U.S. DEPARTMENT OF ENERGY

Effects of Climate Change on Federal Hydropower

The Second Report to Congress
January 2017

United States Department of Energy
Washington, DC 20585

Message from the Acting Assistant Secretary for Energy Efficiency and Renewable Energy

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 second report to Congress contains the updated summary findings from the most recent detailed study, 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 Lisa Murkowski**
  Chairman
  Senate Committee on Energy and Natural Resources

- **The Honorable Maria Cantwell**
  Ranking Member
  Senate Committee on Energy and Natural Resources

- **The Honorable Greg Walden**
  Chairman
  House Committee on Energy and Commerce

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

- **The Honorable Rob Bishop**
  Chairman
  House Committee on Natural Resources

- **The Honorable Raul M. Grijalva**
  Ranking Memher
  House Committee on Natural Resources

If you have any further questions, please contact me or Mr. Christopher King, Acting Assistant Secretary for the Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

David J. Friedman

Executive Summary

The *Effects of Climate Change on Federal Hydropower: The Second Report to Congress,* as directed by Section 9505 of the SECURE Water Act (SWA) of 2009, is the second quinquennial report summarizing the potential effects of climate change on water available for hydropower generation at 132 U.S. federal hydropower plants and on the marketing of that power. A detailed study, the "9505 assessment", utilized the best available scientific research and models to form the basis for the second report's findings and conclusions. The comprehensive assessment for the report was developed by Oak Ridge National Laboratories at the direction of the DOE.[1] Hydropower is a key contributor to the U.S. renewable energy portfolio because of its history of reliability and the diverse benefits it provides to electric power systems. Ensuring the sustainable operation of existing hydropower facilities is of great importance to the U.S. economy. This study is the result of extensive consultation with the federal Power Marketing Administrations (PMAs), as well as with other federal and state water agencies. The report herein introduces a newly developed methodology, followed by a discussion of the main findings and a summary of the potential effects of climate change on projected future hydropower generation.

The intent of this study was to evaluate the large-scale climate change effects on all federal hydropower plants within 18 PMA study areas on annual and seasonal time scales, enabling policymakers to evaluate potential climate change impacts across the entire federal hydropower fleet. This study used a series of models and methods to gradually downscale the global climate model outputs into watershed-scale hydrologic projections for near-term (2011–2030) and midterm (2031–2050) future periods.

Results from this assessment varied across the distinct PMA regions because of diverse topographical and hydrological features, as well as differences in hydropower operation practices. Modeling projections of several hydrometeorological variables helped explain: (1) how fleet-wide hydropower production may change in the future and (2) the impact on marketing Federal hydropower. The most important climate change effects impacting future hydropower generation are likely to be earlier snowmelt, change of runoff seasonality, and increasing frequency of extreme high- and low-runoff events.

Given the projected shift in hydrological conditions, water resource managers may need to allocate their water usage more cautiously. U.S. federal hydropower reservoirs with relatively large storage capacity have the ability to absorb some increased runoff variability and will likely continue to provide stable annual hydropower generation in the projected near-term and midterm future periods. The flexibility that currently exists in PMA marketing practices will likely continue to allow the PMAs to fulfill their missions in the face of climate variability.

The 9505 assessment provides federal hydropower administrators with information that may be useful for operational or contractual planning to address future climate variability and risk. 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. The future assessments that are required every 5 years under Section 9505 could be improved by incorporating improved climate models and data as they become available, further statistical analysis of climate influences on power marketing, and a closer examination of potential indirect effects on hydropower production.

Effects of Climate Change on Federal Hydropower

The Second Report to Congress

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I. Legislative Language

This report responds to legislative language set forth in Section 9505 of The SECURE Water Act of 2009 (Omnibus Public Lands Act, Pub. L. No. 111-11, Subtitle F), 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. Methodology

Scope and objectives

This report, *Effects of Climate Change on Federal Hydropower: The Second Report to Congress*, was prepared by the Department of Energy's (DOE) Wind and Water Power Technologies Office, which engaged Oak Ridge National Laboratory (ORNL) to prepare an assessment of the potential future climate change effects on federal hydropower (herein referred to as the "9505 assessment").[1] The main purpose of the 9505 assessment is to examine possible future effects of climate change on regional hydrologic variability and hydropower generation. The 9505 assessment uses a framework that coordinates a series of models at different spatial resolutions into a regionally cohesive model that simulates hydrologic conditions and hydropower output that can be compared across various geographic locations. Regional models used in this study evaluate the likelihood of change regarding future water availability, high- and low-runoff events, hydropower generation, and power marketing dynamics within each Power Marketing Administration (PMA) study area. Eighteen study areas across four PMAs are examined within the assessment to discuss the projected impacts of climate change on the federal hydropower fleet.

Since the inception of a power-marketing program, the PMAs have marketed hydropower from federally owned multi-purpose water projects to repay the power purpose's share of the government's investment in these projects. These U.S. federal hydropower plants are owned, operated, and maintained by multiple federal water management agencies, including the U.S. Army Corps of Engineers (USACE), Bureau of Reclamation (Reclamation), and International Boundary and Water Commission (IBWC). The four PMAs covered in this assessment include Bonneville Power Administration (BPA), Western Power Administration (WAPA), Southwestern Power Administration (SWPA), and Southeastern Power Administration (SEPA) (Figure 1). Each of the four PMAs is a distinct, self-contained entity within DOE, similar to a wholly owned subsidiary of a corporation.

Given the concerns surrounding changing water availability projected in future climate periods, historical federal hydropower marketing practices may face distinct challenges in continuing to provide low-cost electricity with the same volume or timing. Depending on the geographic location, changes in precipitation and snowmelt can have effects on federal hydropower generation. Water allocation decisions that adhere to operating limits, such as flood control requirements or minimum flow for ecological purposes, can additionally impact the overall level of generation output, while electricity demand (load) can more subtly affect changes in generation levels, e.g. the volume of water allocated to produce electricity increases (decreases) during a high (low) demand, valuable (less valuable) period. . This assessment discusses how the projected annual and seasonal changes in the physical environment may directly and indirectly affect the PMAs' ability to market electricity. Climate change may alter not only water supply and demand, but also the rates that PMA customers pay for energy and capacity services. Certain PMAs have explored other rate structures and use a wide range of market strategies to balance supply and demand (see Section 2.6 for further discussion on rate setting practices and Section 3.1.3 as an example for how BPA has varied its rate structures from the full 9505 report[1] prepared by ORNL). The PMAs also continue to evolve as more non-dispatchable generation assets (e.g., wind or solar) come online. The role and competiveness of federal hydropower power may change as the generation mix in the United States diversifies.

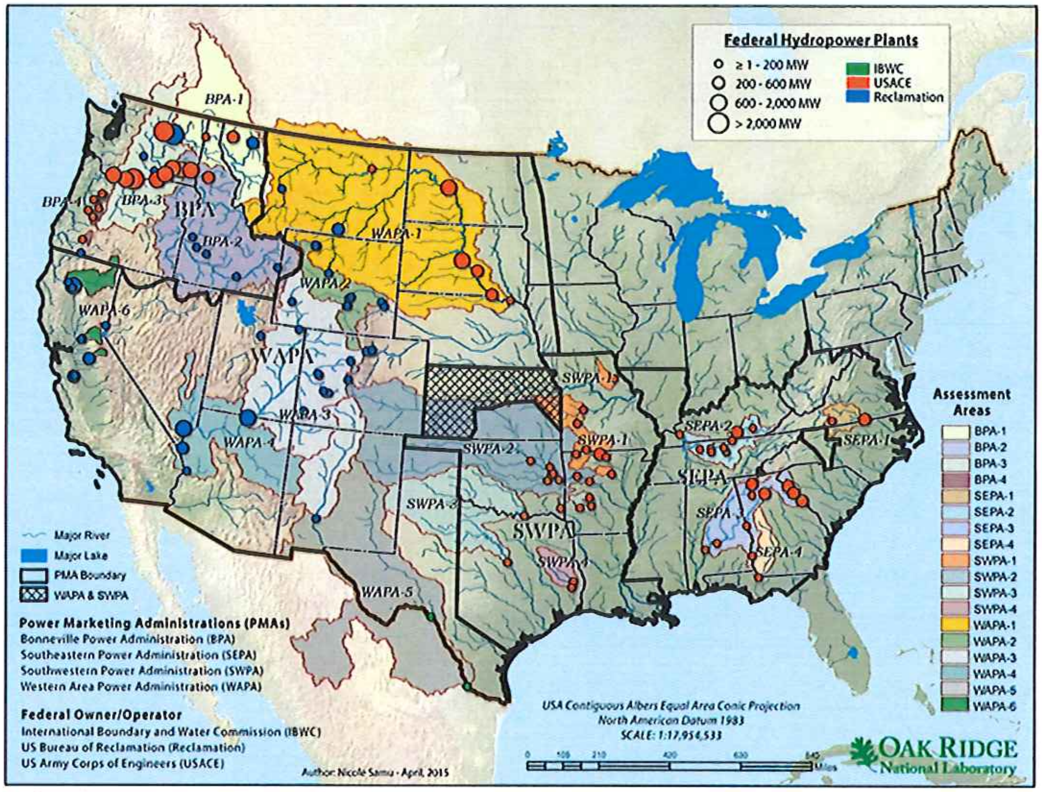

Figure 1. Federal hydropower facilities and power marketing regions in the United States. Note that part of Kansas is supplied by both WAPA and SWPA.

Data

A diverse set of data was used to simulate and project meteorological, hydrologic, hydropower, and power marketing dynamics. The specific data set included hydropower project characteristics, historic hydropower generation, observed hydrology and meteorology, land surface information, and wholesale and locational marginal price data (Table 1). 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. Wholesale electricity price and power purchase data were used to evaluate the relationship between hydropower generation and market dynamics. All data collected for this study were also organized in an integrated, public database for possible use in other future national-scale assessments.[2]

Table 1. Summary of data used in the 9505 assessment

Data type	Data source
Hydropower Project Characteristics	• DOE/ORNL National Hydropower Asset Assessment Project (NHAAP)[2] • USACE National Inventory of Dams (NID) • EIA Form 860 Database[3]
Hydropower Generation	• EIA Form 906, 920, and 923 Database[4] • DOE PMA
Observed Runoff and Streamflow	• USGS National Water Information System (NWIS)[5] • USGS WaterWatch Runoff[6] • Reclamation Hydromet Database[7] • Environment Canada HYDAT Database[8]
Observed Temperature and Precipitation	• Oregon State University PRISM Dataset[9] • ORNL Daymet Dataset[10] • Pacific Northwest Hydroclimate Scenarios Project[11] • Maurer et al. (2002) Gridded Meteorological Data[12]
Observed Wind (re-analysis)	• NCEP North American Regional Reanalysis (NARR)[13]
Watershed Boundary and Hydrography	• USDA/NRCS Watershed Boundary Dataset[14] • EPA/USGS National Hydrography Dataset Plus[15]
Vegetation	• NASA Moderate Resolution Imaging Spectroradiometer (MODIS) Leaf Area Index (LAI)[16]
Soil Parameters	• CONUS-SOIL Dataset[17]
Topography	• USGS National Elevation Dataset (NED)[18]
Observed Snow	• USDA/NRCS SNOTEL and Snow Course Data and Products[19]
Wholesale Electricity Price	• EIA Electricity Wholesale Market Data • Southwestern Power Pool Locational Imbalance Prices • FERC Form 714 (system lambda as a proxy for price)
PMA Wholesale Power Purchases and PMA Total Sales	• EIA Form 861 (Annual Electric Power Industry Report)

Modeling

This assessment is designed to enable an interregional comparison and further the evaluation of large-scale climate change effects on the entire U.S. federal hydropower fleet. A series of models and methods were used to gradually downscale global climate change signals into watershed-scale hydrologic projections to support a hydropower impact assessment (Figure 2). The regional-scale output from this study focused on the federal fleet, but it provides useful information that is relevant to future water resource management for the entire hydropower fleet across the country.

Future climate projections were based on the high-resolution refinement of the global climate models (GCMs) that are the basis of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment (AR5).[20] An ensemble of 10 IPCC AR5 GCMs under the representative concentration pathway (RCP) 8.5 emission scenario were selected, based primarily on the availability of necessary sub-daily atmospheric data for dynamical downscaling. The Abdus Salam International Centre for Theoretical Physics Regional Climate Model version 4 (RegCM4)[21] was used to dynamically downscale the GCM signals from over 150 kilometers (km) to an 18-km grid resolution over the entire conterminous United States (CONUS) for both a 1966–2005 baseline and 2011–2050 future periods. The reasonableness of these downscaled climate projections were further evaluated and validated by historic observation.[1,22] The downscaled daily temperature and precipitation output were then bias-corrected[23] and spatially disaggregated to a 4-km grid resolution for hydrologic simulation.

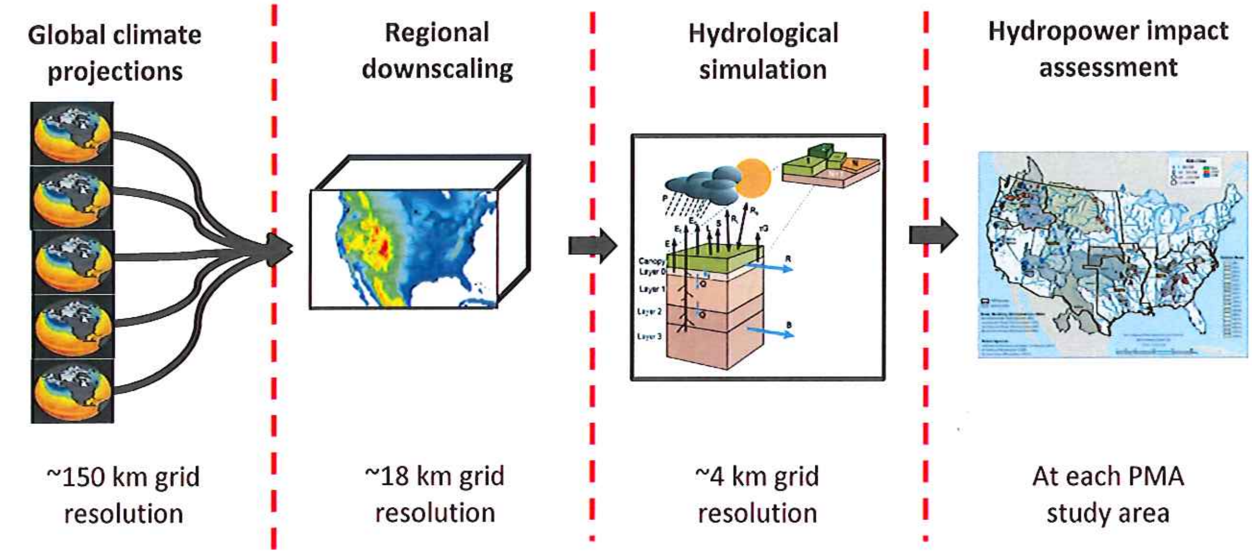

Figure 2. Series of models used for projecting future climate conditions.

Accurately modeling water availability is a principal concern for this assessment, as the timing and volume of water available directly affects hydropower projections. To simulate the watershed response to the projected future meteorological conditions, the widely used Variable Infiltration Capacity (VIC)[24] hydrologic model was used to simulate future water availability for hydropower generation. Substantial efforts were taken to improve the spatial resolution, data quality, and model accuracy of hydrologic simulation through computationally intensive model calibration.[25,26] The hydrologic model outputs were used to simulate future hydropower generation and climate change effects on watersheds upstream of all federal hydropower plants.

Water availability typically dominates water allocation decisions for hydropower production among a suite of other objectives (e.g., flood control, water supply, navigation, environmental protection and recreation). To capture long-term (annual and multi-annual) and sub-annual (daily and seasonal) hydropower generation allocation decisions and how generation would change given future climate conditions, a lumped Watershed Runoff-Energy Storage (WRES) model was developed for this study. For each PMA study area, the WRES model used the monthly precipitation and unregulated runoff as inputs, performed a runoff mass balance calculation for the total monthly runoff storage in all reservoirs and retention facilities in the watershed, and simulated the monthly-regulated runoff release and hydropower generation through the system. These monthly projections provide a unique seasonal and annual perspective for when and to what extent the hydropower fleet may experience challenges in meeting the many, often competing demands.

Interagency consultation and review

The accuracy and applicability of the 9505 assessment benefited greatly from extensive consultation with other federal agencies, as directed by Congress in the SECURE Water Act, and from a thorough technical review that was consistent with Office of Management and Budget policies on information quality. The DOE team conducting the 9505 assessment worked closely with technical staff from the PMAs, Reclamation, and USACE to ensure consistency of methods and data. A review draft of the 9505 assessment was prepared in July 2015 and subjected to a comprehensive peer review. The results of that review are summarized in the full 9505 assessment report[1] prepared by ORNL.

III. Results

Differences from the previous assessment

The previous 9505 assessment[27] was designed to evaluate the potential changes in annual hydropower production for near-term (2010–2024) and midterm (2025–2039) future periods. The ensemble of future climate projection was created by downscaling five realizations from one IPCC Fourth Assessment (AR4)[28] GCM under the A1B emission scenario. The regional climate and hydrologic models were both in their earlier versions and were implemented at a coarser spatial resolution. Given the methodological limitations in the first 9505 assessment, seasonal hydropower generation was not quantitatively studied. This second 9505 assessment built upon the framework established in the previous assessment and improved upon the data collection and modeling of future potential climate change effects on federal hydropower generation by including state-of-the-art scientific information and modeling techniques.

The previous 9505 assessment identified a strong linear relationship between annual regional runoff and historic generation,[29] and this second 9505 assessment also found that the projected seasonal variations in runoff would translate into variations in seasonal hydropower generation. The magnitude of the variation, however, may be nonlinear, depending upon regional storage capabilities. The previous 9505 assessment additionally showed that projected effects of climate change on annual hydropower generation were not significant. Annual hydropower projections in this 9505 assessment show some PMA regions with significant to negligible changes, which can be further explained by watershed storage. Watershed storage may provide a buffer to help absorb part of the runoff variability, resulting in a stable future annual hydropower projection that supports the result in the first study, which used different modeling methods.

U.S. federal hydropower fleet

Hydropower projects operating in the United States today represent 101.2 gigawatts (GW) of capacity, consisting of 79.6 GW of conventional and 21.6 GW of pumped-storage hydropower.[30] The total capacity is divided almost evenly between federal and non-federal projects. Federal hydropower consists of projects owned and/or operated by one of four agencies: USACE, Reclamation, the Tennessee Valley Authority (TVA), and the IBWC. A majority of the non-federal hydropower is regulated by the Federal Energy Regulatory Commission (FERC) and is owned by a variety of entities, such as publicly owned utilities, investor-owned utilities, and state agencies. On average, the capacity of a federal hydropower plant is more than 10 times larger than a non-federal plant.[25] These agencies have influenced the number of facilities established in the U.S. since the early 1900s, each possessing distinct missions shaped by historical policy, geography, and economics.

Most USACE hydropower plants function as multipurpose water projects, providing a suite of services (flood control, navigation, water supply, water quality protection, and ecosystem restoration). USACE owns and operates the most projects, with 75 hydropower plants in 16 states for a total of 21.7 GW. In addition to those federally-owned hydropower plants, there are more than 90 non-federal hydropower plants located at USACE dams with an additional 2.3 GW of capacity regulated by FERC. The oldest USACE hydropower facility is Bonneville Dam, located on the lower Columbia River, which came online in 1938. The most recent USACE project to come online was the R.D. Willis project in Texas in 1989.

Reclamation's primary mission is the delivery of water for irrigation to end users in the western states. Reclamation operates 76 federal hydropower plants for a total of 15.5 GW and operates 53 of these in 11 western states, with 58 hydropower plants marketed through PMAs. There are 60 non-federal hydropower plants on Reclamation dams and canals with a combined capacity of 500 megawatts (MW). Electricity produced at Reclamation facilities is either used internally at projects or sold to external users. The primary use of the power is to deliver water to meet the other authorized purposes of the projects. The oldest Reclamation hydropower plant is the Theodore Roosevelt facility on the Salt River in Arizona, which began operating in 1909. The largest is the Grand Coulee Dam, which has an installed capacity in excess of 6,900 MW, making it among the ten largest hydropower plants in the world.

IBWC owns and operates two small hydropower projects on the Rio Grande River. Their total installed capacity reaches 100 MW. WAPA markets the hydropower from these two plants.

Based on the legislative language, the scope of this report is limited to the 132 federal hydropower plants marketed through the PMAs. Since TVA is not a PMA and the hydropower generated from TVA facilities is not marketed by a PMA, the 30 TVA hydropower plants are not included in this assessment. Similarly, the assessment does not include the USACE Saint Mary's Falls and St. Stephen projects because the electricity generated from these projects is not marketed through the PMAs. Since Reclamation Pilot

Butte was decommissioned in 2009, only 57 Reclamation plants that are currently marketed through PMAs are considered in this assessment.

Table 2. Federal hydropower plants evaluated in this assessment

	Number of power plants	Total capacity (MW)
USACE	73 [a]	21,500
Reclamation	57 [b]	15,100
IBWC	2	100
Total federal [c]	*132*	*36,600*

[a] Does not include USACE Saint Mary's Falls and St Stephen, which are not marketed through PMAs.
[b] Does not include Reclamation Pilot Butte that was decommissioned in 2009.
[c] Does not include 30 TVA hydropower plants because its power is not marketed through PMAs.

Water availability for hydropower

Hydropower generation at federal facilities varies from year to year for a number of reasons, including variations in weather and runoff, changing condition of hydropower equipment, competing water demands from non-power uses, and environmental requirements such as regulations protecting species listed under the Endangered Species Act. Changes in precipitation and runoff more directly impact the expected hydropower production for rainfall-dominated PMAs, such as SEPA and SWPA, which contain run-of-river facilities with relatively smaller storage capabilities that are more directly influenced by water availability in their generation practices.

Changes in runoff for BPA and WAPA are more directly controlled by climate-induced changes in snowmelt; those PMAs, in particular, cover a topographically diverse area and are typically tasked with providing water delivery services before providing generation. Given that many facilities in these PMAs possess larger storage capabilities, runoff projections may not directly translate to generation projections, as they can store and release runoff and continue to provide generation similar to historical levels.

Future climate and effects on generation

Change in federal hydropower production is mainly controlled by precipitation and runoff and indirectly by temperature. This assessment performed an in-depth analysis of the percentage change in the projected multi-model median temperature, precipitation, runoff, and hydropower generation in each PMA study area from the ten downscaled climate models. Overall, air temperature is projected to increase in all PMA areas annually and seasonally for both the near-term (2011–2030) and midterm (2031–2050) future periods. While the increase in temperature may not have a strong influence directly on annual runoff, it will cause earlier snowmelt and a shifted seasonal pattern in runoff. This temperature-triggered, earlier snowmelt effect in the BPA area represents a highly significant finding from the future climate projections. The 9505 assessment report[1] prepared by ORNL at the direction of DOE provides a more detailed discussion. The following discussion focuses on the changes in projected precipitation, runoff and hydropower for each PMA in the near-term (2011–2030) and midterm (2031–2050) future periods.

BPA encompasses a variety of topographical features that are projected to undergo different spatial and temporal precipitation changes. Small but statistically significant increases in annual precipitation are projected for the upper Columbia River, Snake River, and Mid-lower Columbia areas (BPA 1-3). Within the Cascade Mountains (BPA-4), a slight decreasing shift in annual precipitation is projected, but it is not statistically significant. In the near-term future period (2011–2030), the most significant seasonal change is projected during the fall – a small decrease in precipitation. In contrast, the midterm future period (2031–2050) shows a general increase in precipitation during the winter and spring across most of the BPA areas, excluding the summer season in the Cascade Mountains (BPA-4). The projected winter increase in precipitation represents an important climate change signal, and it is more pronounced in the upper Columbia River during all seasons.

Across the whole of WAPA, future annual projections in precipitation do not show clear long-term trends. In the near-term future (2011–2030) period, increasing winter precipitation is projected across all of WAPA except in the lower Rio Grande area (WAPA-5). In the Rio Grande area, precipitation is projected to decrease during wintertime. For the lower Colorado River and Central Valley to the Sierra Nevada Mountains in California, precipitation is projected to decrease in spring and summer. In the other WAPA areas, the change in summer precipitation is small, or there is nearly no change across the many model projections.

A higher increase of precipitation is projected in SWPA by the end of 2050. While increases in precipitation are more pronounced in the spring and summer in all assessment areas, the winter changes show a decreasing trend, especially throughout most of SWPA (SWPA-2, -3, and -4). For the upper White, Osage, and Salt Rivers (SWPA-1), precipitation is projected to increase for most all seasons and future periods. Changes are generally smaller in the fall, with some projections showing both small positive and small negative changes in mean fall precipitation.

The SEPA region does not present a clear and consistent pattern regarding the changes in mean annual precipitation. The strongest indicators of change in precipitation result in drier summers in all areas, but those are balanced by increased precipitation in all other seasons. The summer and winter results possess an especially large spread for the two more southern SEPA areas (SEPA-3 and SEPA-4), indicating high model uncertainty for precipitation in this region.

The most important climate change effects are likely earlier snowmelt as temperatures increase and a change in runoff seasonality among all federal hydropower facilities. Spatial runoff projections vary significantly across the four PMA regions (Figure 3). In terms of annual runoff, statistically significant increases are projected in the Upper Missouri (WAPA-1), Lower Colorado (WAPA-4), Rio Grande (WAPA-6), and all SWPA and SEPA areas. The midterm future period is generally wetter than the near term, but areas such as the lower Colorado River (part of WAPA-4), Wyoming (WAPA-2), and western Texas (part of WAPA-5) are projected to be drier. With the increasing winter/spring runoff and decreasing summer/fall runoff, water resource managers may need to consider water allocations more cautiously. More pronounced changes can be seen in the seasonal patterns discussed below.

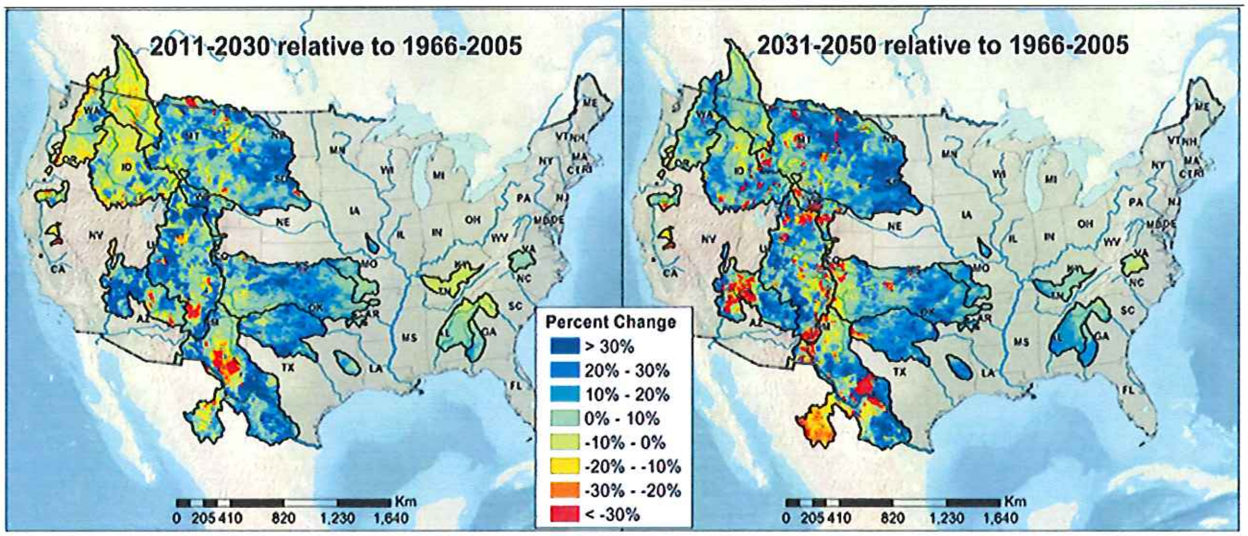

Figure 3. Change in runoff projected for PMA regions over the near-term period (2011–2030, left) and the midterm period (2031–2050, right), based on the median multimodel ensemble quantiles.

In the snowmelt-dominated regions (BPA and WAPA's regions), this predicted shift in runoff seasonality is likely caused by the increasing air temperature and earlier snowmelt. The strongest change projected in total runoff within BPA for both future periods is an increase in winter and a decrease in summer for the entire area. The most prominent change projected in total runoff within WAPA for both future periods is an increase in spring and decrease in summertime runoff, particularly in the central portion of WAPA (WAPA-1 through WAPA-4). The California area (WAPA-6) shows decreasing runoff in all seasons for both future periods, except in the winter, when a modest increase is projected during the midterm future period.

In the rainfall-dominated regions (SWPA, SEPA, and certain areas of BPA and WAPA), the change in precipitation mainly controls the variability in runoff. The Cascade Mountains area (BPA-4) stands out with the largest projected decreases in summertime runoff. In Rio Grande (WAPA-5), an increase in total runoff is projected in all seasons, with a greater increase in summer. Winter runoff does not show consistent increasing or decreasing trends across the SWPA areas, though runoff in the lower half of southeastern Texas is projected to increase in the midterm future period. All SWPA assessment areas for both future time periods are projected to have consistently higher runoff in the spring and summer seasons, as well as annually. Runoff changes for the southern areas of SEPA show a slight increase annually and seasonally in the midterm time period. The northern area of SEPA (SEPA-1) shows a slight decreasing trend in the spring and summer runoff by 2050, with an increase in runoff projected by the end of the mid-century in winter and spring in Cumberland River basin (SEPA-2).

The annual hydropower generation from each PMA and PMA total is summarized in Figure 4. To show the multimodel variability, each bar consists of ten smaller bars for each downscaled climate model, sorted from top to bottom. The multimodel baseline (1966–2005) average is marked with a bold vertical line. In terms of the annual generation from the PMA total (i.e., 132 federal hydropower plants that are marketed through the four PMAs), the projected hydropower generation in the near-term future period is varied. Half of the models suggest increasing generation, and the other half suggest decreasing generation. More hydropower generation is projected in the midterm future period, with eight out of ten models showing an increasing hydropower trend. Among all PMAs, the near-term BPA hydropower generation is projected to decrease. The change in the near-term WAPA and SEPA regions is also varied, with the multimodel median close to the baseline reference. In other regions and time periods, the annual hydropower generation is generally projected to increase. Such results are consistent with the projected change of total annual runoff in each PMA study area.

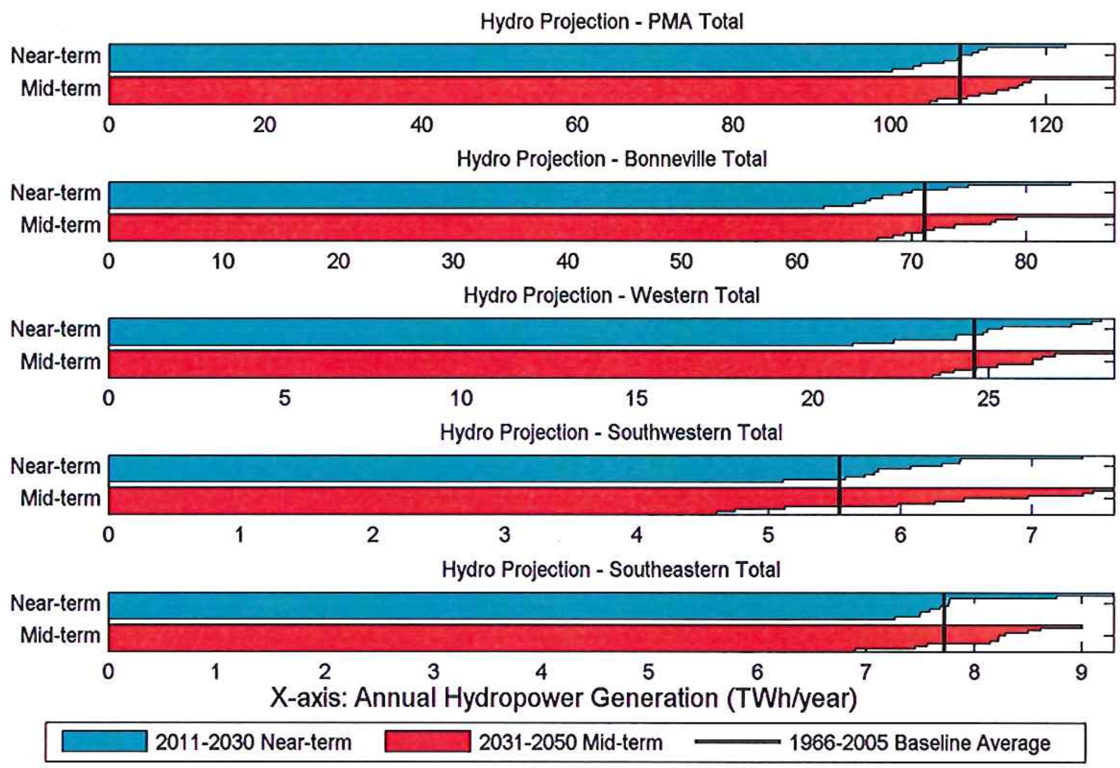

Figure 4. Summary of annual hydropower projection in the near-term (2011–2030) and midterm (2031–2050) future periods for each PMA. Each bar consists of ten smaller bars for each downscaled climate model (sorted descending from top to bottom). The multimodel baseline (1966–2005) average is marked in a bold black vertical line for comparison.

This second 9505 assessment includes seasonal projections not calculated in the previous 9505 assessment that illustrate increases and decreases in projected hydropower generation (Figure 5); these vary depending upon the local topography, main water availability source (i.e., snowpack versus precipitation), runoff levels, and storage capabilities. The total seasonal generation from all PMAs displays increasing generation in winter and spring and decreasing generation in summer and fall. Earlier snowmelt and changing runoff seasonality in the BPA region mainly contribute to this seasonal change in projected generation for PMA total.

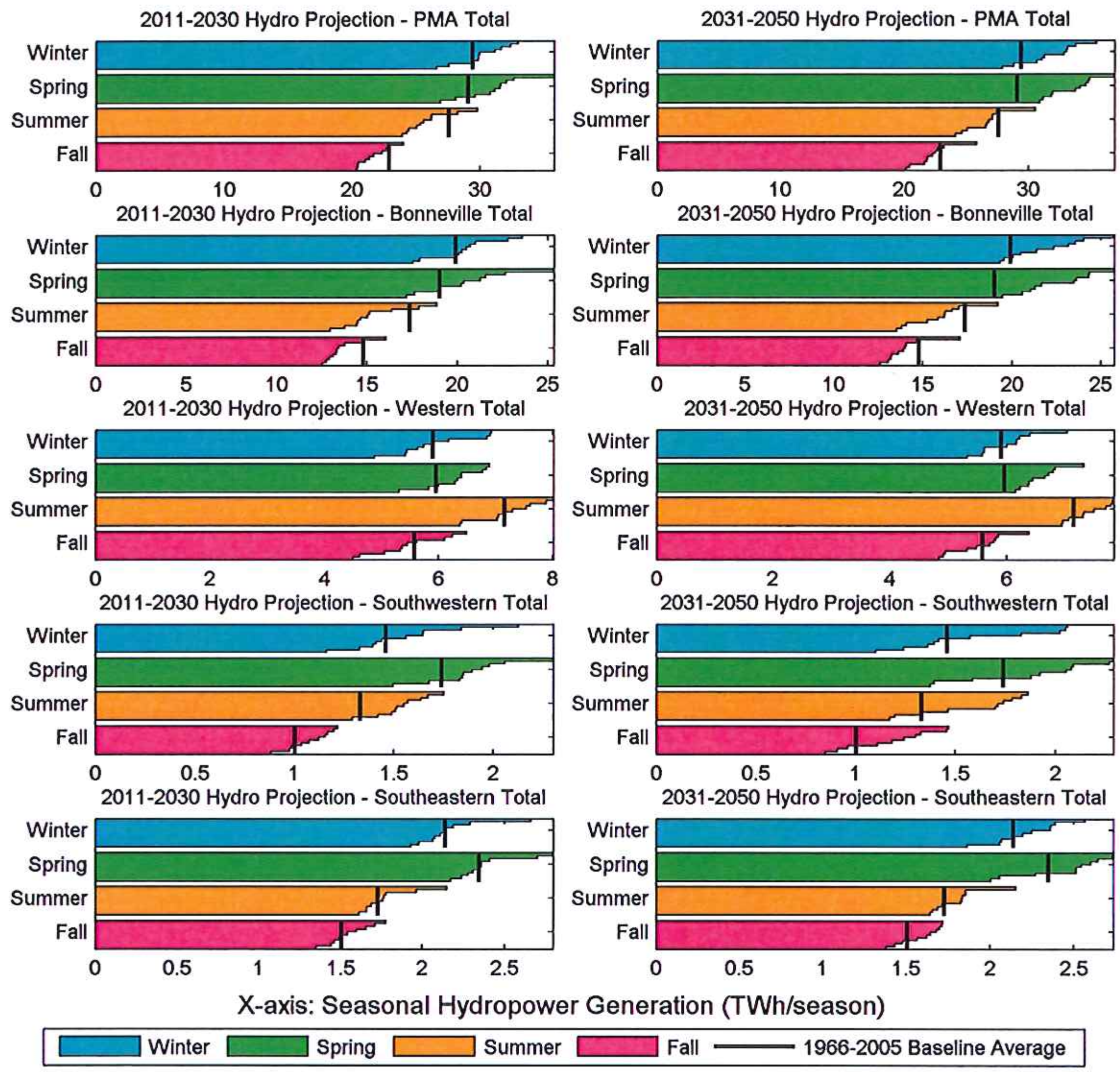

Figure 5. Summary of the seasonal hydropower projection in the near-term (2011–2030) and midterm (2031–2050) future periods for each PMA. Each bar consists of 10 smaller bars for each downscaled climate model (sorted descending from top to bottom). The multimodel baseline (1966–2005) average is marked in the bold line for comparison.

Seasonal changes within the BPA region, in contrast to the annual projections, are more pronounced. Apart from the Cascade mountain region in southwestern BPA, increased generation persists in the spring for the Columbia River facilities. A reduction in hydropower generation is projected in the summer and fall across all BPA study areas. The shift in seasonal generation patterns (i.e., higher generation in winter and spring) is likely caused by earlier snowmelt triggered by increasing air temperature.

The central areas of WAPA (WAPA-2 and -3) are in the snowmelt-dominated region, similarly showing a relatively small change in annual generation and fairly prominent changes seasonally. The lower Colorado River region shows increasing projected annual generation, although this study finds a range in projected seasonal generation partially caused by diverse projections from the ten selected climate models. Rio Grande (WAPA-5) reveals no noticeable trend in annual projected generation, and the seasonal projections are subject to a good deal of uncertainty as a result of low modeling performance. Annual projected generation for the California portion of WAPA (WAPA -6) decreases in the near-term but shows little projected change in the midterm future period. Winter season generation projections range in direction and magnitude in the near-term and midterm future periods.

Increasing seasonal generation is projected for both SWPA and SEPA, which is heavily controlled by the seasonal variability of precipitation and runoff. Compared with BPA and WAPA, the hydropower reservoirs in the SWPA and the SEPA areas have less storage capacity, so the projected change in seasonal hydropower generation will follow the projected change of seasonal runoff more closely. The variability in future precipitation remains the most crucial climate change factor in modeling potential hydropower decisions for SWPA and SEPA

Climate change impacts on federal power marketing

This assessment extensively analyzes the potential climate change impacts on federal power marketing. It discusses how climate change will impact hydropower generation, the electricity demand profile, customer rates, and how the PMAs might respond to the costs incurred from system variability. The PMAs market hydropower generation from federal multipurpose water resource projects. A PMA's power marketing function involves managing power allocation decisions and setting the rates at which the federal hydropower is sold. By law, PMAs sell electricity at the lowest rate possible to cooperatives and public bodies, such as municipalities and irrigation districts that this assessment collectively defines as preference customers.[31] Most of the contracts between PMAs and preference customers have a long-term duration. The attributes of the capacity or energy sold (e.g., firm power, non-firm power, or peaking power) vary across PMAs and projects. Climate change will most likely directly affect PMAs by altering the volume and timing of available runoff, which is further complicated by the other multiple reservoir services (e.g. recreation, navigation, flood control, and irrigation). PMAs also have a vested interest in understanding and potentially planning for climate-related seasonal/diurnal shifts in their customer demand profiles in order to shape, to the extent possible, the generation schedule to sell electricity during the most valuable periods for the customer, while adhering to operational conditions. The full assessment report[1] prepared by ORNL at the direction of the DOE provides further discussion regarding the impact of projected regional climate variables, namely increases (flooding) and decreases (drought) in water availability (runoff and precipitation), at various timescales on hydropower production in each PMA.

BPA uses various types of contracts for providing long-term hydropower delivery to meet customer demands, along with selling excess generation to the wholesale market. It is the only PMA responsible for serving the load growth of those preference customers that request it.[32] With its tiered rate system, BPA clearly distinguishes the cost of federal hydropower (Tier 1 rate) from that of replacement power purchases used as a complement to serve customer loads (Tier 2 rate).[33] BPA will have to manage climate-related seasonal deviations from the historical Federal Columbia River Power System (FCRPS) generation patterns. Projected increases in generation in the late winter and spring (early snowmelt) and projected decreases in the summer present a challenge for BPA because temperature-sensitive demand is expected to decrease in winter and increase in summer. In response to these mismatched changes, surplus power sales to the wholesale market would increase during high-flow periods, whereas more replacement power would be purchased during low-flow summer months. Higher replacement power purchase expenditures during low-flow periods would need to be offset by larger surplus power sales revenue in the rest of the year to avoid altering customer rates.

The variety of hydroclimatic zones across WAPA's footprint translates into a strong regional component in WAPA's marketing activities and non-uniform climate change effects on generation. WAPA offers different types of contracts corresponding to various time lengths and product services (i.e., energy versus capacity) at rates that also vary among the hydropower projects. Summer peak demand in most of the region where WAPA operates has historically exceeded winter peak demand. Since regional temperatures are expected to increase, the differences between summer and winter peak demands by WAPA customers may be exacerbated in the future. WAPA is tasked only with marketing available generation and not with serving a specific percentage of customer demand. The ability to shape available generation to the customer's demand profile varies across WAPA's marketing regions depending on reservoir sizes and constraints placed by other reservoir purposes. In some of WAPA's marketing regions, customers have the choice of handling their own replacement power purchases. Larger customers that own generation assets and participate more actively in the wholesale markets are more likely to prefer to arrange their own wholesale purchases and rely less on the PMA.

SWPA markets its hydropower assets for peaking power allocations, as SWPA has limited storage capacity and relies upon rainfall for the water supply for hydropower generation. In SWPA's region, peak demand typically occurs during the summer, and projections show an increase in summer peak demand and a decrease in winter peak demand. Future annual generation is projected to increase along with seasonal precipitation changes (large increase in summer and a smaller increase during the winter) that coincide with the peak season. The combination of projected increases in SWPA's supply and changes in customer demands signify favorable conditions for both the PMA and its customers. The projected average future year would entail a lower reliance on replacement power purchases caused by drought and more supplemental power available. However, there may be an increasing reliance on replacement power purchases during significant flood events when hydropower operations become constrained as a result of release restrictions for reducing downstream flooding, and loss of unit capability from either too great or too low hydropower head conditions. The revenue from additional supplemental sales would help keep peaking power rates stable while collecting enough revenue to repay the U.S. Treasury.

SEPA similarly manages smaller-capacity facilities whose hydropower supply comes mainly from rainfall. The annual change in generation is projected to be positive but small, which seasonally breaks down into projected drier summers and wetter months for the remainder of the year. Because of rising temperatures, preference customers' summer peak demand is projected to increase. On the other hand, the median generation projected for summer months does not display sizable increases. Operational changes that would shift generation from winter to summer would be valuable for SEPA's customers. However, the ability of these USACE facilities to shift generation across seasons to accommodate this preference is severely limited. Increased replacement power purchases may be needed in the summer, along with a larger volume of surplus power sales in the winter months to balance out the mismatch in available seasonal generation and demand.

The flexibility that currently exists in PMA marketing practices will likely continue to allow the PMAs to fulfill their missions in the face of climate variability and the trends projected for the coming decades. Nonetheless, climate-driven changes in total annual generation, seasonality of generation, and frequency of extreme events (floods and droughts) might impact water availability and marketing generation from existing federal hydropower facilities. Consistent and available generation from non-dispatchable generation assets (wind and solar) may also add constraints on hydropower scheduling that may or may not correlate well with PMA customers' preferences. The three PMAs that also operate load balancing authority areas (BPA, WAPA, and SWPA) are developing strategies for minimizing the cost of integrating variable renewables and co-evolving their hydropower assets with the other renewable resources. Maintaining current levels of federal hydropower could require flexibility in the operational rules and constraints set by the USACE or Reclamation as climate-induced changes in the environment persist.

Assessment limitations

This study used a regional assessment framework to evaluate the potential large-scale climate change effects on all federal hydropower plants within 18 PMA study areas at annual and seasonal timescales. A series of models and methods were used to gradually downscale the IPCC AR5 GCM outputs into watershed-scale hydrologic and hydropower projections for near-term (2011–2030) and midterm (2031–2050) future periods. The framework is generally consistent with other concurrent hydroclimate studies, with variations on the choice of emission scenario, GCMs, downscaling approach, and hydrologic and hydropower models. A variety of historic meteorological and hydrologic observations, hydropower facility characteristics, and geospatial datasets were collected to support model development, calibration, and verification. This generalized approach allows for spatial consistency throughout all study areas, enabling policymakers to evaluate potential climate change impacts across the entire federal hydropower fleet; and it may provide a first-order assessment to identify areas with the higher risks. The 9505 assessment results therefore fulfill the Congressional direction.

However, to achieve a comprehensive evaluation of possible climate change effects across a large number of hydropower plants along distinct river systems, this study focused on regional assessment at each PMA study area rather than at individual reservoirs or power plants. Regionally lumped models or generalized indices were used to evaluate the likelihood of change in future water availability, high- and low-runoff events, hydropower generation, environmental flow constraints, and power marketing dynamics within each PMA study area. The site-specific features, such as reservoir operation rules, water withdrawal/return, competing water and energy demand, and environmental minimum flow requirements, were not explicitly modeled at each power plant. The assessment also did not attempt to project climate change effects on hydropower beyond 2050 because there are many other non-climate issues that will interact with potential climate effects and that are dependent on policy decisions of several types.

The findings of this study suggest that the relatively large storage capacity of many of the U.S. federal hydropower reservoirs will likely allow the fleet to absorb part of the increasing runoff variability and thus continue to provide stable, annual hydropower generation in the projected near-term and midterm future periods. However, such findings are based on the assumption that there is no significant change in the future installed capacity and operation. The overlapping complexity of physical and policy-related constraints, such as issues of aging infrastructure that may result in decreases in performance,[34] competing water uses, and environmental requirements, may reduce the fleet's ability to mitigate climate-induced variability in runoff and may increase the complexity of future hydropower operations. Moving forward, resource managers may consider conducting more in-depth, site-specific studies to explore how operational changes or infrastructure investments may help reduce the impacts of increasing future climate variability. The proposed assessment method in this study does not replace the existing site-specific models and tools now used by water and energy resource managers. Future assessment needs are discussed in further detail in the full technical assessment report.

VI. Recommendations from Administrators

Bonneville Power Administration (BPA)

This second 9505 assessment builds upon BPA's growing understanding of the potential impacts of climate change on the hydropower system in the Northwest and generally complements BPA's own research in this area. Existing research continues to indicate that climate change will likely lead to warmer temperatures, declining snowpack, increased winter streamflows, earlier winter-spring runoff, and reduced summer streamflow in BPA's region.

The primary risks to BPA operations and contract practices identified in the second 9505 assessment are the following:

- Changes in seasonal generation: increased winter and spring generation and decreased summer and fall generation. However, little to no change in annual generation is predicted.
- Expectations that energy demand and use will increase in the summer as a result of higher air temperature. Coupled with the predicted decreased summer hydropower generation, this risk may be magnified.
- Potential higher replacement power purchase costs due to the changes in timing and availability of FCRPS generation, which may lead to eventual increases in rates for customers.

BPA's own studies suggest similar risks. In 2010, operating through the River Management Joint Operating Committee (RMJOC), BPA, Reclamation, and USACE, along with other regional parties, completed the first of its long-term planning studies of climate change impacts on the Northwest. This study emphasized flood control and hydropower generation impacts affecting the FCRPS.

A second similar study is currently under way using the latest GCMs from AR5. This new study, which will be complete in 2017, will not only use these newer climate models, but also give BPA and its regional partners a better understanding of the uncertainties involving both climate change and the techniques used in hydroclimate modeling. Data from these studies will be integrated into BPA's planning efforts later this decade.

BPA does not recommend any immediate changes to its operation or contracting practices in response to potential climate change effects. For hydropower operations, the temperature, snowpack, and streamflow variability predicted through the 2040s by both the second 9505 assessment and the RMJOC-I study is still within the variability seen in the 80-year historical water-year record. The predicted weather events over this time frame will still be manageable under BPA's current power operations and planning, as well as USACE's current flood control operations.

However, BPA takes this risk seriously. As a result of these studies and emerging climate change science, BPA has intensified its monitoring and planning efforts as described below. If future research solidifies these trends and shows results outside the historical record, operations may be reexamined to determine appropriate responses.

BPA's current long-term power sales contracts with its customers extend through 2028. These contracts are take-or-pay contracts for prescribed amounts of power and anticipate potential changes to the amount and timing of power from the FCRPS. Changes in the output capability of the FCRPS — due to climate change, fish and wildlife measures, or any other reason — may affect the rates customers pay for power and BPA's competitiveness in the future. BPA is currently engaging in dialogue with its stakeholders regarding its long-term costs. The interplay between BPA's costs, revenues, and streamflow changes as a result of climate change over time deserves some attention in this dialogue.

Since the first 9505 assessment, BPA has intensified its monitoring of climate change in the Northwest and climate change research efforts. For example, BPA has provided matching funds through its Technology and Innovation Program to the University of Washington and Oregon State University to update the regional climate change streamflow datasets using the latest GCMs and state-of-the-art-science. It is also closely monitoring runoff timing throughout the Columbia Basin for long-term trends that could suggest climate change is beginning to impact the region's hydroclimate system. It is also documenting and investigating impacts to system operations during 2015, when persistently warm regional temperatures resembled several climate change projections in the RMJOC-I study.

BPA has also integrated data from the RMJOC-I climate change study into its decision-making and long-term planning processes. BPA's internal Climate Change Risk Management Team, which was created to improve BPA's ability to understand and adapt to climate change impacts, developed a Climate Change Adaptation Plan. The Adaptation Plan serves as a guide to enable BPA to adequately plan and prepare for the physical impacts of climate change by identifying and prioritizing the timing of climate analysis in decision-making processes, such as project reviews under the National Environmental Policy Act in the areas of power, transmission, and fish and wildlife. The inclusion of climate change data and impacts into BPA's planning and decision-making thus far has resulted in:

- Consideration of climate change in the U.S. Entity's final regional recommendation concerning the future of the Columbia River Treaty to the U.S. Department of State, including the recommendation for a strategy for adapting the Treaty to future changes in climate that are resilient, adaptable, flexible, and timely;

- Incorporation of climate change data to inform and prioritize habitat restoration decisions and identify actions that have the most potential to ameliorate climate change effects and contribute to habitat and life history diversity and overall resilience of salmonid populations;

- Development of alternative load scenarios for the near-term future based on RMJOC-I temperature data;

- Inclusion of a climate change scenario from RMJOC-I data into BPA's long-term power planning needs assessment; and

- Continued collaboration and sharing of information with other Federal agencies on the results of climate change studies and adaptation practices

These and other activities to monitor climate change and apply the best available information to BPA's operation and contracting practices should put BPA in a good position to respond effectively and in a timely manner to the physical impacts of climate change as they emerge.

Western Area Power Administration (WAPA)

WAPA currently has substantial capabilities for dealing with climate uncertainty and variability including the following:

- Large capacity for water storage in both reservoirs and natural ice/snow fields;
- Reliable short-term models for forecasting hydrologic and operational conditions;
- Flexible contract terms allowing for adjustments in commitments of energy delivery; and
- Power purchase ability during drought periods and hydroelectric generation sales during periods of surplus.

WAPA recommends that it continue to collaborate with its customers and Reclamation in managing the operation of hydroelectric dams and the transmission system in the Colorado River Basin. Infrastructure upgrades to hydroelectric dams could offset or mitigate the impacts of hydrologic variability by taking advantage of emerging technologies to enhance production efficiency in reduced streamflow conditions. Environmental actions, as they apply to dam operations, must be prudently evaluated to minimize impacts to power generation while protecting the environment.

A power marketing recommendation is the continued ability for WAPA to manage energy and capacity allocations within current and future contractual arrangements. Maintaining this type of flexibility allows WAPA to adjust contractual commitments based on observed changes to generation over time, giving WAPA the most flexibility to meet the needs of the power customer.

WAPA will continue to honor existing contractual obligations by using administrative discretionary authorities to appropriately respond to changing hydroelectric generation resulting from climate change. Marketing and delivering cost-based hydroelectric power to more than 700 customers through 17,000 miles of transmission lines remains our primary focus.

Southwestern Power Administration (SWPA)

Unlike river systems in other regions that contain large surface water reservoirs that can store water over multiple years, SWPA's river systems do not have large water storage capacity. The SWPA region also lacks mountains with ice and snowpack that provide natural water storage; SWPA's projects therefore must rely directly on rainfall for hydropower generation. The 9505 assessment demonstrates that SWPA's region already encounters significant variability in annual runoff and that although the near-term period impact from climate change falls largely within that experienced range, the midterm period shows a potential for a significant increase in the upper range for runoff. Differing from the first 9505 assessment, which pointed to a potential increased frequency of drought conditions, this second 9505 assessment reveals strong indicators for increased runoff, particularly in the spring and summer seasons, although the occasional severe drought is still expected.

All of the SWPA region hydropower projects are multi-purpose projects, and the various competing uses affect the operation and available storage of each project, including flood control, water supply, navigation, fish and wildlife, both in-lake and downstream recreation, and tourism. SWPA actively participates in numerous water resource committees and work groups; participates in, reviews, and comments on studies; and continuously communicates with USACE and stakeholders concerning the balance of power and non-power uses and the availability of water at each project and for the region as a whole. SWPA is 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 for federal hydropower that already contains 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 ensuring 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. Current funding mechanisms for the purchase of replacement power include the use of power receipts authority, alternative financing arrangements with customers, and a Continuing Fund (for emergency power expenses in periods of below-average hydropower generation). SWPA is seeking new authority for a special Treasury account (Purchased Power Drought Fund) that would provide access to precollected customer funds obtained through a component in SWPA's power rate for replacement power purchase needs during times of drought. It would allow 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 so that it becomes imminently unlikely that SWPA can meet contractual power obligations because of a severe water shortage, the Uncontrollable Forces provision can be used.

Even though the 9505 assessment indicates a reduction in the probability of dry years (drought) and potential for significant increase in runoff (flood events), purchases remain necessary to meet contractual obligations through times of drought. Additionally, similar flexibility is needed during significant flood events when hydropower operations become constrained as a result of release restrictions for reducing downstream flooding and loss of unit capability from either too great or too low hydropower head conditions.

SWPA will continue to review and monitor the concerns that were identified in the 9505 assessment and incorporate those, along with the various other concerns that impact SWPA's hydropower production capability.

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 9505 assessment did not exceed the variances already incorporated into SEPA's marketing strategy. SEPA participates in hydrologic studies, modeling groups, and other stakeholder activities concerning the operation of the Federal projects. The USACE and SEPA routinely communicate and adjust project operations to optimize water use and power production.

All of 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.

Purchased power and pumped power 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 shortfalls in generation. SEPA can then make a preemptive decision to purchase replacement power and conserve project storage for times when replacement power would be more expensive or seasonal operations would restrict the delivery of replacement power.

SEPA uses customer funding agreements, when possible, to provide for replacement and refurbishment of failed or damaged generating equipment. Customer funding expedites the rehabilitation of generating equipment, which increases power production, enhances equipment reliability, and maximizes the availability of renewable generation resources. SEPA believes these processes have been implemented to respond to the expected climate changes presented in this report. SEPA will continue to monitor the issues set forth in this study, and will seek to participate in any process that is beneficial to hydropower and aids SEPA's ability to meet contractual obligations. It is therefore recommended that SEPA continue its current strategy of operational reviews and rate studies, which are viable responses to the expected climate changes presented in this report.

V. Conclusion

The second 9505 assessment addresses how climate change may affect future U.S. federal hydropower generation, using enhanced modeling methods at finer timescales to further inform policymakers. A spatially consistent assessment approach was designed to evaluate hydropower generation from 132 federal hydropower plants that are marketed by 4 PMAs. A variety of historical meteorological and hydrologic observations, hydropower facility characteristics, and geospatial datasets were collected to support the model development, calibration, and verification. The results present a discussion of the potential regional effects and risks of climate change with regard to this hydropower fleet at the annual and seasonal level in the near-term (2011–2030) and midterm (2031–2050) future periods.

Management of the U.S. hydropower fleet in the face of uncertain and changing climate conditions will benefit from long-term projections, showing a range of extreme events at the sub-regional level that carefully consider local hydrological conditions and power marketing practices. The most important climate change effects on hydropower generation are likely to be early snowmelt and change of runoff seasonality. Since future hydropower generation will be largely controlled by changes in runoff and precipitation conditions, reservoir storage provides a vital buffer to help absorb runoff variability. For regions with smaller storage capacity, the change in future hydropower generation will more closely follow the projected change in runoff. With the relatively large storage capacity at many U.S. federal hydropower reservoirs, the fleet is likely to be able to absorb part of the runoff variability and hence may continue to provide stable annual hydropower generation in the projected near-term and midterm future periods. However, such findings are based on the assumption that there will be no significant change in the future installed capacity and operation. Growing competition for water uses, and environmental services that are likely to be under greater future stresses due to climate change may reduce the U.S. hydropower fleet's ability to mitigate runoff variability and increase the difficulty of future operations. Resource managers (1) should consider the risk of changing runoff conditions during water resource planning and (2) may consider conducting more in-depth, site-specific studies that explore how adjusting current operating rules may help reduce the impact of climate variability in the future.

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[29] Kao, S.-C., M.J. Sale, M. Ashfaq, R. Uría Martínez, D. Kaiser, Y. Wei, and N.S. Diffenbaugh (2015), Projecting changes in annual hydropower generation using regional runoff data: an assessment of the United States federal hydropower plants, *Energy, 80*, 239–250, doi:10.1016/j.energy.2014.11.066

[30] Uría Martínez, R., P.W. O'Connor, and M.M. Johnson (2015), *2014 Hydropower Market Report*, DOE/EE-1195, U.S. Department of Energy Wind and Water Power Technologies Office, Washington, D.C.

[31] GAO (Government Accountability Office) (2000), *Power Marketing Administrations: Their Ratesetting Practices Compared with Those of Nonfederal Utilities*, Report to the Chairman, Subcommittee on Water and Power, Committee on Resources, House of Representatives. GAO/AIMD-00-114, March.

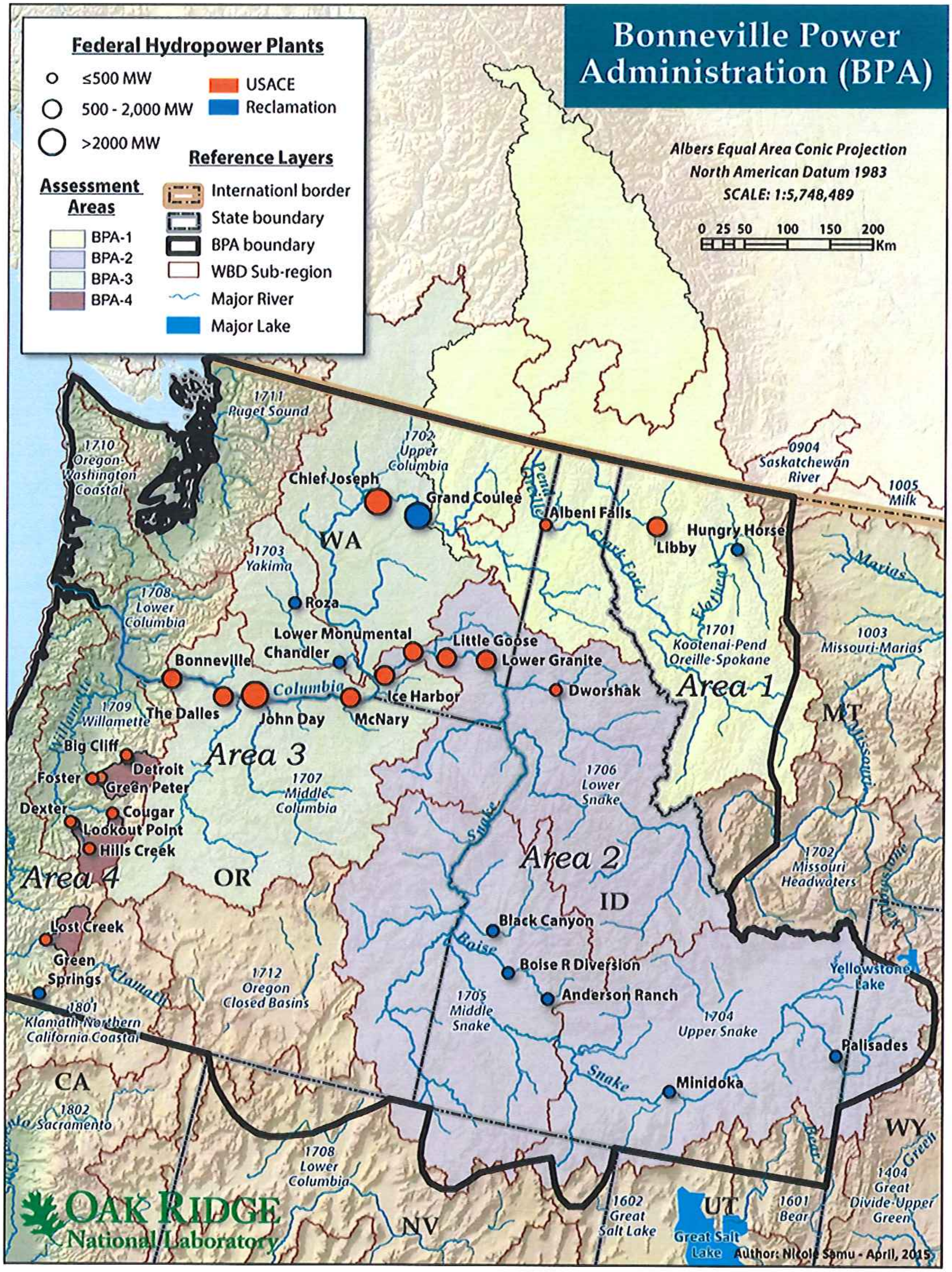
[32] In 1980, the Pacific Northwest Electric Power Planning and Conservation Act (Northwest Power Act) required BPA to provide its customers enough megawatt-hours to cover their growing electricity demand rather than just providing the available capacity and energy from the FCRPS projects.

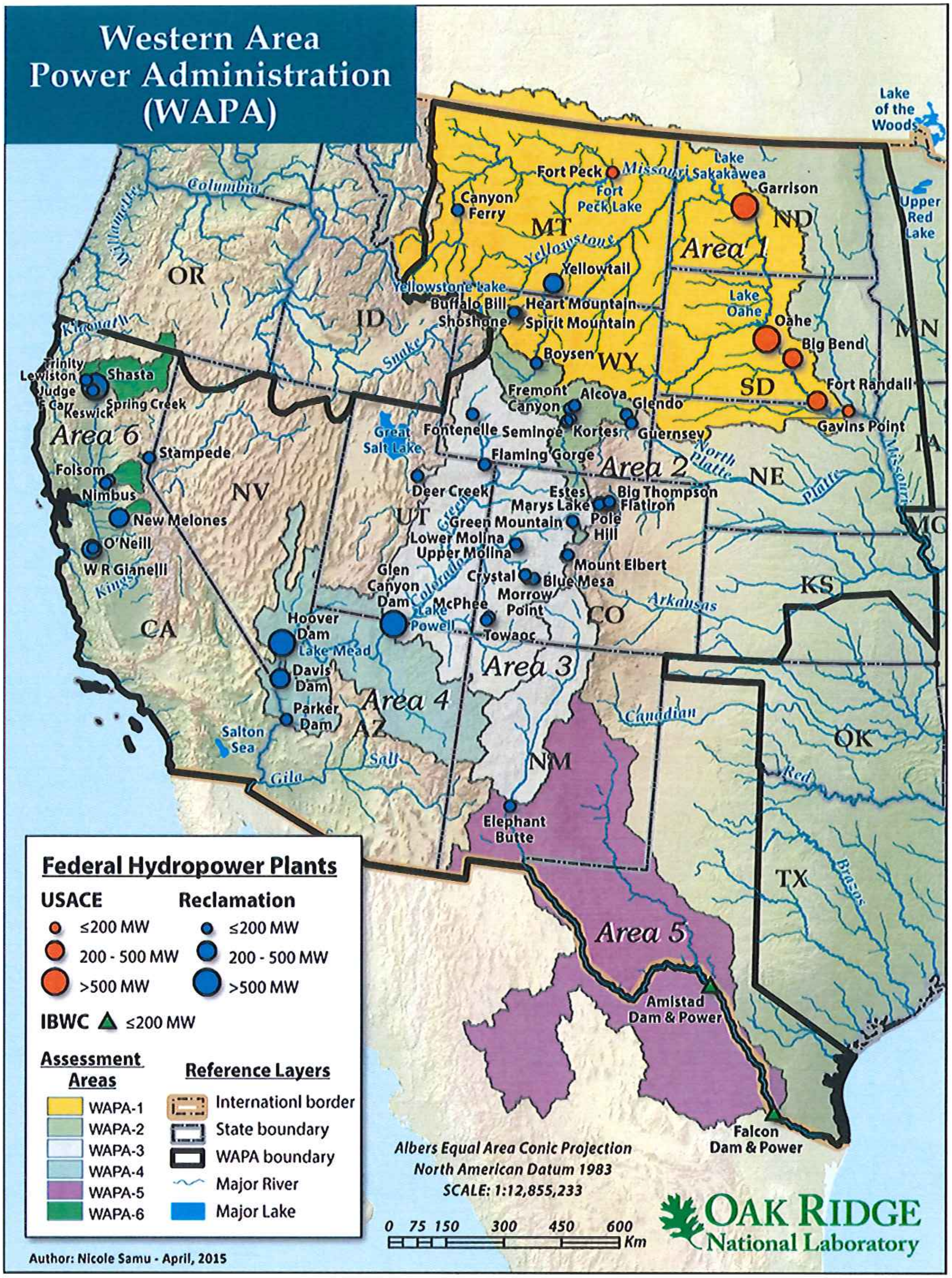
[33] BPA (Bonneville Power Administration) (2007), Bonneville Power Administration Long-Term Regional Dialogue Final Policy, available at http://www.bpa.gov/power/PL/RegionalDialogue/07-19-07_RD_Policy.pdf, accessed on May 2015.

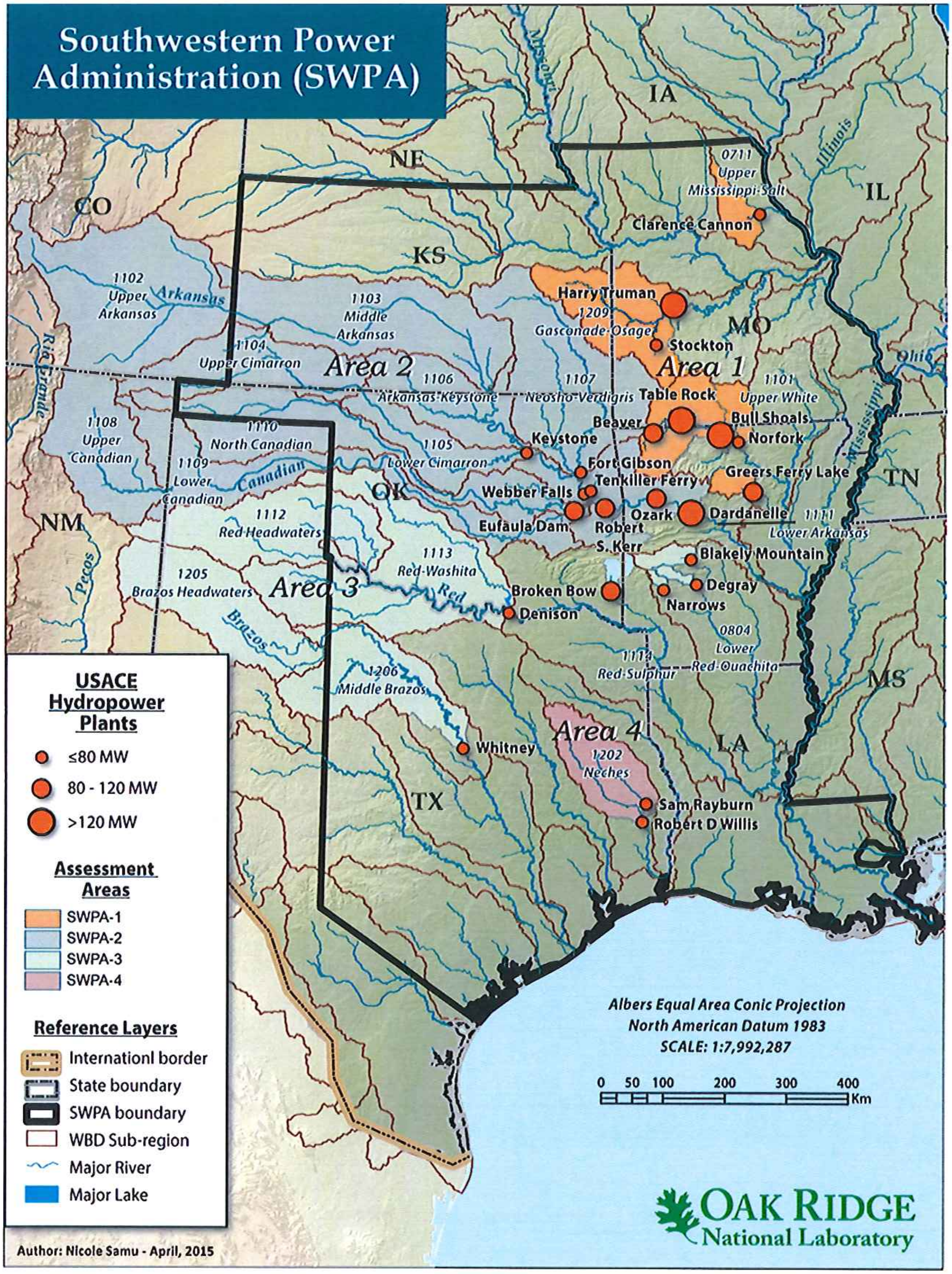
[34] Sale, M.J. (2011), *Outlook for the U.S. Army Corps of Engineers Hydropower Program*, U.S. Army Corps of Engineers, Institute for Water Resources, 2011-WRO-P-02, Washington, DC, p.1.

Appendix. Regions and Assessment Areas

Assessment areas	*Rivers and federal dams*	*Federal power systems*
	BPA region	
BPA-1	The Upper Columbia River upstream and including Grand Coulee Dam	Federal Columbia River Power System
BPA-2	The Snake River upstream of its confluence with the Columbia River	Federal Columbia River Power System
BPA-3	The lower and mid-Columbia River, from Bonneville Dam upstream to the tailwater of Grand Coulee	Federal Columbia River Power System
BPA-4	The Cascade Mountain projects in southeastern Oregon	Federal Columbia River Power System
	WAPA region	
WAPA-1	The upper Missouri River and tributaries upstream of the USACE Gavins Point project	Pick-Sloan Missouri River Basin Program
WAPA-2	Smaller watersheds in the upper parts of the North Platte, South Platte, Bighorn, upper Arkansas, and upper Colorado Rivers	Loveland Area Projects
WAPA-3	The upper Colorado and upper Rio Grande river basins	Salt Lake City Area Integrated Projects and Provo River Project
WAPA-4	The lower Colorado River Basin, including Reclamation's Hoover, Davis, and Parker dams	Boulder Canyon, Central Arizona and Parker-Davis Projects
WAPA-5	The lower Rio Grande River, including two small projects operated by the International Boundary and Water Commission	Falcon-Amistad Project
WAPA-6	The Central Valley of California (Trinity, Sacramento, American, Stanislaus, and San Joaquin river systems) and Truckee and lower Carson River systems	Central Valley and Washoe Projects
	SWPA region	
SWPA-1	Ozark Plateau rivers in Missouri and northern Arkansas (Osage, upper White, and Salt River Basins)	Financially Integrated Projects in the Interconnected System
SWPA-2	The Arkansas River Basin in Oklahoma and Arkansas, plus the Broken Bow project in the Red River Basin, included for interconnected system reasons	Financially Integrated Projects in the Interconnected System
SWPA-3	The Red and Brazos River Basins in Oklahoma and Texas, plus parts of the Ouachita River Basin in Arkansas and Oklahoma	Financially Integrated Projects
SWPA-4	The Neches River Basin in southeastern Texas	Isolated Projects
	SEPA region	
SEPA-1	The Roanoke River Basin in Virginia and North Carolina	Kerr-Philpott System
SEPA-2	The Cumberland River Basin in Kentucky and Tennessee	Cumberland System
SEPA-3	The combination of the Savannah, upper Apalachicola, and Alabama River Basins in South Carolina, Georgia, and Alabama	Georgia-Alabama-South Carolina System
SEPA-4	The lower Apalachicola and Flint River Basins in Georgia and Florida	Jim Woodruff System


Bonneville Power Administration (BPA)
Federal Hydropower Plants
≤500 MW
500 - 2,000 MW
>2000 MW
USACE
Reclamation
Reference Layers
Assessment Areas
BPA-1
BPA-2
BPA-3
BPA-4
Internationl border
State boundary
BPA boundary
WBD Sub-region
Major River
Major Lake
Albers Equal Area Conic Projection
North American Datum 1983
SCALE: 1:5,748,489
0 25 50 100 150 200 Km
Chief Joseph
Grand Coulee
Albeni Falls
Libby
Hungry Horse
Roza
Lower Monumental
Chandler
Little Goose
Lower Granite
Bonneville
Ice Harbor
Dworshak
The Dalles
John Day
McNary
Big Cliff
Detroit
Foster
Green Peter
Dexter
Cougar
Lookout Point
Hills Creek
Lost Creek
Green Springs
Black Canyon
Boise R Diversion
Anderson Ranch
Palisades
Minidoka
Area 1
Area 2
Area 3
Area 4
WA
OR
ID
MT
WY
CA
NV
UT
Author: Nicole Samu - April, 2015
OAK RIDGE National Laboratory


Western Area Power Administration (WAPA)
Lake of the Woods
Lake Sakakawea
Fort Peck
Missouri
Fort Peck Lake
Garrison
Canyon Ferry
MT
ND
Area 1
Upper Red Lake
Yellowstone
Yellowtail
Yellowstone Lake
Buffalo Bill
Heart Mountain
Shoshone
Spirit Mountain
Lake Oahe
Oahe
Big Bend
MN
Boysen
WY
SD
Fort Randall
Gavins Point
Fremont Canyon
Alcova
Glendo
Fontenelle
Seminoe
Kortes
Guernsey
North Platte
Great Salt Lake
Flaming Gorge
Area 2
NE
Platte
Missouri
IA
Deer Creek
Estes
Marys Lake
Big Thompson
Flatiron
Green Mountain
Pole Hill
UT
Green
Lower Molina
Upper Molina
Mount Elbert
Glen Canyon Dam
Crystal
Blue Mesa
Morrow Point
Colorado
Lake Powell
McPhee
Towaoc
CO
KS
Arkansas
MO
Columbia
Willamette
OR
Snake
ID
Klamath
Trinity
Lewiston
Judge F Carr
Keswick
Shasta
Spring Creek
Area 6
Stampede
Folsom
Nimbus
NV
New Melones
O'Neill
W R Gianelli
Kings
CA
Hoover Dam
Lake Mead
Davis Dam
Parker Dam
Area 4
AZ
Area 3
Salton Sea
Salt
Gila
NM
Canadian
OK
Red
Elephant Butte
TX
Brazos
Area 5
Amistad Dam & Power
Falcon Dam & Power
Federal Hydropower Plants
USACE
Reclamation
≤200 MW
200 - 500 MW
>500 MW
IBWC ≤200 MW
Assessment Areas
WAPA-1
WAPA-2
WAPA-3
WAPA-4
WAPA-5
WAPA-6
Reference Layers
Internationl border
State boundary
WAPA boundary
Major River
Major Lake
Albers Equal Area Conic Projection
North American Datum 1983
SCALE: 1:12,855,233
0 75 150 300 450 600 Km
OAK RIDGE National Laboratory
Author: Nicole Samu - April, 2015


Southwestern Power Administration (SWPA)
USACE Hydropower Plants
≤80 MW
80 - 120 MW
>120 MW
Assessment Areas
SWPA-1
SWPA-2
SWPA-3
SWPA-4
Reference Layers
Internationl border
State boundary
SWPA boundary
WBD Sub-region
Major River
Major Lake
Area 1
Area 2
Area 3
Area 4
1102 Upper Arkansas
1103 Middle Arkansas
1104 Upper Cimarron
1106 Arkansas-Keystone
1107 Neosho-Verdigris
1101 Upper White
1108 Upper Canadian
1110 North Canadian
1105 Lower Cimarron
1109 Lower Canadian
1112 Red Headwaters
1113 Red-Washita
1205 Brazos Headwaters
1206 Middle Brazos
1111 Lower Arkansas
0804 Lower Red-Ouachita
1114 Red-Sulphur
1202 Neches
0711 Upper Mississippi-Salt
1209 Gasconade-Osage
Clarence Cannon
Harry Truman
Stockton
Table Rock
Beaver
Bull Shoals
Norfork
Keystone
Fort Gibson
Tenkiller Ferry
Greers Ferry Lake
Webber Falls
Eufaula Dam
Robert S. Kerr
Ozark
Dardanelle
Blakely Mountain
Broken Bow
Denison
Degray
Narrows
Whitney
Sam Rayburn
Robert D Willis
Albers Equal Area Conic Projection
North American Datum 1983
SCALE: 1:7,992,287
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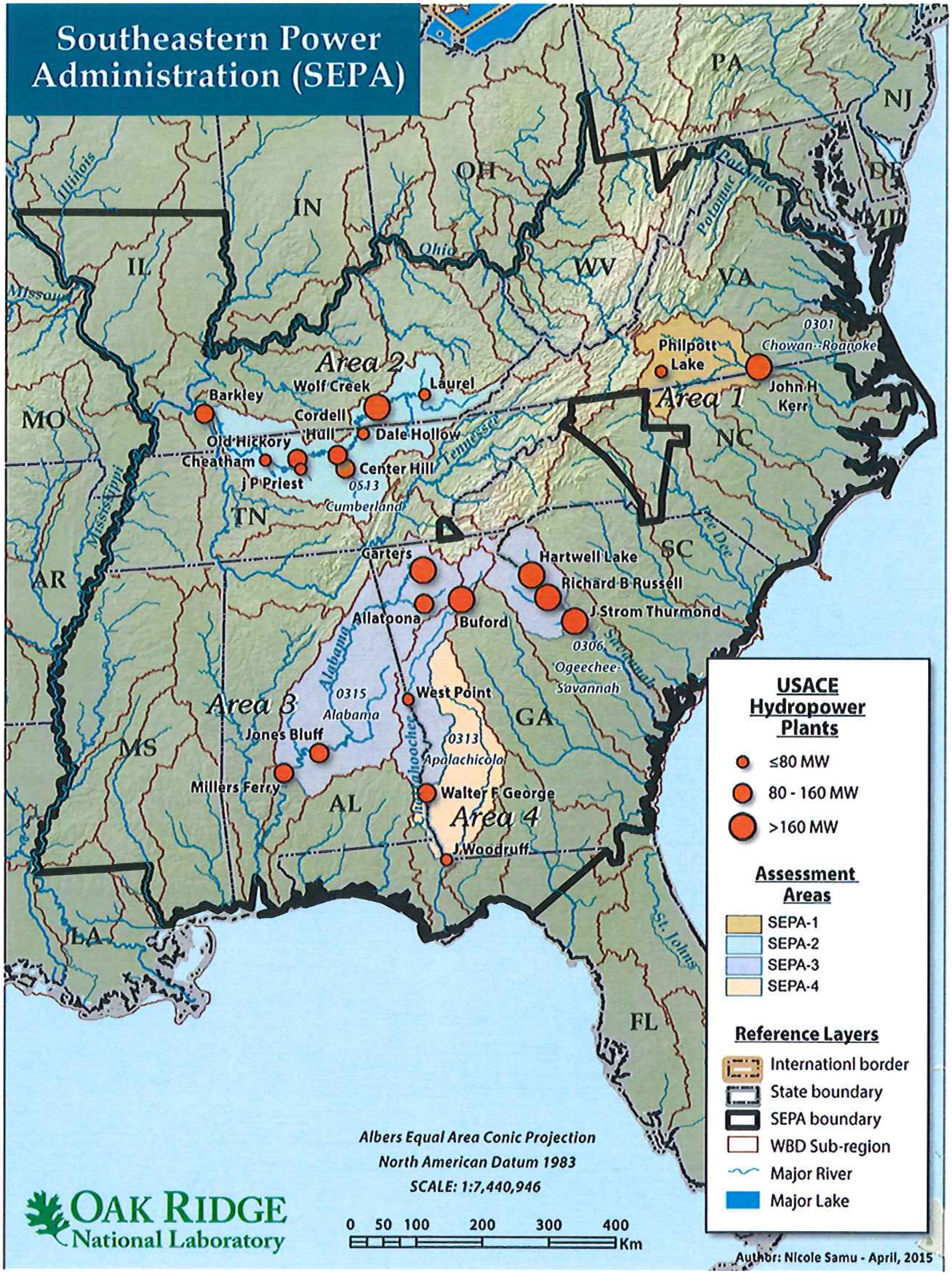
Southeastern Power Administration (SEPA)
PA
NJ
OH
IN
IL
WV
VA
MO
NC
TN
SC
AR
GA
MS
AL
LA
FL
Ohio
Illinois
Mississippi
Potomac
Tennessee
Area 1
Area 2
Area 3
Area 4
Philpott Lake
John H Kerr
0301
Chowan - Roanoke
Barkley
Wolf Creek
Laurel
Cordell Hull
Dale Hollow
Old Hickory
Cheatham
J P Priest
Center Hill
0513
Cumberland
Carters
Hartwell Lake
Richard B Russell
J Strom Thurmond
Allatoona
Buford
0306
Ogeechee-Savannah
0315
Alabama
West Point
Jones Bluff
Millers Ferry
0313
Apalachicola
Walter F George
J Woodruff
USACE Hydropower Plants
≤80 MW
80 - 160 MW
>160 MW
Assessment Areas
SEPA-1
SEPA-2
SEPA-3
SEPA-4
Reference Layers
Internationl border
State boundary
SEPA boundary
WBD Sub-region
Major River
Major Lake
Albers Equal Area Conic Projection
North American Datum 1983
SCALE: 1:7,440,946
0 50 100 200 300 400 Km
OAK RIDGE National Laboratory
Author: Nicole Samu - April, 2015