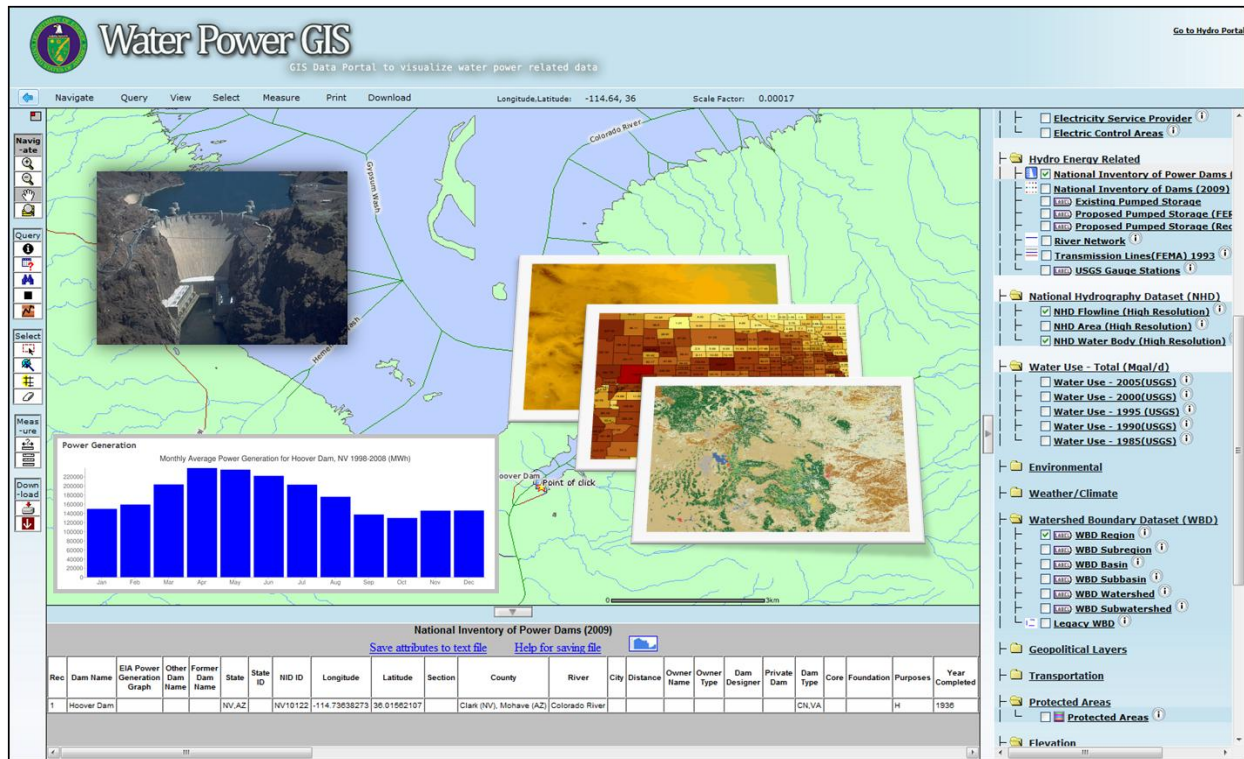


## National Hydropower Asset Assessment Project (NHAAP)



**Prepared by:** The ORNL NHAAP Team

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## **EXECUTIVE SUMMARY**

This report on the National Hydropower Asset Assessment Project (NHAAP) describes the development and construction of the baseline engineering and geospatial information systems and integrated data sets that characterize the hydropower generation fleet in the U.S. These systems and data are capable of capturing, storing, analyzing, and displaying geographically referenced information data identified according to location and their application to hydropower trend analysis and hydrologic assessment. The product is designed to assess and analyze the existing national hydropower infrastructure and to provide historical data to study and plan for future potential hydropower upgrades, as well as potential increases in U.S. hydropower generation. The data are accessed, maintained, updated, and integrated with other generation resource assessments through the Water Power Geographic Information System (WPGIS). The integrated datasets, WPGIS, and documentation are maintained to support ongoing research and development programming and policy analysis. The database will be coordinated with other ongoing hydropower resource analyses, including upgrades of existing facilities, non-powered dams, and pumped-storage projects. The NHAAP data sets currently support program analysis and decision-making within DOE, and can be used internally within DOE to inform national policy analysis upon request. Many of the data within the NHAAP data sets are proprietary or sensitive contributions from hydropower asset owners. For this reason, future work to provide public access to portions of the NHAAP data will be conditional upon protecting the confidentiality of sensitive data while affording useful access to publically available data.

Ownership of and authority over U.S. hydropower assets are distributed among multiple agencies. No single agency has responsibility for maintaining current data on the hydropower infrastructure and operations in the U.S. One of the initial efforts of the NHAAP was to collect the most up-to-date information from a wide range of sources. Hydropower-related data were incorporated from the following agencies: the U.S. Energy Information Administration (EIA), the Federal Energy Regulatory Commission (FERC), the U.S. Army Corps of Engineers (USACE), the U.S. Bureau of Reclamation (Reclamation), and the U.S. Geological Survey (USGS). The data collected describe power generation, plant capacity, turbine types and ages, dam characteristics, historic streamflow records, stream segments, and meteorological observations. Many other types of data and geospatial features needed for resource assessment have also been included, such as transmission lines, meteorological data, streamflow gauge locations and measurements, various environmental data layers, elevation, and transportation infrastructure. Given the large differences in data formats, definitions, coverage, quality, credibility, and extent of missing data values, combining these different datasets was a challenging task. To develop a standardized, cross-referenced data structure that can organize all hydropower data with clear metadata for future reference, ORNL has utilized a uniform hydropower complex classification and naming system in building the WPGIS.

The newly integrated WPGIS has been applied to assess the following: (1) the current state of the hydropower infrastructure in the U.S. (age, type, ownership, etc.), (2) generation patterns from these assets, and (3) hydrologic conditions. Over the past 25 years, no significant upgrades in conventional hydropower installed capacity were observed. Approximately 50% of the hydro turbines in the U.S. were found to be greater than 50 years of age. Well over 50% of all the

turbines in the U.S. are Francis turbines, and about 65% of all U.S. hydropower generation originates in the Pacific Northwest and California.

The NHAAP data sets and information systems are intended to support several DOE projects, including studies of climate change impacts on federal hydropower, and non-powered dam and pumped storage resource assessment projects. They will also support any other existing hydropower asset modernization projects.

## **BACKGROUND AND INTRODUCTION**

The National Hydropower Asset Assessment Project (NHAAP) presents a new assessment of hydropower assets and a new integrated database constructed from available federal and non-federal sources to describe: (1) the current state of the hydropower infrastructure in the U.S. (age, type, ownership, etc.), (2) generation patterns from these assets, and (3) hydrologic conditions. The database was designed to integrate monthly hydrology and civil works information by river basin, for a period of at least the last 10 years. The database will be used to study patterns in generation variability, their causes, and opportunities for upgrading hydropower facilities to stabilize and increase generation.

The existing hydropower infrastructure of the U.S. is aging. Total annual generation, capacity factors, and plant availability at federal projects are declining and no comprehensive assessment has been undertaken in the past 20 years. These losses of important renewable energy are offsetting gains from other renewable sources. No federal agency had taken the responsibility to analyze the national hydropower sector, largely because responsibilities are divided among many organizations. Furthermore, no comprehensive database existed to describe all hydropower facilities in the U.S. There are separate sources of information on federal and non-federal dams, but they often have missing or erroneous data (i.e., not fully populated) and are not linked to generation or hydrology data (other than some average annual values, which include serious estimation errors and provide no variability information). New sources of information are available (e.g., U.S. Army Corps of Engineers' infrastructure analyses), but these have not been used in any kind of comprehensive analysis. Without new data and analyses, it is impossible to determine how new technology could be applied to improve hydropower generation and reverse current trends.

The NHAAP database is consistent with the most current geospatial data standards of the Federal Geographic Data Committee and the National Spatial Data Infrastructure to maximize future uses of the assembled data and the utility of this new information resource. Data sources include the Federal Energy Regulatory Commission (FERC), U.S. Army Corps of Engineers (USACE), U.S. Bureau of Reclamation (Reclamation), Tennessee Valley Authority (TVA), U.S. Department of Energy (DOE), and the U.S. Geological Survey (USGS). Because of the sensitive nature of some of the data (dam locations and site-specific generation), databases will be maintained inside the ORNL firewalls.

## **The NHAAP Team and Development Tasks**

Oak Ridge National Laboratory (ORNL), as the lead coordinating laboratory, interfaces with DOE Headquarters staff to ensure that staff has strategic oversight for the NHAAP and to ensure that the NHAAP effort is responsive to the immediate and long-term needs of DOE Water Power Program staff, DOE national laboratories, and other program participants. The FERC, Reclamation, USGS, USACE, and TVA are important providers of data for the NHAAP. The NHAAP Team also engages multiple industry experts in hydropower development and operations to aid in crafting developmental and operational models of hydropower projects and to validate results of analyses.

The NHAAP is divided into functional tasks that are described below:

- (1) Constructing and implementing an integrated geospatial database of river, stream, dam, powerhouse, and other electric power infrastructure data to serve as the foundation for NHAAP analyses;
- (2) Locating, receiving, cataloging, and securing hydropower production data on behalf of DOE and incorporating the data into the NHAAP database;
- (3) Integrating hydrologic monitoring data into the NHAAP database;
- (4) Implementing advanced spatio-temporal and statistical modeling with these aforementioned data sets to characterize the time-varying energy potential available to U.S. hydropower assets;
- (5) Analyzing and reporting a basic suite of temporal and spatial trends in hydropower production, services, and value within the U.S.

ORNL leverages geospatial data management expertise and information technology infrastructure within its Environmental Data Science and Systems (EDSS) group to accomplish tasks 1, 2, and 3 in the above list, with particular attention to long-term data availability, maintenance and updating of the database, and adherence to federal standards for geospatial databases. Modeling, analysis, and reporting of the data and results (tasks 4 and 5 above) are accomplished by the water resource and hydropower engineers and statistical hydrologist in ORNL's Energy-Water-Ecosystem Engineering (EWEE) group.

### **DATA INFRASTRUCTURE**

## **Foundational Geospatial Database Development**

One major goal of the NHAAP is to create a comprehensive database of hydropower assets. The NHAAP database integrates several related datasets for the purposes of analyzing existing hydropower assets. Assets include dams and power plants and associated information about their generators, turbines and power production; these are combined with river flow and climate data. Due to the nature of the many overlapping, but sometimes incomplete datasets collected by various regulatory agencies, it was necessary to compile an integrated dataset with a unique structure. It was found reasonable to group dams, power plants and their associated production

based on their physical location and interaction with reservoirs. The assets are hence grouped into “hydropower complexes” based on their physical location of headwater source. A complex can include a main dam, several saddle dams and dikes, and one or more power plants and associated generators and turbines. This makes the task of evaluating a site for potential production more straightforward. However, each dam and power plant can still be analyzed separately. Data collected and integrated go back at least 30 years for power production and as long as 100 years for some climatological and plant characteristics records.

## Datasets

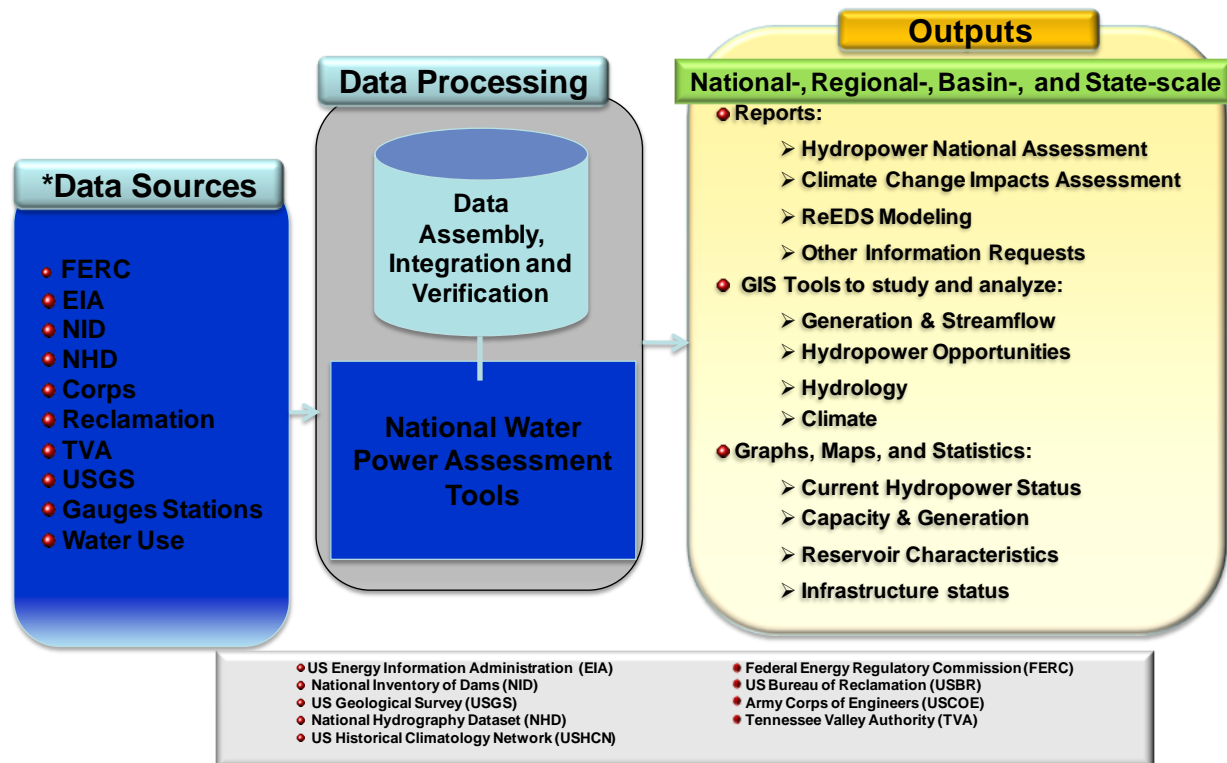
The following data sources and existing datasets are included in the integrated NHAAP database. A summary is shown in Table 1. Datasets marked with an “\*” were obtained through non-disclosure agreements.

- FERC\* – The Federal Energy Regulatory Commission (FERC) is responsible for licensing new and existing hydropower projects above a certain size, and oversight of ongoing operations. The FERC Division of Dam Safety and Inspections Database that contained information about dams, power plants, and generating units for federal and non-federal hydropower projects was utilized.
- NID\* – The U.S. Army Corps of Engineers (USACE) maintains the National Inventory of Dams (NID) with information about all of the powered and non-powered dams above certain size and hazard classifications. The 2009 database has information on more than 80,000 dams.
- NHD – The National Hydrography Dataset (NHD), which is jointly maintained by the U.S. Geological Survey (USGS) and Environmental Protection Agency (EPA), contains a comprehensive set of digital spatial data relating to surface water features in the United States. Both NHD (high resolution, <http://nhd.usgs.gov/>) and NHD-Plus (medium resolution, <http://www.horizon-systems.com/nhdplus/>) are included.
- EIA – The Energy Information Administration (EIA) publishes annual reports related to energy production. Hydropower-related information from the EIA860 database (Annual Electric Generator, <http://www.eia.doe.gov/cneaf/electricity/page/eia860.html>) and the EIA923 database (Utility, Non-Utility, and Combined Heat & Power Plant, [http://www.eia.doe.gov/cneaf/electricity/page/eia906\\_920.html](http://www.eia.doe.gov/cneaf/electricity/page/eia906_920.html)) provided monthly and yearly production and consumption data.
- Reclamation\* – The U.S. Bureau of Reclamation (Reclamation) manages a number of projects in the western U.S., but mainly in the Northwest. The dataset contains information relating to the characteristics of these projects.
- TVA\* – The Tennessee Valley Authority (TVA) manages several hydropower projects in the Southeast.
- USACE\* – The USACE manages projects across the entire country and provided data related to the operation of their hydropower projects.
- USGS – The USGS National Water Information System (NWIS, <http://waterdata.usgs.gov/nwis>) monthly streamflow discharge and WaterWatch (<http://waterwatch.usgs.gov/>) computed Regional runoff data are included.

- USHCN – The U.S. Historical Climatology Network (USHCN) database contains daily and monthly temperature and precipitation data from over 1200 observing stations across the 48 contiguous states.
- PRISM – The parameter-elevation regressions on independent slopes model (PRISM, Daly et al., 2002) temperature and precipitation outputs, developed by the Oregon State University, is adopted. PRISM provided grid-based meteorological observations for the conterminous U.S.

## Data Issues

There are many data issues that must be addressed when attempting to compile a comprehensive hydropower database. Because there are several agencies such as the TVA, Reclamation, and USACE tasked with very similar responsibilities but different geographical areas, generating a complete, comprehensive dataset requires combining information. Additionally, certain characteristics may be recorded in somewhat different fashions, or not recorded to the same level of detail across all agencies. Finally, some records may not be as thoroughly maintained and may contain inaccurate data. Wherever possible, ORNL has attempted to cross-reference information by comparing information from different agencies relating to the same structures. Reclamation, TVA and USACE dam information can be verified by comparing it with the similar FERC, EIA and NID data. The workflow for the resulting process is summarized in Figure 1.



**Figure 1.** Summary of workflow for hydro-related dataset integration

## **Graphs and Maps**

To illustrate the kinds of data available from the NHAAP database, and its power to elucidate the relationships from the compiled datasets, several graphs and maps related to hydropower production in the U.S. were created and are presented in the following sections and in the appendices. These include but are not limited to:

- Power generation per plant by year, with monthly averages over the period of record
- Streamflow per USGS site as monthly averages, yearly totals, and months for specific years
- Temperature and precipitation as monthly or yearly averages
- Power production by PMA and Agency
- Nameplate capacity by region or basin

## **Stream Network Implementation**

Current versions of the USGS- and EPA-developed National Hydrography Dataset and extensions (NHD and NHDPlus) that enable nationwide stream network analysis have been included in the NHAAP database. These datasets are cataloged and indexed with geographic information system (GIS) software. This full GIS implementation of the NHD and NHDPlus as part of the NHAAP foundation enables automated tracing of water flow through systems of hydropower projects and automated analyses of a hydropower project based on its position in a network of projects within a river basin. Because the NHD implements the hydrologic unit codes (HUC) that define hydrologic regions in the U.S., NHAAP data that are linked to the NHD are inherently organized into appropriate hydrologic units. Other basic data layers (political boundaries, population density, land-use-land-cover, transportation networks, etc.) are also aligned and registered in the NHAAP foundational database.

## **National Inventory of Dams Integration**

Significant effort was employed to integrate the National Inventory of Dams (NID) into the NHAAP database. The NID is well-maintained by the USACE as a water storage and structural information resource, but individual elements of the NID must be uniquely associated with stream segments of the NHD and cross-referenced with existing hydropower installations to take full advantage of the energy-relevant dam and reservoir configuration attributes that are included in the NID. The NHAAP database links the individual records (powered dams) in the NID with stream segments, segment attributes, and hydrology to enable assessment of water availability and variability for energy production (beyond the averaged hydrologic statistics already included in the NID attributes). Some NID coordinates were replaced by the latest NHD coordinates to ensure consistency between the geospatial datasets.

## **Hydropower Project Configuration Data Collection and Reporting**

The configuration data for 163 federal installations from the three primary federal agencies that operate hydropower projects (USACE, Reclamation, and TVA) were included in the NHAAP. Configuration data for non-federal hydropower installations were obtained from multiple internal

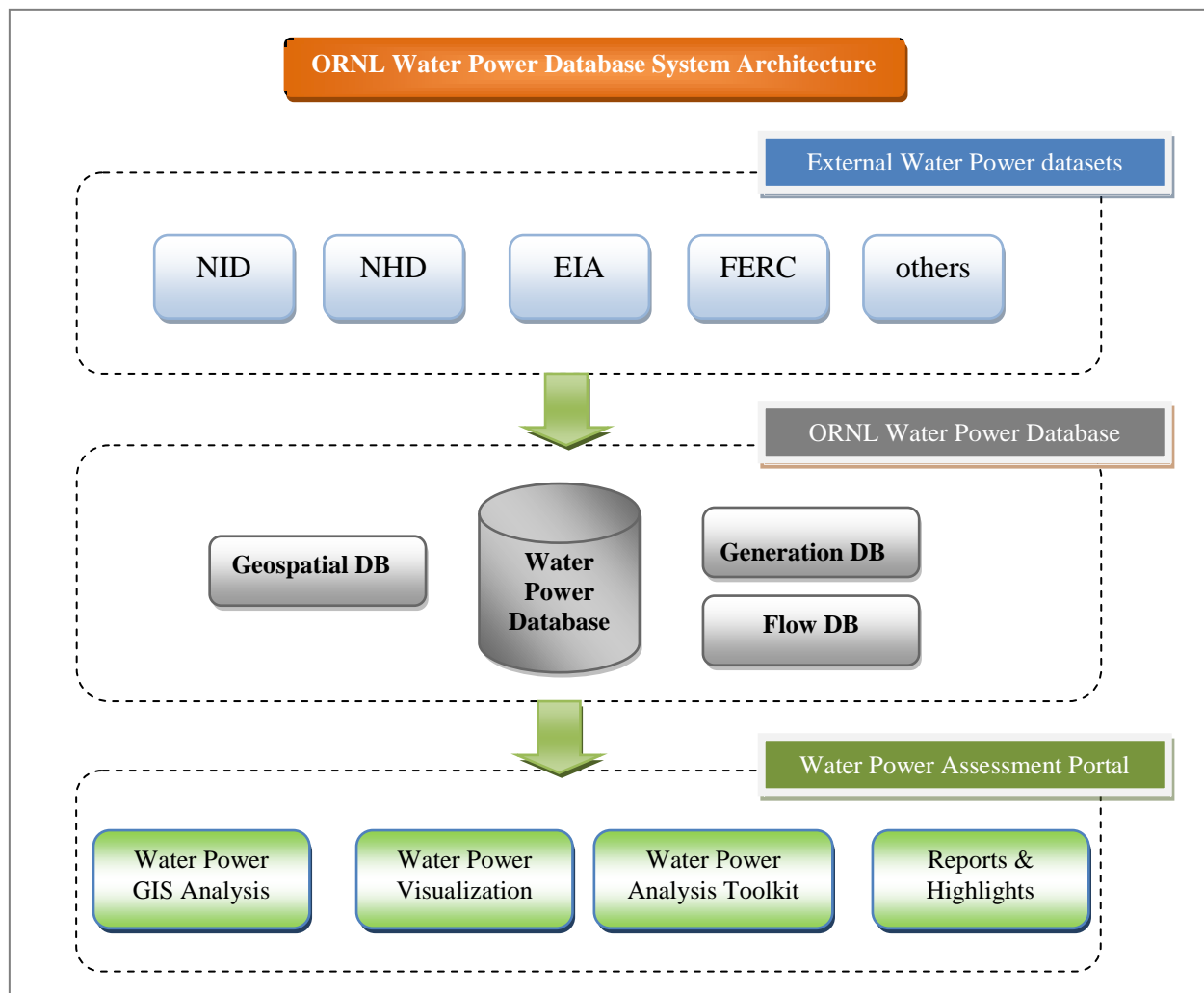
datasets maintained by the staff of FERC. Many of these data are sensitive because of their physical and power system security implications and commercial value in forecasting hydropower production and capacity; thus, ORNL has engaged in non-disclosure agreements (NDAs) with the agencies providing these data. The release of site-specific configuration data via the NHAAP, ORNL, or DOE is not anticipated within the NHAAP strategy; such data will only be used in analyses that provide some level of aggregation and anonymity in the results that the NHAAP provides to policy-makers, decision-makers, and the public.

This national and regional infrastructure database and other spatial distributions of hydropower assets across multiple parameter groups include:

- Turbine (rated head, rated flow, rated output, seasonal capacity, specific speed, diameter, submergence, turbine type, governor type, intake type, age, upgrade status, manufacturer)
- Generator (capacity, power factor)
- Reservoir and Dam (surface areas, storage volumes, shoreline length, dam type, dam width, dam length, spillway characteristics, firm yield)

## **Water Power Database**

The ORNL Water Power Database (Water Power DB) integrates a wide range of geospatial and power generation datasets from external sources such as NID, NHD, EIA and FERC. The Water Power DB currently contains geospatial information for about 2300 hydropower plants (both current and historic). Over 90% of the EIA hydropower facilities have been mapped, and most of them have generation data over the period 1999-2008. Various database services were developed that allow analysts and model tools to query the generation and flow data from the Water Power DB. The Water Power DB system architecture is shown in Figure 2.



**Figure 2.** System Architecture of ORNL’s Water Power Database (Water Power DB)

## Water Power Geographic Information System

ORNL has developed a web-based Water Power Geographic Information System (WPGIS) that the NHAAP staff can use to explore, summarize, and analyze data that are continually being collected and integrated into the project’s Water Power DB. This WPGIS uses proprietary and open-source software that allows the analyst to open the GIS application in a standard web browser to select any region in the U.S. and explore numerous data “layers” associated with interrelated infrastructure, power generation, and hydrologic parameters held in the Water Power DB. In addition, various electric power and environmental data layers have been incorporated into the WPGIS to assist with analysis and assessment of infrastructure and wildlife/land-use issues that could affect potential hydropower development or upgrades.

The WPGIS system was developed within a 3-tier distributed architecture. This architecture splits the whole WPGIS system into 3 tiers based on their functionalities: data tier, logic tier, and presentation tier. This architecture has several benefits:

1. The architecture properly balances the functions and loads between client side and server side. The Web browser-based rich client provides users convenient interactive tools for browsing, viewing, and analyzing water power-related resources. The architecture also minimizes data communication between client and server.
2. This modular architecture gives the WPGIS the capability to integrate distributed resources into a seamless system. For example, the WPGIS not only contains useful layers and resources managed inside the ORNL Distributed Active Archive Center (DAAC), but also external resources like Bing Virtual Earth and Open Street Map.
3. This architecture eases the maintenance of the entire WPGIS. For example, the ESRI ArcIMS servers in the logic tier can be upgraded or replaced with ArcGIS servers with minimum impact on other tiers.

## Water Power Visualization Tool

The Water Power Visualization tool is a web user interface which, using the Water Power DB, allows analysts to dynamically view monthly and yearly power generation graphs and other time series graphs for selected powered dams. The Water Power Visualization Tool has been integrated into the WPGIS client interface. As shown in Figure 3, users can find all the powered dams using spatial query, view detailed dam information, and view monthly/annual power generation graphs and data for each individual dam or all selected dams.

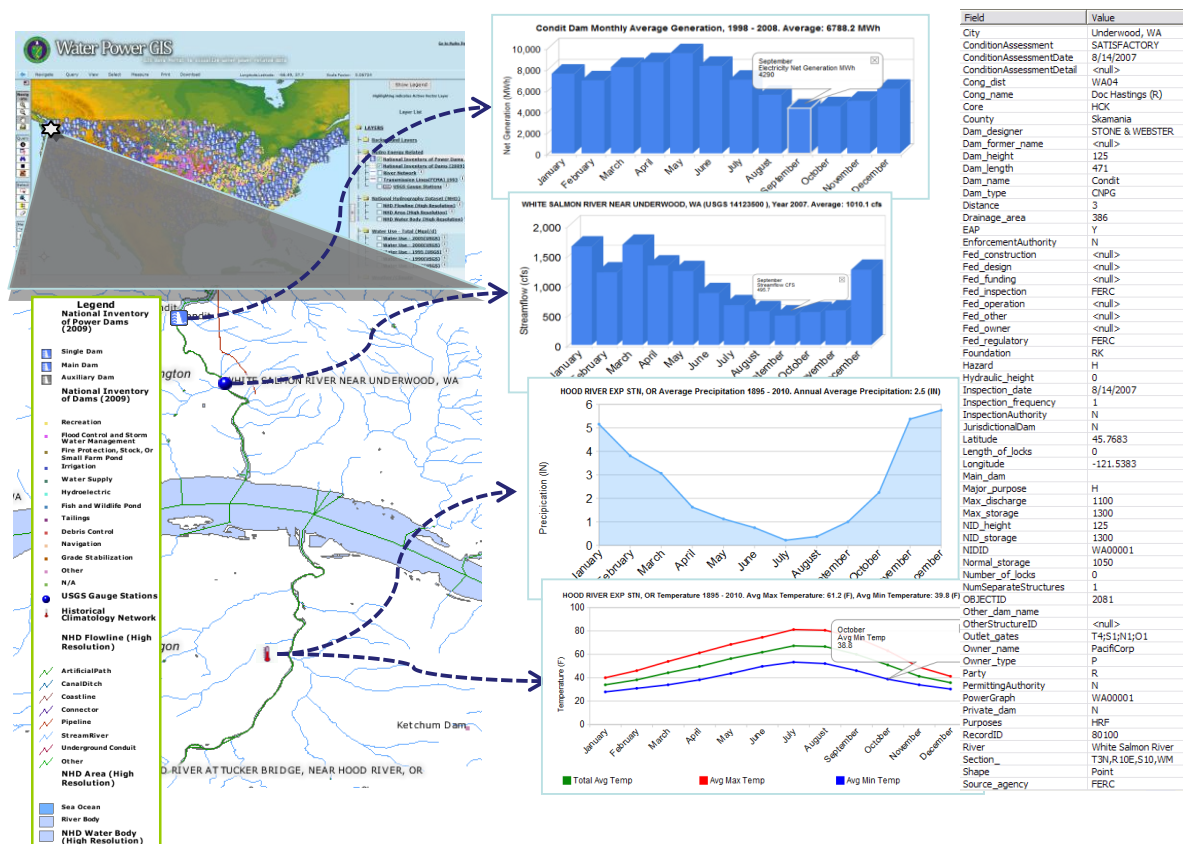


Figure 3. Example of output from ORNL Water Power Visualization tool

## **Hydropower Asset Maps**

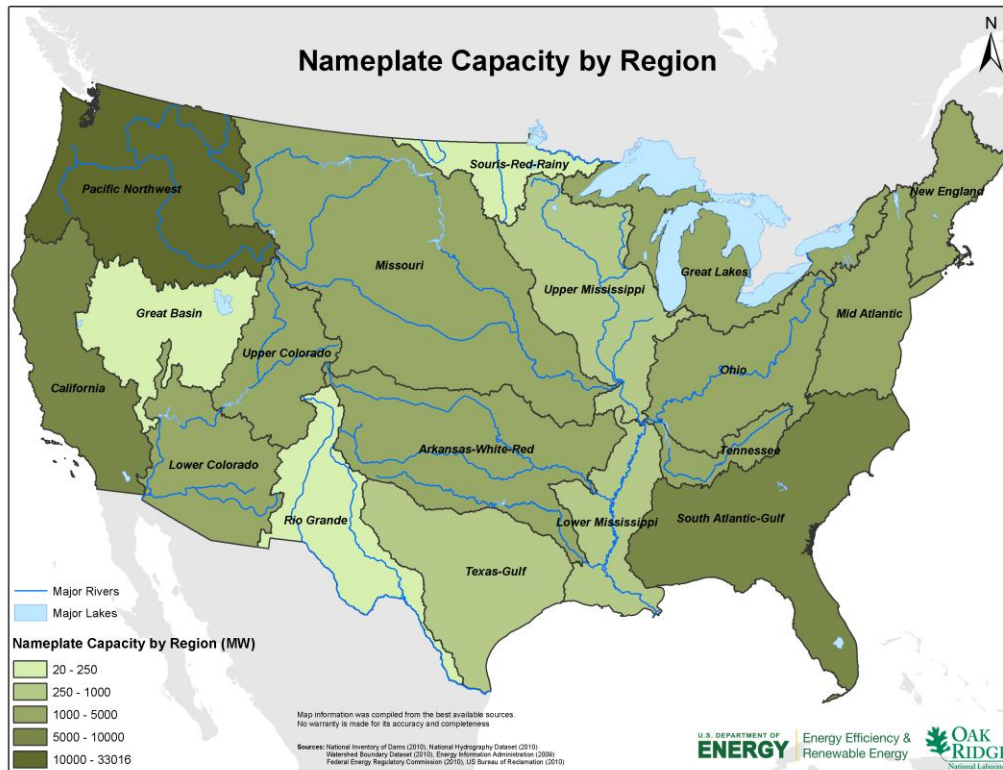
ORNL is creating display-quality maps for users to have an overall picture of the hydropower assets, capacity, generation, and plant characteristics in the U.S. The maps are created in high resolution using ArcMap. The current map size is 3168 by 2448 pixels and the resolution is 288 dpi. The sources for the base layers used in these maps (country background layer, U.S. state boundaries, major rivers in the U.S., and major lakes in the U.S.) come from the ESRI Data & Maps database release version 9.3.

## **Capacity and Generation Assessment**

An extensive asset assessment was conducted to evaluate the current state of hydropower in the U.S. conventional hydropower has grown very little over the last 25 years. The addition of pumped storage plants since the 1960s has increased total capacity by about 20% as of 2008.

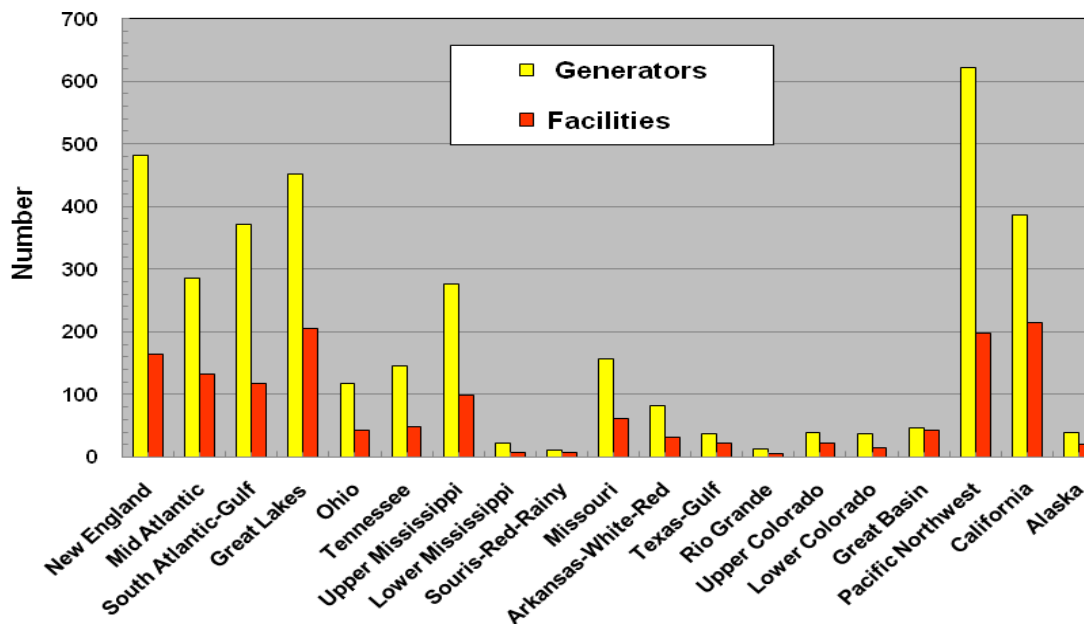
Power generation varies greatly with hydrology. Comparing the years 1997 and 2001, the total yearly generation was 337 Billion KWh and 209 Billion KWh, respectively. Although the total installed capacity was about the same for the last 20 years, the variation in generation was about 48% less in 2001 compared to 1997. This pattern clearly indicates that the variability of power generation depends on other variables, mainly the hydrology.

It is important to assess by region the power generation, capacity, number of facilities, and generation to evaluate the distribution of hydropower in the U.S. Figure 5 shows a wide variation in the number of facilities and generators across the nation. However, interestingly, the number of facilities is not always a good indicator of power generation. As shown in Figure 4, although the number of facilities is about the same in California, the Great Lakes, and the Pacific Northwest, the Pacific Northwest alone contributes to about 50% of the total U.S. generation as shown in Figure 6. The reason is that among the 10 top generating facilities in the nation, 8 of them are in the Pacific Northwest Region.

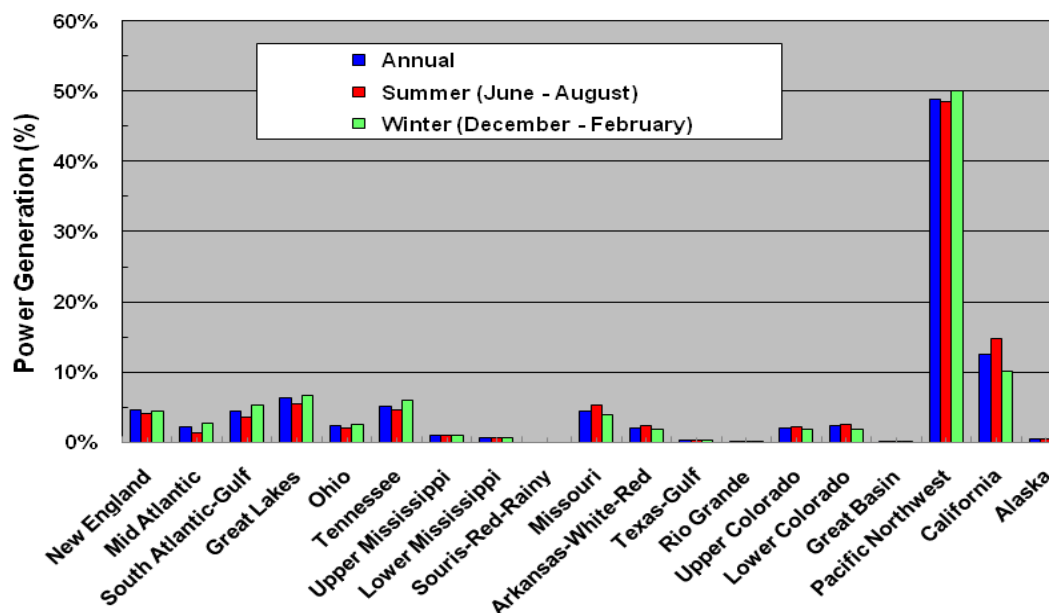


**Figure 4.** Nameplate Capacity by Region

Conventional hydropower capacity has been rather stable over the last 25 years, while generation has been quite variable.



**Figure 5.** Regional facilities and generators assessment, 2008



**Figure 6.** The Pacific Northwest and California were responsible for about 60% of the national generation from 1999–2008

## SUMMARY AND RECOMMENDATIONS

Fifty years ago, the hydropower industry in the U.S. was in a unique period of expansion. Today, the industry is in another unique period, with extraordinary opportunity as well as major challenges. Driven by the current interest in renewable energy, federal support for hydropower is greater than it has been since the growth periods of the 1950s and 1960s. The DOE has set a strategic goal of doubling generation from hydropower by 2030, and there is strong support for that type of goal in other federal agencies and in industry. National energy planning is seriously looking at such ambitious objectives as providing 80% of the nation's electricity from renewable sources.

This report describes a new effort to build a comprehensive database constructed from available federal and non-federal sources to describe: (1) the current state of the hydropower infrastructure in the U.S. (age, type, ownership, etc.), (2) the installed capacity of these assets, and (3) generation patterns from these assets. The database is now capable of integrating monthly hydrology and civil works information by region and river basin, for a period of at least the last 10 years. The database will be used to study regional patterns in generation variability, their causes, plus opportunities for upgrading hydropower facilities to stabilize and increase generation.

## PROPOSAL FOR UPDATING NHAAP

The NHAAP Database, Water Power GIS, Hydropower Generation Catalog, and various infrastructure and hydrological assessments described in this report represent major strides in developing the integrated information and analysis tools required by the DOE Water Power Program for guiding our nation's efforts to increase electricity generation from hydropower resources. However, given the scale and complexity of this national undertaking, there are numerous additions and enhancements that could bolster these capabilities and result in significant NHAAP improvements. Potential enhancements are outlined below.

- Identify and include the state-level datasets (especially needed for HI, AK, CA, PA, UT, and NV).
- Add the FERC HPRRA dataset to include the planned/under-construction projects. This would allow comparisons to previous studies, and to track progress in new project development.
- Build connections to project owners to retrieve the most accurate data (generator, turbine flow, storage, etc.) and for NHAAP verification.
- Investigate applications of other climate-meteorological datasets (NOAA climate normal, meteorological re-analyses, GCM projections) to support climatic assessment.
- Develop a more project-specific data archive to include more detailed site characteristics, e.g. drainage coverage as GIS layers, linkage and relationship to neighboring streams and projects, satellite images, site photos, storage-height characteristic curves, water storage and use of storage at projects, and prior reports.
- Streamline the process of updating the NHAAP database and associated tools and analyses when new data sources become available.
- Develop an internal/external data review procedure.
- Develop a strategy to deal with requests from DOE, Federal and Non Federal Agencies

## **Presentation and Interface Upgrades**

- Water Power GIS interface upgrades using the latest ESRI software
- Add selection function (by drawing a random polygon) and dynamic plot capability to the Water Power GIS
- Collaborate with DOE, industry, and other interested parties to develop a user-friendly interfaces for various feature selections. For instance, identify candidates for system upgrades and fish-friendly turbines.
- Prepare and have available template reports and maps to enable quick response to emergency information requests or analyses.
- Implement a cross-reference system on the NHAAP archive.
- Compile Google Earth images for all the dams and reservoirs.