reclamation	Conventional Hydro	12.9	50.2
17	Bonneville		USACE	Conventional Hydro	1,162	4,933.0
18	Chief Joseph		USACE	Conventional Hydro	2,456.2	11,242.9
19	John Day		USACE	Conventional Hydro	2,160	9,801.4
20	McNary		USACE	Conventional Hydro	990.5	5,937.4
21	The Dalles		USACE	Conventional Hydro	1,819.7	7,222.5
BPA-4 Cascade Mountains						
22	Green Springs	Federal Columbia River Power System (FCRPS)	Reclamation	Conventional Hydro	17.2	62.7
23	Big Cliff		USACE	Conventional Hydro	18	87.4
24	Cougar		USACE	Conventional Hydro	26	124.1
25	Detroit		USACE	Conventional Hydro	100	353.1
26	Dexter		USACE	Conventional Hydro	15	70.1
27	Foster		USACE	Conventional Hydro	20	90.5
28	Green Peter		USACE	Conventional Hydro	80	234.4
29	Hills Creek		USACE	Conventional Hydro	30	148.1
30	Lookout Point		USACE	Conventional Hydro	120	313.6
31	Lost Creek		USACE	Conventional Hydro	49	266.1
WAPA-1 Upper Missouri						
32	Canyon Ferry	Pick-Sloan-Eastern Division	Reclamation	Conventional Hydro	49.8	353.4
33	Big Bend		USACE	Conventional Hydro	538.3	923.1
34	Fort Peck		USACE	Conventional Hydro	179.7	922.9

N	Power plant name	Power system	Owner	Generation type	Capacity (MW)	1980–2019 average annual generation (GWh/year)
35	Fort Randall		USACE	Conventional Hydro	320	1,636.4
36	Garrison		USACE	Conventional Hydro	583.4	2,105.7
37	Gavins Point		USACE	Conventional Hydro	132.3	699.8
38	Oahe		USACE	Conventional Hydro	786.1	2,460.3
39	Yellowtail[a]	Pick-Sloan-Eastern Division / Loveland	Reclamation	Conventional Hydro	268.8	805.3
WAPA-2 Loveland Projects						
40	Alcova	Loveland Area Projects (LAPs)	Reclamation	Conventional Hydro	41.4	111.6
41	Boysen		Reclamation	Conventional Hydro	15	64.4
42	Buffalo Bill		Reclamation	Conventional Hydro	18	70.0
43	Shoshone		Reclamation	Conventional Hydro	3	16.0
44	Heart Mountain		Reclamation	Conventional Hydro	5	19.8
45	Spirit Mountain		Reclamation	Conventional Hydro	4.5	15.0
46	Flatiron		Reclamation	Conventional Hydro	86	214.8
				Pumped Storage	8.5	
47	Big Thompson		Reclamation	Conventional Hydro	4.5	9.0
48	Fremont Canyon		Reclamation	Conventional Hydro	66.8	223.2
49	Glendo		Reclamation	Conventional Hydro	38	81.3
50	Green Mountain		Reclamation	Conventional Hydro	26	54.1
51	Guernsey		Reclamation	Conventional Hydro	6.4	17.8
52	Kortes		Reclamation	Conventional Hydro	36	135.5
53	Mary's Lake		Reclamation	Conventional Hydro	8.1	37.2
54	Estes		Reclamation	Conventional Hydro	45	100.4
55	Mount Elbert		Reclamation	Pumped Storage	200	
56	Pole Hill		Reclamation	Conventional Hydro	38.2	169.3
57	Seminoe		Reclamation	Conventional Hydro	51.6	130.5
WAPA-3 Upper Colorado						
58	Blue Mesa	Salt Lake City	Reclamation	Conventional Hydro	86.4	259.2
59	Crystal		Reclamation	Conventional Hydro	28	164.9
60	Elephant Butte		Reclamation	Conventional Hydro	27.9	78.8
61	Flaming Gorge		Reclamation	Conventional Hydro	151.8	481.2
62	Fontenelle		Reclamation	Conventional Hydro	10	49.5
63	Glen Canyon Dam		Reclamation	Conventional Hydro	1,312	4,587.3
64	Upper Molina		Reclamation	Conventional Hydro	9.9	28.9
65	Lower Molina		Reclamation	Conventional Hydro	5.6	16.7
66	McPhee		Reclamation	Conventional Hydro	1.2	3.7
67	Towaoc		Reclamation	Conventional Hydro	11.4	14.4
68	Morrow Point		Reclamation	Conventional Hydro	173.2	341.7
69	Deer Creek	Provo River	Reclamation	Conventional Hydro	4.8	24.3
WAPA-4 Lower Colorado						
70	Hoover Dam	Boulder Canyon	Reclamation	Conventional Hydro	2,078.8	4,590.8
71	Davis Dam	Parker-Davis	Reclamation	Conventional Hydro	254.8	1,212.6

N	Power plant name	Power system	Owner	Generation type	Capacity (MW)	1980–2019 average annual generation (GWh/year)
72	Parker Dam		Reclamation	Conventional Hydro	120	512.3
WAPA-5 Rio Grande						
73	Amistad Dam & Power	Falcon-Amistad	IBWC	Conventional Hydro	66	127.1
74	Falcon Dam & Power		IBWC	Conventional Hydro	31.5	69.9
WAPA-6 California						
75	Folsom	Central Valley	Reclamation	Conventional Hydro	198.6	572.9
76	Judge F Carr		Reclamation	Conventional Hydro	154.4	399.3
77	Keswick		Reclamation	Conventional Hydro	117	414.9
78	New Melones		Reclamation	Conventional Hydro	300	449.7
79	Nimbus		Reclamation	Conventional Hydro	13.4	57.8
80	ONeill		Reclamation	Pumped Storage	25.2	
81	W R Gianelli		Reclamation	Pumped Storage	424	
82	Shasta		Reclamation	Conventional Hydro	714	1,866.0
83	Spring Creek		Reclamation	Conventional Hydro	180	477.4
84	Trinity		Reclamation	Conventional Hydro	140	431.7
85	Lewiston		Reclamation	Conventional Hydro	0.35	2.4
86	Stampede	Washoe	Reclamation	Conventional Hydro	3.6	10.1
SWPA-1 Upper White, Osage, and Salt						
87	Beaver	Southwestern financially integrated projects	USACE	Conventional Hydro	112	152.0
88	Bull Shoals		USACE	Conventional Hydro	340	784.4
89	Clarence Cannon		USACE	Conventional Hydro	27	93.8
				Pumped Storage[b]	31	
90	Greers Ferry		USACE	Conventional Hydro	96	185.9
91	Harry S Truman		USACE	Pumped Storage[c]	161.4	273.8
92	Norfork		USACE	Conventional Hydro	80.4	199.2
93	Stockton		USACE	Conventional Hydro	52	52.0
94	Table Rock		USACE	Conventional Hydro	200	513.8
SWPA-2 Arkansas						
95	Dardanelle	Southwestern financially integrated projects	USACE	Conventional Hydro	160.8	613.6
96	Eufaula		USACE	Conventional Hydro	90	273.9
97	Fort Gibson		USACE	Conventional Hydro	44.8	215.9
98	Keystone		USACE	Conventional Hydro	70	267.8
99	Ozark		USACE	Conventional Hydro	100	255.0
100	Robert S Kerr		USACE	Conventional Hydro	110	555.7
101	Tenkiller Ferry		USACE	Conventional Hydro	39	120.1
102	Webbers Falls		USACE	Conventional Hydro	70	196.1
103	Broken Bow[d]		USACE	Conventional Hydro	100	154.5
SWPA-3 Ouachita, Red, and Brazos						
104	Blakely Mountain	Southwestern financially integrated projects	USACE	Conventional Hydro	75	174.3
105	DeGray		USACE	Conventional Hydro	40	81.0
				Pumped Storage (Reversible)	28	

N	Power plant name	Power system	Owner	Generation type	Capacity (MW)	1980–2019 average annual generation (GWh/year)
106	Denison		USACE	Conventional Hydro	101.6	246.5
107	Narrows		USACE	Conventional Hydro	25.5	38.1
108	Whitney		USACE	Conventional Hydro	41.8	50.5
SWPA-4 Neches						
109	Robert D Willis	Southwestern isolated projects	USACE	Conventional Hydro	8	25.6
110	Sam Rayburn		USACE	Conventional Hydro	52	119.8
SEPA-1 Kerr-Philpot						
111	John H Kerr	Kerr-Philpot	USACE	Conventional Hydro	296.8	433.5
112	Philpott Lake		USACE	Conventional Hydro	14	24.2
SEPA-2 Cumberland						
113	Barkley	Cumberland	USACE	Conventional Hydro	130	629.6
114	Center Hill		USACE	Conventional Hydro	140	334.1
115	Cheatham		USACE	Conventional Hydro	36	159.5
116	Cordell Hull		USACE	Conventional Hydro	99.9	361.6
117	Dale Hollow		USACE	Conventional Hydro	54	118.4
118	J P Priest		USACE	Conventional Hydro	28	65.0
119	Laurel		USACE	Conventional Hydro	70	63.6
120	Old Hickory		USACE	Conventional Hydro	103.7	459.5
121	Wolf Creek		USACE	Conventional Hydro	270	872.0
SEPA-3 GA/AL/SC						
122	Allatoona	GA/AL/SC	USACE	Conventional Hydro	86.6	125.8
123	Buford		USACE	Conventional Hydro	131.2	163.7
124	Carters		USACE	Conventional Hydro	250	454.2
				Pumped Storage	250	
125	Hartwell Lake		USACE	Conventional Hydro	420	419.8
126	J Strom Thurmond		USACE	Conventional Hydro	361.9	610.6
127	Millers Ferry		USACE	Conventional Hydro	101.1	335.7
128	Jones Bluff		USACE	Conventional Hydro	82	297.3
129	Richard B Russell		USACE	Conventional Hydro	300	636.2
				Pumped Storage	328	
130	Walter F George		USACE	Conventional Hydro	168	382.8
131	West Point		USACE	Conventional Hydro	73.3	173.3
SEPA-4 Jim Woodruff						
132	J Woodruff	Jim Woodruff	USACE	Conventional Hydro	43.5	202.1

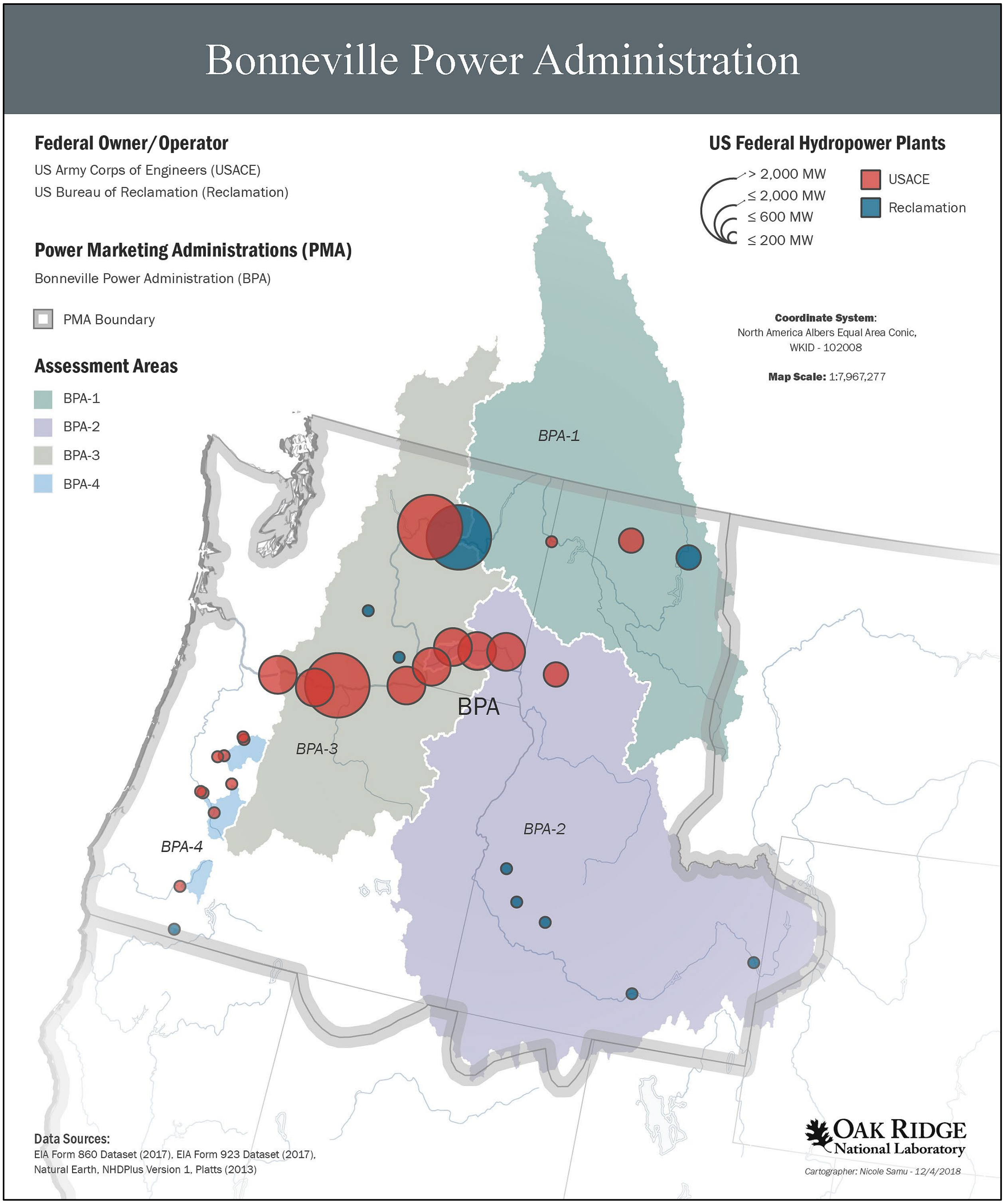
[a] Two of the four Yellowtail units are marketed as a Pick-Sloan-Eastern Division resource and two are marketed as a Loveland Area Projects (LAPs) resource. For the purposes of this analysis, the entire Yellowtail plant is included in the Pick-Sloan-Eastern Division.

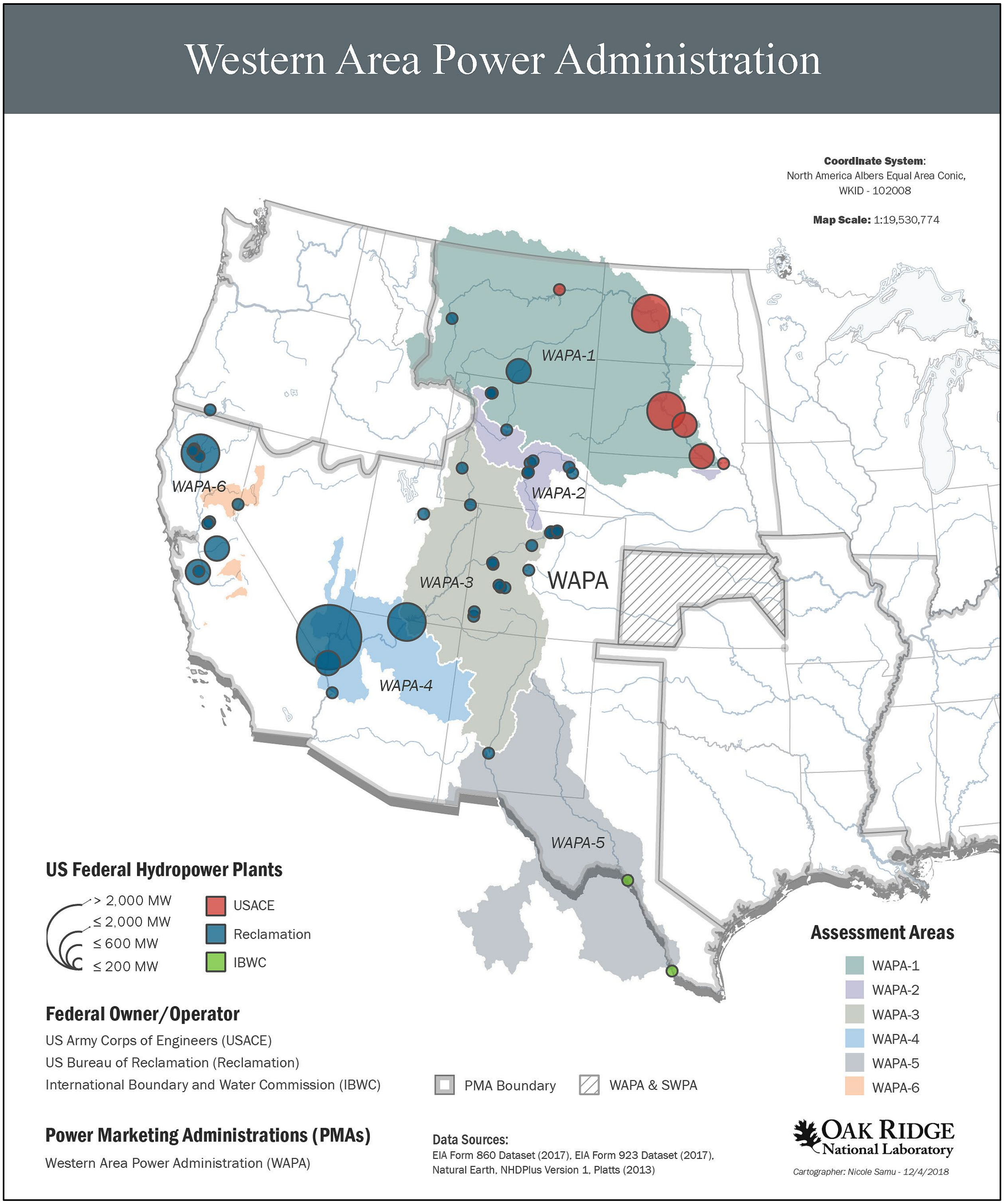
[b] The pumpback feature of the reversible unit at Cannon has not been used in regular operation (other than initial tests). As the reservoir has to be significantly low for the pumpback to function, it has not been practical to use the feature. The reversible unit is used regularly like conventional hydro.

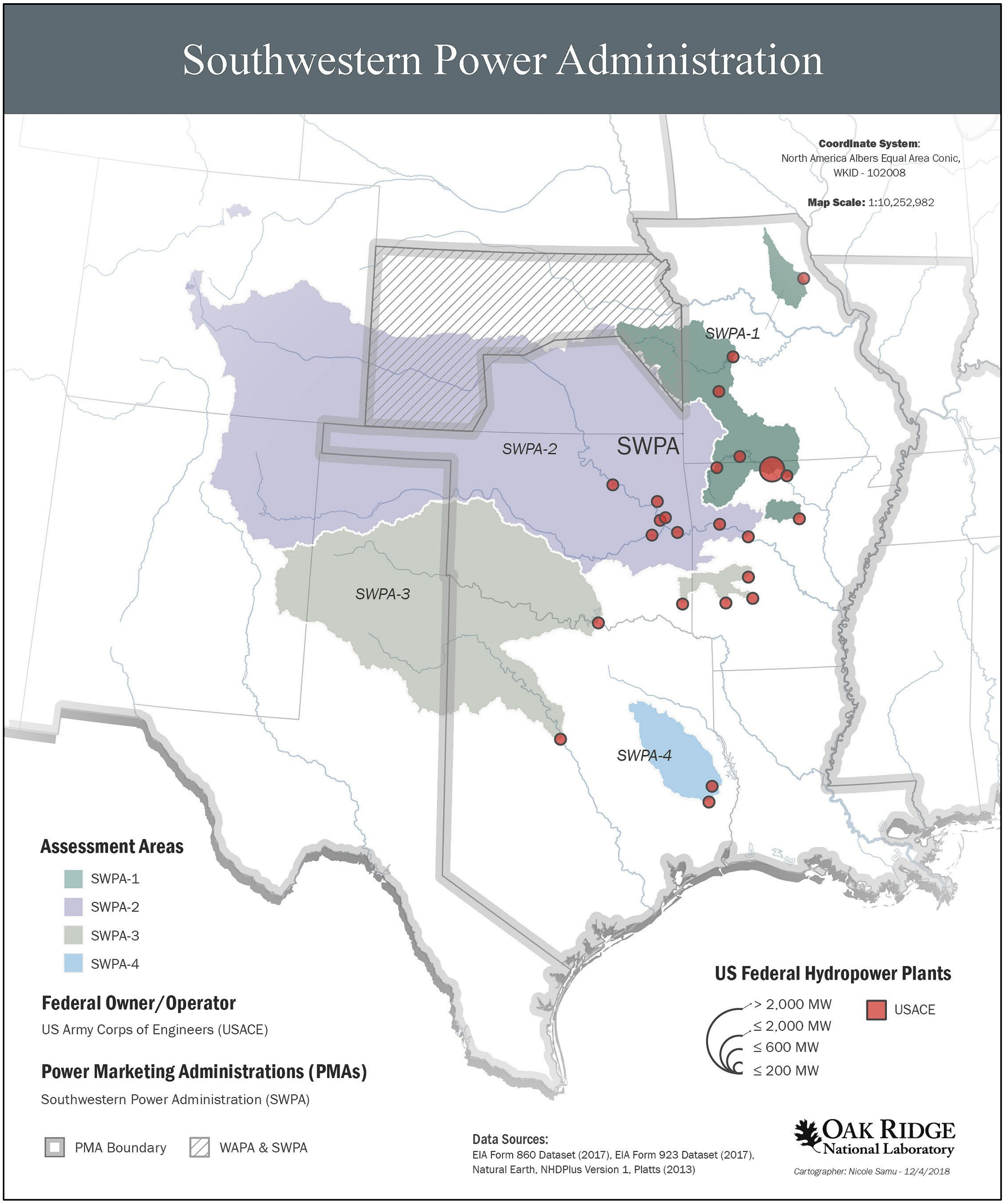
[c] Although Harry S. Truman has the capability of pumped storage through multiple reversible units, it is used as conventional hydro because of state objections to the use of the pumpback function. It is currently not available as a pumped storage project.

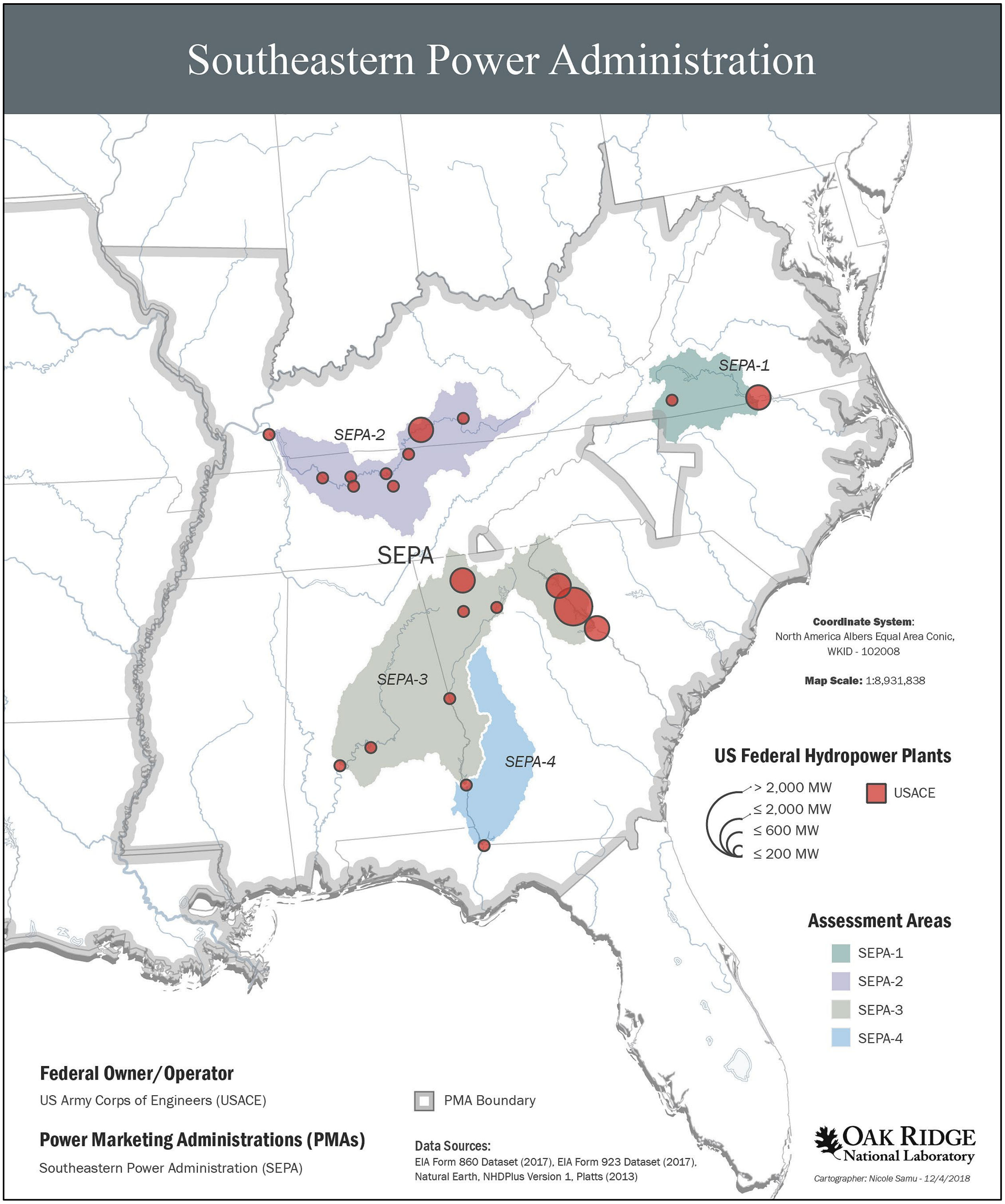
[d] Broken Bow in the Red River Basin is included in SWPA-2 due to interconnected system reason.

APPENDIX B. *REGIONS AND ASSESSMENT AREAS*




Western Area Power Administration
Coordinate System:
North America Albers Equal Area Conic,
WKID - 102008
Map Scale: 1:19,530,774
WAPA-1
WAPA-2
WAPA-3
WAPA-4
WAPA-5
WAPA-6
WAPA
US Federal Hydropower Plants
> 2,000 MW
≤ 2,000 MW
≤ 600 MW
≤ 200 MW
USACE
Reclamation
IBWC
Federal Owner/Operator
US Army Corps of Engineers (USACE)
US Bureau of Reclamation (Reclamation)
International Boundary and Water Commission (IBWC)
PMA Boundary
WAPA & SWPA
Assessment Areas
WAPA-1
WAPA-2
WAPA-3
WAPA-4
WAPA-5
WAPA-6
Power Marketing Administrations (PMAs)
Western Area Power Administration (WAPA)
Data Sources:
EIA Form 860 Dataset (2017), EIA Form 923 Dataset (2017),
Natural Earth, NHDPlus Version 1, Platts (2013)
OAK RIDGE
National Laboratory
Cartographer: Nicole Samu - 12/4/2018


Southwestern Power Administration
Coordinate System:
North America Albers Equal Area Conic,
WKID - 102008
Map Scale: 1:10,252,982
SWPA-1
SWPA-2
SWPA
SWPA-3
SWPA-4
Assessment Areas
SWPA-1
SWPA-2
SWPA-3
SWPA-4
Federal Owner/Operator
US Army Corps of Engineers (USACE)
Power Marketing Administrations (PMAs)
Southwestern Power Administration (SWPA)
PMA Boundary
WAPA & SWPA
US Federal Hydropower Plants
> 2,000 MW
≤ 2,000 MW
≤ 600 MW
≤ 200 MW
USACE
Data Sources:
EIA Form 860 Dataset (2017), EIA Form 923 Dataset (2017), Natural Earth, NHDPlus Version 1, Platts (2013)
Oak Ridge National Laboratory
Cartographer: Nicole Samu - 12/4/2018


Southeastern Power Administration
SEPA-1
SEPA-2
SEPA
SEPA-3
SEPA-4
Coordinate System:
North America Albers Equal Area Conic,
WKID - 102008
Map Scale: 1:8,931,838
US Federal Hydropower Plants
> 2,000 MW
≤ 2,000 MW
≤ 600 MW
≤ 200 MW
USACE
Assessment Areas
SEPA-1
SEPA-2
SEPA-3
SEPA-4
Federal Owner/Operator
US Army Corps of Engineers (USACE)
PMA Boundary
Power Marketing Administrations (PMAs)
Southeastern Power Administration (SEPA)
Data Sources:
EIA Form 860 Dataset (2017), EIA Form 923 Dataset (2017),
Natural Earth, NHDPlus Version 1, Platts (2013)
OAK RIDGE
National Laboratory
Cartographer: Nicole Samu - 12/4/2018

APPENDIX C. *SUMMARY OF DATA SOURCES*

Data type	Data source	Reference/website
Hydropower project characteristics	• Previous 9505 assessments • HydroSource • National Inventory of Dams (NID) • Global Reservoir and Dam Database (GRanD)	• Kao et al. (2016); Sale et al. (2012) • HydroSource, https://hydrosource.ornl.gov; Johnson et al. (2021) • NID, https://nid.sec.usace.army.mil • GRanD, https://www.globaldamwatch.org/grand
Historic hydropower generation	• PMA • EIA Form 923 Database	• Historic generation records provided by PMAs • EIA (2020), https://www.eia.gov/electricity/data/eia923
Electricity sales for PMA customers	• EIA Form 861 (Annual Electric Power Industry Report)	• https://www.eia.gov/electricity/data/eia861
Total retail load of BPA's customers	• BPA	• Personal communication with BPA staff
Meteorological observations	• Daymet • Livneh • Parameter-elevation Regressions on Independent Slopes Model (PRISM) • NCEP North American Regional Reanalysis (NARR) wind speed	• https://daymet.ornl.gov; Thornton et al. (2021) • https://psl.noaa.gov/data/gridded/data.livneh.html; Pierce et al. (2021) • https://prism.oregonstate.edu; Daly et al. (2002) • https://www.esrl.noaa.gov/psd/data/gridded/data.narr.html; Mesinger et al. (2006)
Hydrologic observations	• USGS National Water Information System (NWIS) • Environment Canada HYDAT Database • WaterWatch • Bias Correction and Quality Control (BCQC) SNOTEL Data • Historical reservoir storage and area	• https://waterdata.usgs.gov/nwis • https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity/monitoring/survey/data-products-services/national-archive-hydat.html • https://waterwatch.usgs.gov; Brakebill et al. (2011) • Sun et al. (2019); Yan et al. (2018) • Zhao and Gao (2018) and (2019)
Income per capita	• Bureau of Economic Analysis Annual Personal Income by County (CAINC1) series	• https://apps.bea.gov/regional/downloadzip.cfm
Air conditioning ownership in the Pacific Northwest	• Northwest Energy Efficiency Alliance (NEEA) Residential Building Stock Assessment II	• https://neea.org/resources/rbsa-ii-combined-database
City boundary	• US Census Bureau's Topologically Integrated Geographic Encoding and Referencing (TIGER) dataset	• https://www.census.gov/geo/maps-data/data/tiger.html

APPENDIX D. *PROGRESSION OF THREE 9505 ASSESSMENTS*