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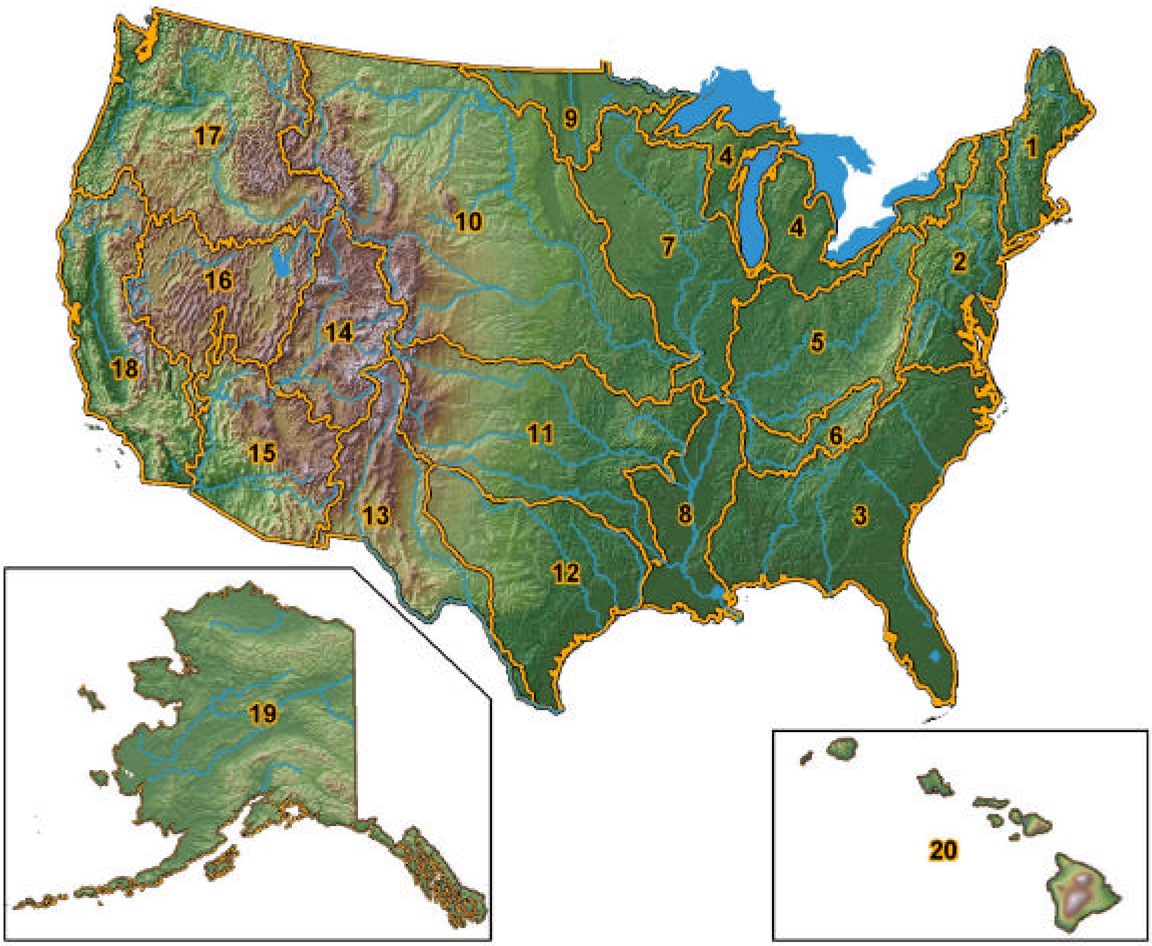
Water Energy Resources of the United States with Emphasis on Low Head/Low Power Resources



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Water Energy Resources of the United States with Emphasis on Low Head/Low Power Resources

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ABSTRACT

Analytical assessments of the water energy resources in the 20 hydrologic regions of the United States were performed using state-of-the-art digital elevation models and geographic information system tools. The principal focus of the study was on low head (less than 30 ft)/low power (less than 1 MW) resources in each region. The assessments were made by estimating the power potential of all the stream segments in a region, which averaged 2 miles in length. These calculations were performed using hydrography and hydraulic heads that were obtained from the U.S. Geological Survey's Elevation Derivatives for National Applications dataset and stream flow predictions from a regression equation or equations developed specifically for the region. Stream segments excluded from development and developed hydropower were accounted for to produce an estimate of total available power potential. The total available power potential was subdivided into high power (1 MW or more), high head (30 ft or more)/low power, and low head/low power total potentials. The low head/low power potential was further divided to obtain the fractions of this potential corresponding to the operating envelopes of three classes of hydropower technologies: conventional turbines, unconventional systems, and microhydro (less than 100 kW). Summing information for all the regions provided total power potential in various power classes for the entire United States. Distribution maps show the location and concentrations of the various classes of low power potential. No aspect of the feasibility of developing these potential resources was evaluated. Results for each of the 20 hydrologic regions are presented in Appendix A, and similar presentations for each of the 50 states are made in Appendix B.

SUMMARY

The U.S. Department of Energy (DOE) has an ongoing interest in assessing the water energy resources of the United States. Previous assessments have focused on potential projects having a capacity of 1 MW and above. These assessments were also based on previously identified sites with a recognized, although varying, level of development potential. In FY 2000, DOE initiated planning for an assessment of low head (less than 30 ft) and low power (less than 1 MW) resources.

The Idaho National Engineering and Environmental Laboratory in conjunction with the U.S. Geological Survey recently completed assessments of all 20 hydrologic regions in the United States, which in combination provide assessment results for this entire area of the United States. Parsing of the regional assessment results using geographic information system (GIS) tools produced assessment results for each of the 50 states. The assessments provided not only estimates of the amount of low head/low power potential, but also estimates of power potential in several power classes defined by power level and hydraulic head, and an estimate of the total power potential of water energy resources in individual states and hydrologic regions and in the nation.

The method used in this study uses state-of-the-art digital elevation models and GIS tools to assess the power potential of a mathematical analog of every stream segment within each region. Only water energy resources associated with natural water courses were assessed (e.g., effluent streams, tides, wave power, and ocean currents were not included). Summing the estimated power potential of all the stream segments in the region provided an estimate of the total power potential in the region. Stream segments that had power potentials less than 1 MW and hydraulic heads less than 30 ft and power potentials less than 100 kW (microhydro) were segregated and summed to provide an estimate of total low head/low power potential in the region. Having power potential estimates in such small increments allowed the low head/low power potential to be further divided to determine the amounts of potential corresponding to the operating envelopes of three classes of low head/low power hydropower technologies: conventional turbines, unconventional systems, and microhydro.

In order to calculate the power potential of each stream segment, the hydrography in the region was derived using the U.S. Geological Survey's Elevation Derivatives for National Applications (EDNA) dataset. In addition to the hydrography, the dataset provided the elevations of the upstream and downstream ends of each stream segment, which were used to calculate hydraulic head. The dataset also allowed the calculation of the drainage area providing runoff to each stream segment. Use of the EDNA data in conjunction with climatic data provided the variables needed to calculate the annual mean flow rate for each stream segment using a regression equation or equations developed specifically for each region in the study area. Combining stream flow rate with hydraulic head provided the power potential of the stream segment.

Because the hydrography used was "synthetic," stream segments were compared to streams in the U.S. Geological Survey's National Hydrography Dataset. Unconfirmed stream segments were eliminated from the datasets that

were used to estimate total power potentials. A GIS layer containing streams and areas that are excluded from development by federal statutes and policies was used to segregate excluded and nonexcluded stream segments. The amount of power potential that has already been developed in the region was derived from average annual electricity generation data provided by the Federal Energy Regulatory Commission's Hydroelectric Power Resources Assessment (HPRA) Database. Developed power potential was subtracted from the total, nonexcluded, power potential in each power class to produce estimates of "available" power potentials. No feasibility assessments were made; therefore, the results are gross numbers that do not include the elimination of "available" sites that probably would not be developed at this time. Also, "available" power potential only refers to amounts of potential that have not been developed and are not excluded from development by federal statute or policy. No assessment of actual availability for hydropower development was performed.

The study produced an engineering estimate of the magnitude of United States water energy resources on a comprehensive scale and with delineation that was not previously possible. While the results contain significant uncertainties, comparison of the relative magnitudes of power potentials within power categories, power classes, and geographic boundaries provide useful insights, such as the relative status of development and exclusion and the abundance and concentration of water energy resources. The amounts of "available" power potential are gross numbers that would be greatly reduced by a feasibility assessment accounting for the viability of resources based on such parameters as site accessibility, proximity to load centers and infrastructure, and constraints on development that have not been addressed in this study.

The assessment estimated that the total annual mean power potential of the United States is approximately 300,000 MW. Of this amount, about 90,000 MW is excluded from development. With about 40,000 MW of annual mean power already developed (corresponding to a total hydropower capacity of approximately 80,000 MW), the total available power potential is estimated to be about 170,000 MW or about 60% of the total power potential. The density of available power potential is approximately 50 kW/sq mi. Low head/low power potential makes up about 21,000 MW of the total available potential. Division of the available low head/low power potential among low head/low power technology classes showed that 34% fell within the operating envelope of conventional turbines, 16% fell within the operating envelope of unconventional systems, and 50% fell within the operating envelope of microhydro technologies. In addition to the low head/low power potential, it is estimated that there is a total of 26,000 MW of high head (30 ft or greater)/low power potential available in the 50 states.

A map of the locations of low head/low power sites by technology class shows that conventional turbine sites and unconventional system sites are numerous except in the central part of the country, arid areas of the West and where there are high concentrations of high power or high head/low power potential. Microhydro sites are abundant and exist everywhere in the country except in the plains from North Dakota to the Texas panhandle and in Hawaii, where virtually all the resources are in the high power (equal or greater than 1 MW) or high head/low power classes. A second map shows that high head/low power sites are abundant and are generally located in the mountainous areas of the country.

The regional and state potentials are compared to each other and to the total results for the 20 regions and 50 states. These comparisons show that a majority of the water energy resources in regions and states are underdeveloped compared to the national percentages of potential developed to date (12%) and potential that is available for development (57%). Available power potential is most concentrated in Hawaii, Alaska, 4 Western states and 12 states east of the Mississippi River. The states having the highest concentrations of low head/low power potential are all in the eastern United States with the vast majority being east of the Mississippi River; but in general, low power (<1 MW) sites exist in large numbers throughout the country.

The study showed that the combined amounts of available high head/low power and low head/low power power potential in the study area constitutes 30% of the total available potential. However, realizing nearly two-thirds of the low head/low power potential would require unconventional systems or microhydro technology requiring significant turbine and system configuration research and development. The fact that this source of distributed power could be realized without the need for water impoundments is a positive attribute. The greatest sources for additional hydropower lie in the combination of high power sites, high head/low power sites, and part of the low head/low power potential sites, constituting 90% of the total available power potential. This potential could be realized wit333h conventional turbine technology, but perhaps in new configurations not requiring impoundments to be determined by future research and development.

The assessment results for each of the hydrologic regions are presented in Appendix A. Each subsection is devoted to a specific region and contains a description of the region with a map showing its geographic and hydrographic features. The regional assessment results are presented in a table listing power potential by power class and category. Pie charts illustrate the division of total power potential, available power potential, and low head/low power power potential amongst their constituent parts. A two-part map shows the locations of existing power plants and high head/low power potential sites in one part, and low head/low power sites in the other part. Similar presentations of assessment results for each state are made in Appendix B.

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FIGURES

TABLES

ACRONYMS

BNI	Bechtel National, Incorporated
DOE	U.S. Department of Energy
EDNA	Elevation Derivatives for National Applications An analytically derived, three-dimensional dataset in which hydrologic features have been determined based on elevation data from the NED resulting in three-dimensional representations of "synthetic streams" (stream path coordinates plus corresponding elevations) and an associated catchment boundary for each synthetic reach (based on 1:24K-scale data for the conterminous United States and 1:63,360-scale data for Alaska) (*Note: EDNA synthetic stream reaches do not uniformly coincide with NHD reaches. Conflation of EDNA and NHD features to improve the quality of both datasets is a later phase EDNA development.) (http://edna.usgs.gov)*
FERC	Federal Energy Regulatory Commission
GIS	geographic information system A set of digital geographic information, such as map layers and elevation data layers, that can be analyzed using both standardized data queries as well as spatial query techniques.
HPRA	Hydroelectric Power Resources Assessment
HUC	hydrologic unit code
INEEL	Idaho National Engineering and Environmental Laboratory
NED	National Elevation Dataset A three-dimensional representation of topographic features composed of geographic coordinates on a 30-m grid with corresponding elevations that numerically represent the topography based on 1:24K-scale data for the conterminous United States and 1:63,360-scale data for Alaska (available for the entire United States from the U.S. Geological Survey). *(*http://ned.usgs.*gov)*
NHD	National Hydrography Dataset A comprehensive set of digital spatial data that contain information about surface water features such as lakes, ponds, streams, rivers, springs, and wells. *(*http://nhd.usgs.gov*)*
NPS	Nuclear Placement Services
PRISM	Parameter-elevation Regressions on Independent Slopes Model An expert system that uses point data and a digital elevation model to generate gridded estimates of climate parameters. *(http://www.ocs.orst.edu/prism/overview.html)*
USGS	U.S. Geological Survey

NOMENCLATURE

Annual mean flow rate	The statistical mean of the flow rates occurring at a particular location during the course of 1 year. The stream flow regression equations used in this study estimate the mean of the annual mean flow rates that occurred over a period of many years, hence the mean flow rate for the period of record. The annual mean flow rate in any given year will usually differ from the value predicted by the equations.
Annual mean power	A measure of the magnitude of a water energy resource's potential power producing capability equal to the statistical mean of the rate at which energy is produced over the course of 1 year. When based on the predicted annual mean flow rate and associated hydraulic head of a stream reach, the predicted annual mean power is the mean of the reach annual mean power that would occur over a period of many years. The actual annual mean power in a given year will usually differ from the predicted value of annual mean power. A power rating of a hydroelectric plant based on electricity generation at this rate throughout the course of a year would produce the average annual electricity generation of the plant; sometimes referred to as average megawatt power rating denoted in some usages by "aMW."
Capacity	Typically refers to the design power rating of a hydroelectric plant and is on average equal to twice the annual mean power of the plant for existing United States hydroelectric plants.
Catchment	The local portion on a drainage basin supplying runoff to a particular stream reach.
Drainage area	The total surface area of the topography of a drainage basin.
Drainage basin	The geographic area supplying runoff to a particular point on a stream equal to the area of all the catchments associated with upstream stream reaches supplying flow to the point.
EDNA stream node	Starting point of an EDNA synthetic stream, a confluence on it, or its terminus where it enters a saltwater body or a sink.
EDNA stream reach	That portion of an EDNA synthetic stream between two EDNA stream nodes. (Note: Each stream reach has an associated local catchment and an associated drainage basin.)
Pour point flow rate	The estimated flow rate of a stream reach equal to the runoff rate from the corresponding drainage basin.
Power category	The power category names used in this report to differentiate between different categories of power potential are: "total," "developed," "excluded," and "available." "Total" refers to all the power potential in a study area. "Developed" refers to the power potential corresponding to the sum of the annual mean power of all the existing hydroelectric plants in a study area. "Excluded" refers to the power potential existing within zones in a study area where hydropower

development is prohibited by federal law or policy. “Available” refers to the balance of power potential after subtracting amounts of developed and excluded potential from the total amount. (Note: “Available” only means that the power potential has not been developed and is not excluded from development by federal law or policy. It does not denote availability based on ownership or control or that the potential can feasibly be developed.)

Power class — The power classes into which power potential has been divided in this report include:

- Total power = high power + low power
- High power = high head/high power + low head/high power
- High head/high power
- Low head/high power
- Low power = high head/low power + low head/low power
- High head/low power
- Low head/low power

where high power refers to ≥1 MW, low power refers to <1 MW, high head refers to ≥30 ft, and low head refers to <30 ft.

Additional power classes include those corresponding to the operating envelopes of conventional turbines, unconventional systems, and microhydro low head/low power technologies. (Note: See Figures 6 and 7 for the boundaries of these power classes.)

Power potential — Ideal hydroelectric power based on an annual mean flow rate and an associated hydraulic head. The actual value in any given year will usually differ from the predicted value due to annual variations in annual mean flow rate. (Note: In the case of the developed power potential of an actual hydroelectric plant, the developed power potential is approximated by the annual mean power of the plant.)

Water Energy Resources of the United States with Emphasis on Low Head/Low Power Resources

1. INTRODUCTION

In June 1989, the U.S. Department of Energy (DOE) initiated the development of a National Energy Strategy to identify the energy resources available to support the expanding demand for energy in the United States. Past efforts to identify and measure the undeveloped hydropower capacity in the United States have resulted in estimates ranging from about 70,000 MW to almost 600,000 MW. The Federal Energy Regulatory Commission's (FERC's) capacity estimate was about 70,000 MW, and the U.S. Army Corps of Engineers' theoretical estimate was 580,000 MW. Public hearings conducted as part of the strategy development process indicated that the undeveloped hydropower resources were not well defined. One of the reasons was that no agency had previously estimated the undeveloped hydropower capacity based on site characteristics, stream flow data, and available hydraulic heads.

As a result, DOE established an interagency Hydropower Resources Assessment Team to ascertain the country's undeveloped hydropower potential. The team consisted of representatives from each power marketing administration (Alaska Power Administration, Bonneville Power Administration, Western Area Power Administration, Southwestern Power Administration, and Southeastern Power Administration), the Bureau of Reclamation, the Army Corps of Engineers, the FERC, the Idaho National Engineering and Environmental Laboratory (INEEL), and the Oak Ridge National Laboratory. The interagency team drafted a preliminary assessment of potential hydropower resources in February 1990. This assessment estimated that 52,900 MW of undeveloped hydropower capacity existed in the United States.

Partial analysis of the hydropower resource database by groups in the hydropower industry indicated that the hydropower data included redundancies and errors that reduced confidence in the published estimates of developable hydropower capacity. DOE has continued assessing hydropower resources to correct these deficiencies, improve estimates of developable hydropower, and determine future policy. Modeling of the undeveloped hydropower resources in the United States identified 5,677 sites that have a total undeveloped capacity of about 70,000 MW (Connor et al. 1998). Consideration of environmental, legal, and institutional constraints resulted in an estimate of about 30,000 MW of viable, undeveloped United States hydropower resources.

The previous resource assessments have focused on potential projects that have a capacity of 1 MW or more. DOE identified a need to assess the United States water energy resources for projects of less than 1 MW. In FY 2000, DOE initiated planning for an assessment of low head (less than 30 ft) and low power (less than 1 MW) resources. The INEEL in conjunction with the U.S. Geological Survey completed a pilot study of low head/low power hydropower water energy resources in the Arkansas-White-Red hydrologic region in July 2002 (Hall et al. 2002a). The principal objective of this pilot study was to develop and demonstrate a method of estimating the power potential of water energy resources in a large geographic area. The method that was developed uses state-of-the-art digital elevation models and geographic information system tools. Using this method, the power potential of a mathematical analog of every stream segment within a chosen study area is assessed. Summing the estimated power potential of all stream segments in the area provides an estimate of the total power potential of the area. This method was subsequently used to assess the Pacific Northwest hydrologic region as a demonstration of its applicability to a region with large extremes in elevation and hydrology. The results of this study are reported in Hall et al. 2002b. An additional regional assessment was undertaken at the request of DOE, which assessed the combined study area of the North Atlantic and Mid-Atlantic hydrologic regions. The results of this study are reported in Hall et al. 2003.

The ultimate result of the project that produced the four regional assessments has been to produce a fundamental assessment of the water energy resources of the entire United States with emphasis on low head/low power resources. This has been accomplished by assessing the remaining 16 hydrologic regions and collating the regional data into results for the country. These results were subsequently parsed to produce results for each of the 50 states. The method used to determine power potential did not include evaluating any aspect of the feasibility of developing a discrete water energy resource or collective group of resources other than location inside or outside a zone in which hydropower development is prohibited by federal law or policy. The study only assessed water energy resources associated with natural water courses (e.g., effluent streams, tides, wave power, and ocean currents were not included).

The assessment results reported in this document were analytically derived using validated mathematical analogs of stream segments and predictive equations to calculate their annual mean flow rate. The analysis method employed produced power potential estimates in stream segment increments that allowed the total power potential in a study area to be divided into subcategories: high power potential (1 MW or greater), high head/low power potential (less than 1 MW with 30 ft of hydraulic head or greater), and low head/low power (less than 1 MW with generally less than 30 ft of hydraulic head). It also allowed the low head/low power potential to be further divided to determine the amounts of potential corresponding to the operating envelopes of three classes of low head/low power hydropower technologies: conventional turbines, unconventional systems, and microhydro.

The magnitudes of water energy resources are reported as power potentials expressed in annual mean power—the statistical mean of the rates at which energy would be produced during the course of 1 year. Values are reported to the nearest megawatt to record the values obtained in the calculations. However, this level of precision is not consistent with the much larger uncertainties of the data. Although the results have significant uncertainties, they provide important information about the water energy resources of the United States. The magnitude of these resources has been estimated on a comprehensive scale that was not previously possible. While the magnitudes are useful engineering estimates, the greatest insight is gained by the relative magnitudes when power potentials are compared. Comparison of the magnitudes of state and regional power potentials and densities shows those areas of the country having the most abundant and concentrated water energy resources. The spatial distribution maps included in the report also provide a visual measure of the relative concentration of low power, water energy resources in the country. Comparison of developed, excluded, and available power potentials to the total power potential provides relative measures of these quantities that can be compared between areas to see the trends of past policy and development decisions and opportunities for future development. Comparison of power potential in the various power classes shows the relative abundance of water energy resources having certain hydraulic head and power characteristics, which can be used to guide future technology development.

The reader is cautioned about an important distinction that is made in the presentation of assessment results in this report. The assessment method used produced estimates of power potential as annual mean power. This parameter is not the same as hydropower capacity, which has been assessed in other assessment efforts. The difference lies in potential being based on estimates of annual mean flow rate combined with local hydraulic head to produce an estimate of annual mean power potential in the present study. In contrast, hydropower capacity is the design power capacity of a real or hypothetical hydroelectric plant. Plant design capacity is determined by anticipated flow rates, which may not be natural stream flows, economic considerations, and other factors. Because the assessment results are power potential values rather than plant capacity values, total power potential values listed in this report will appear low when compared with the results of prior assessments, which are based on owners' selections of design capacity or an economic model that selects a design capacity.

The amount of power potential that has been developed is accounted for in calculating the available power potentials presented in this report. Developed potential is a derived value based on average annual electricity generation and thus is an annual mean power value that is comparable with the power potential of water energy resources calculated using the combination of annual mean flow rate and hydraulic head. Plant capacity values are not used to account for developed power. The regional reports referred to above did not account for the distinction between developed power potential and developed capacity and simply used total developed capacity for the amount of potential that had been developed in the region. Because these larger values were used, the available power potential values in these reports are, therefore, less than comparable values listed in this report.

It is recommended that the information in this report supersede that in the prior regional reports. At the same time, it should be considered that the available power potential values listed in this report were derived by subtracting developed potential based on actual, average annual plant generation from ideal power potential. Ideal potential values do not account for plant efficiency or any aspect of plant operations. It should also be noted that the term "available" power potential only denotes an amount of potential equal to the difference between the total amount of potential and the amounts of developed potential and potential excluded from development by federal statute or policy in a specific area. "Available" does not denote any knowledge on the part of the authors of actual availability for, interest in, or intent to develop any water energy resource.

This report is organized by presenting a description of the study area, details of the assessment method that was employed to perform the assessments, results of the assessments considering the study area at large, and ends with general conclusions based on the study results and recommendations for refining the assessment. Regional assessment results are presented in Appendix A. These results were combined and segregated along state boundaries to produce assessment results by state, which are presented in Appendix B.

2. STUDY AREA ¾ TWENTY HYDROLOGIC REGIONS OF THE UNITED STATES

The United States is divided into 20 hydrologic regions as shown in Figure 1. The hydrologic regions have been numbered using a hydrologic unit code (HUC) of 1 through 20. For example, the North Atlantic Hydrologic Region has been assigned a hydrologic unit code of 1 and is sometimes referred to as "HUC 1." Eighteen hydrologic regions, HUC 1 through HUC 18, have been assigned to the conterminous United States. The remaining two hydrologic regions, HUC 19 and HUC 20, are assigned to Alaska and Hawaii, respectively. An additional region assigned to Puerto Rico, HUC 21, was not evaluated during this study. The hydrologic regions are listed by region or HUC number in Table 1.

Table 1. Hydrologic regions of the United States.

Region (HUC) No.	Name
1	North Atlantic
2	Mid-Atlantic
3	South Atlantic-Gulf
4	Great Lakes
5	Ohio
6	Tennessee
7	Upper Mississippi
8	Lower Mississippi
9	Souris Red-Rainy
10	Missouri
11	Arkansas-White-Red
12	Texas Gulf
13	Rio Grande
14	Upper Colorado
15	Lower Colorado
16	Great Basin
17	Pacific Northwest
18	California
19	Alaska
20	Hawaii
21	Puerto Rico

The conterminous United States, from east to west, consists of a coastal plain along the Atlantic, the Appalachian Mountains, a vast interior lowland, and the western Cordillera, a wide system of mountains and valleys extending to the Pacific Ocean. The Atlantic Coastal plain is narrow in the mid-Atlantic states, but gradually widens toward the south to form a broad coastal plain in the Carolinas and Georgia. Estuaries and bays form deep indentations in the coastal plain, especially Delaware Bay and Chesapeake Bay in Delaware, Maryland, and Virginia. Inland from the coastal plain, the Piedmont forms a gentle rolling upland that borders the eastern slope of the Appalachians. The Appalachian Mountains form a long southwest-northeast trending chain of mountains that extend from northern Alabama to New England. From New York southward, the Appalachians are composed of a long series of alternating ridges and valleys, created by folding and erosion of ancient rock layers. The mountains continue into New England, but the ridge and valley pattern is absent. Breaks in mountain ridges, known as "water gaps," allow several major rivers to cross part or all of this mountain chain, for example, the Connecticut River in New England, the Hudson River in New York, the Delaware River in Pennsylvania, the Susquehanna River in New York, Pennsylvania, and Maryland, and the Potomac River in Virginia, West Virginia, and Maryland.

West of the Appalachians lies a vast interior lowland that covers nearly half of the conterminous United States. It includes the drainage of the Mississippi River and its two major tributaries, the Ohio and Missouri rivers. The Mississippi River is the principal feature of this lowland, forming a major north-south waterway into the heartland of the United States. The lowland includes a wide coastal plain bordering the Gulf of Mexico, with rolling hills, river valleys, and extensive prairies lying north of the coastal plain. Dense deciduous woodlands originally covered the eastern portion of the lowland, transitioning to pine forests in the south. Further west, the woodland gives way to prairie, a

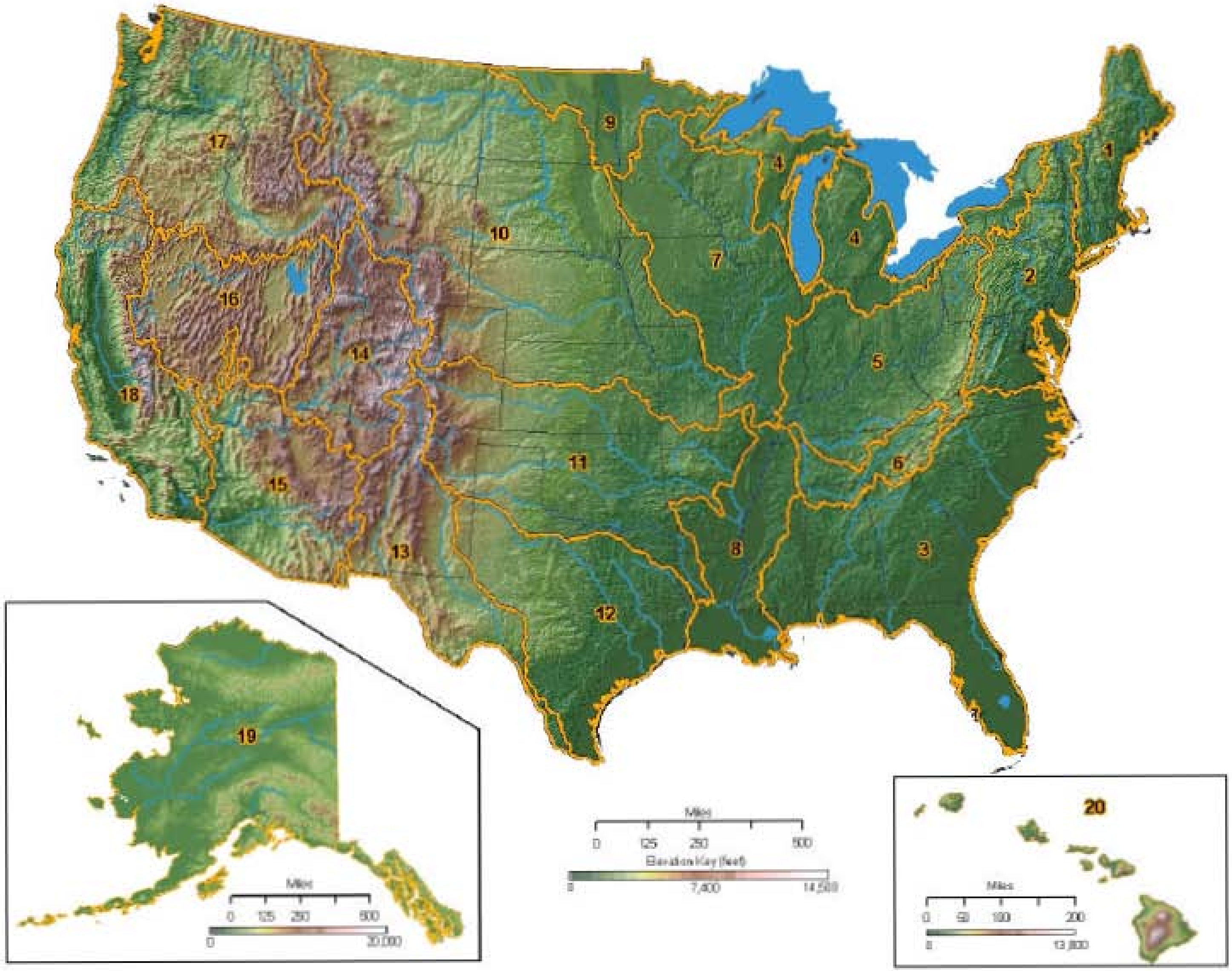

Figure 1. The 20 hydrologic regions (units) of the United States.

vast grassland mostly devoid of trees. Much of the woodland and prairie has been converted to agricultural use. The climate ranges from warm in the south to cold in the north, with precipitation decreasing toward the west.

A complex series of high mountain ranges, valleys, canyons, and plateaus create a spectacular landscape in the western United States. The Great Plains, which form the western portion of the interior lowlands, gradually rise thousands of feet in elevation to meet the abrupt eastern front of the Rocky Mountains. The Rocky Mountains are a chain of high mountain ranges extending from Mexico through the western United States into Canada. The crest of the Rocky Mountains form the continental divide. Streams east of the continental divide flow to the Atlantic Ocean, the Gulf of Mexico and Hudson Bay. Most streams west of the continental divide flow to the Pacific Ocean or to the Gulf of California. However, streams in many areas west of the continental divide discharge into saline lakes or mud flats. These streams remain within the Great Basin, a series of semi-arid to arid mountains, valleys, and plains with no outlet to the sea. More high mountains are found in the West Coast states: the Cascades in Washington and Oregon and the Sierra Nevada in California. An additional set of mountain ranges, known as the Coast Ranges, borders the Pacific coastline of these three states.

The landscape varies greatly in the West. Cool, damp rainforests cover the slopes of the Coast Ranges in the Pacific Northwest. The Cascades and the Sierra Nevada have extensive coniferous forests due to abundant Pacific moisture. However, these ranges create a rain shadow that forms dry steppes and deserts immediately to their east. The two major rivers of the West, the Columbia River and the Colorado River, have been extensively developed for hydropower. The Grand Coulee Dam in Washington and the Hoover Dam on the Nevada-Arizona border are the best known of the West's hydropower mega-projects. Interior valleys have fertile soils suitable for farming, including the Great Central Valley of California, the Willamette Valley of Oregon, and the Snake River Plain in Idaho. In many places, irrigation water from mountains or rivers is imported to water crops in arid areas. Water is also imported for hundreds of miles to supply the domestic needs of major coastal cities in California.

Alaska, the largest, northernmost, and least densely populated state, extends from temperate rainforests on the southeastern panhandle, to arctic tundra on the arid North Slope. High coastal and near-coastal mountain ranges receive abundant Pacific moisture as snow and ice to create the largest glaciated area outside of Antarctica and Greenland. Further inland, the Alaska Range reaches elevations exceeding 20,000 feet on Mt. McKinley, the highest point in North America. Approximately one-third of the state lies north of the Arctic Circle.

A large interior lowland, extending across the central portion of the state, is drained primarily by the Yukon River and its tributaries. Rivers and streams in this area are typically braided and are subject to intense season flooding due to rapid melting of snow and ice during the spring/summer thaw. The east-west trending Brooks Range lies north of this lowland. North of the Arctic Circle, the North Slope, a flat, arid plain slopes northward from the Brooks Range to the Arctic Ocean. Permafrost and tundra dominate the North Slope, home to the Arctic National Wildlife Refuge, as well as some of the United States' most productive oil fields.

Hawaii, a chain of eight volcanic islands, lies near the center of the Pacific Ocean, approximately 2,200 miles from the U.S. mainland. The island chain formed by motion of the Pacific Plate over a stationary volcanic hot spot that extrudes molten rock to create a series of volcanic islands. The islands nearest to the hot spot, Hawaii and Maui, have active volcanoes and are the largest islands in the chain. Islands further from the hot spot no longer contain active volcanoes and are generally smaller due to subsidence and erosion. Islands with northern and eastern exposures to the Pacific receive abundant moisture up to several hundred inches per year. The opposite southern and western slopes lie in a rain shadow, where arid conditions predominate. Some of the smaller islands are relatively dry because they lie entirely within the rain shadow of larger islands.

The Hawaiian Islands lack the large watersheds found on the U.S. mainland. Instead, streams on the islands generally run outward in a radial pattern from volcanic summits and mountain ridges toward the sea. The largest streams with the highest flow levels are found on the wetter northern and eastern slopes of the major islands.

3. TECHNICAL APPROACH

The fundamental approach of this study was to calculate the power producing potential of mathematical analogs of every stream reach within each of the 20 hydrologic regions in the study area. A stream reach was generally the stream segment between two confluences and had an average length of 2 miles. After producing a master set of reach power potentials, this set was validated using data from the National Hydrography Dataset (NHD). The validated version of the master dataset was filtered to account for waterways excluded from development. No other feasibility assessments were performed. Additional filtering produced subsets corresponding to various power classes; one of which was low head/low power. The low head/low power class was further filtered to produce subsets based on the operating envelopes of three classes of low head/low power hydropower technologies. Summing the resulting subsets of reach power potentials produced total power potentials of interest. Developed hydropower in the region was deducted in the process of determining "available" power potentials. (Note: The term "available power potential" in this report simply equates to total power potential minus the sum of developed power potential and excluded power potential with no assessment of economic or development feasibility.)

The calculation of reach power potential requires two values: the reach flow rate and the hydraulic head corresponding to the elevation difference between the upstream and downstream ends of the reach. The reach flow rate was the average of the calculated flow rates at the inlet and outlet of the reach. The flows were calculated using regional regression equations in which such parameters as drainage area, mean annual temperature, and mean annual precipitation are typical independent variables. The reach hydraulic head was derived from the hydrography as defined by a digital elevation model. No explicit accounting was made for stream flow energy losses, because these losses are "built in" to the flow rate regression equations considering that they are based on gauged stream flows. An explicit accounting for stream flow energy losses, which depend on flow velocity and stream bed characteristics, would require localized data that are not generally available.

The reach power potential values are annual mean power values because the flow regression equations used estimate annual mean flow rates. Use of annual mean power for power potential has the advantage of being directly convertible to ideal energy production by multiplying power values by the number of hours in a year (8,760 hr).

The subsections that follow describe the details of the various aspects of the technical approach as applied to each hydrologic region:

- Calculation of reach power potential
- Filtering processes to validate streams, account for excluded waterways, and parse potentials between power classes and classes of low head/low power hydropower technologies
- Determination of available power potential accounting for developed power potential.

It further describes how total power potential values of interest were determined for individual states and for the entire United States study area from values calculated for each of the 20 hydrologic regions.

3.1 Calculation of Stream Flow, Hydraulic Head, and Power Potential

The calculation of the stream flow rate, hydraulic head, and subsequently, power potential requires a three-dimensional representation of the hydrography and related drainage basin information. The three-dimensional hydrography provides the extent of stream networks and the elevation differences required to calculate hydraulic heads. Related drainage basin information provides essential data for the calculation of stream flow rates. While the NHD provides the best two-dimensional depiction of the United States hydrography, it does not provide the required elevation information or related drainage basin information. In order to obtain the required hydrography parameters, the Elevation Derivatives for National Applications (EDNA) dataset was used. This dataset provided the needed three-dimensional hydrography in the form of analytically derived stream networks with associated elevation values and the drainage area associated with each stream reach that could be summed to produce the drainage basin supplying runoff to points of interest along a stream.

A graphical illustration of the hydrography related information provided by the EDNA dataset is shown in Figure 2. This figure shows synthetic stream reaches each with an associated, local runoff area or catchment shown as a colored area encompassing the reach. Flow rates were calculated at the upstream and downstream ends of each synthetic stream reach. The downstream end of a synthetic reach has been termed the "pour point" for the catchment encompassing the reach. The drainage area supplying runoff to a pour point is equal to the sum of the areas of all the upstream catchments, including that of the local catchment.

3.1.1 Flow Rate Calculations for the 18 Hydrologic Regions of the Conterminous U.S.

Annual mean flow rates were calculated using regression equations developed specifically for each hydrologic region (Vogel et al. 1999). These equations are of the form:

$$Q = e^a * A^b * P^c * T^d$$

where

e = the base of natural logarithms

Q = annual mean flow rate in cubic meters/second

A = drainage basin area in square kilometers

P = mean annual precipitation in millimeters/year

T = mean annual temperature in degrees Fahrenheit times 10.

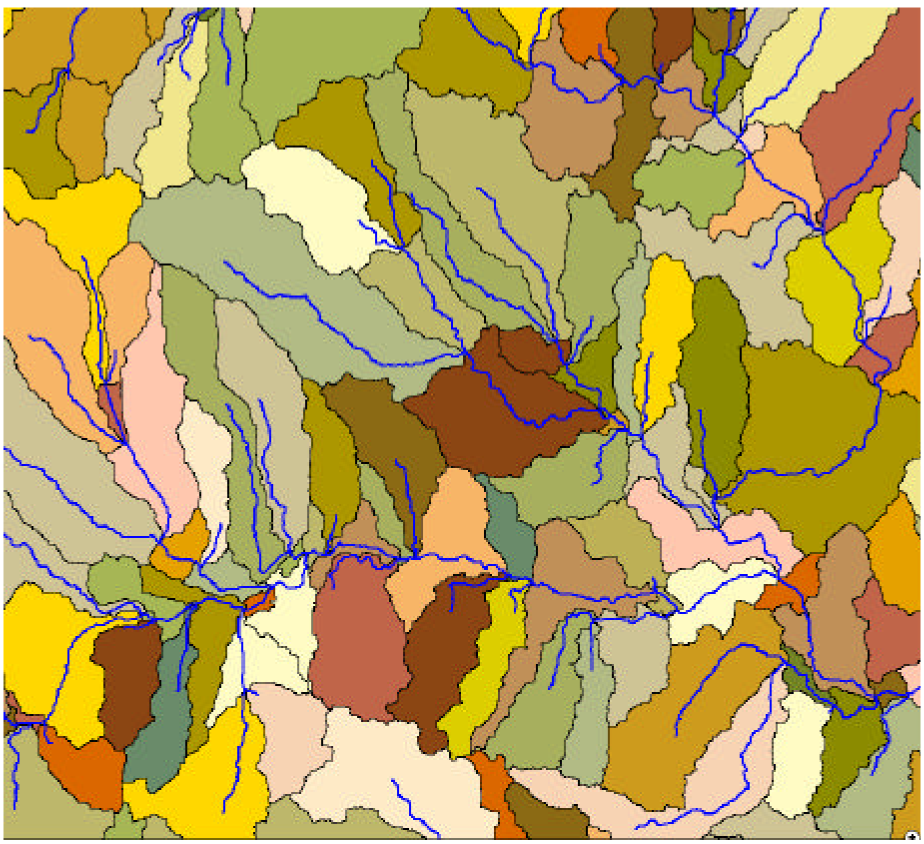

Figure 2. EDNA-derived catchments and synthetic streams.

The region-specific exponents are listed in Table 2.

These equations are based on gauged stream flows within the regions spanning many years. The drainage area used is the sum of the upstream catchment areas. The other two variables, mean annual precipitation and mean annual temperature, were derived from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (Daly et al. 1994).[a] Both temperature and precipitation data contained in the PRISM dataset are in grid format. The cells of the grids are much larger than the grid cells on which the EDNA dataset is based (30×30 m); therefore, an averaging function was used to calculate the mean annual precipitation and mean annual temperature for each catchment in the EDNA data. The catchment temperature and precipitation values were used to produce an area-weighted value for each drainage basin. Precipitation and temperature values for each drainage basin along with the drainage basin area were used to calculate the estimates of the annual mean flow rate at the upstream and downstream ends of each reach. (Note that upstream and downstream drainage basin values only differ by the contribution of the local catchment.)

3.1.2 Flow Rate Calculations for the Alaska Region[b]

Annual mean flow rates for the Alaska Region were calculated using regression equations developed specifically for the five of the six subregions of the state (Parks and Madison 1985). These equations are of the form:

$$Q = 10^a * A^b * P^c$$

where

Q = annual mean flow rate in cubic feet/second

A = drainage basin area in square miles

P = mean annual precipitation in inches/year.

The Alaska subregions are shown in Figure 3 and the exponents used in the flow rate regression equation for each subregion are listed in Table 3.

These equations are based on gauged stream flows within the subregions spanning many years. The drainage basin area used is the sum of the upstream catchment areas. The mean annual precipitation was derived from the *Environmental Atlas of Alaska* (Hartman and Johnson 1978).[c] Precipitation values were area weighed to obtain a value for each drainage basin. Precipitation values along with the drainage basin areas were used to calculate estimates of the annual mean flow rate at the upstream and the downstream end of each reach.

3.1.3 Flow Rate Calculations for the Hawaii Region[b]

Annual mean flow rate regression equations for Hawaii were taken from a USGS Open-File Report (Yamanaga 1972). These regression equations were developed using a step-wise technique that found that the variables of significance varied depending on the windward/leeward orientation of the drainage basin. Therefore, separate regressions were

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a. Portions of drainage basins within the conterminous U.S. receive flow from Canada and Mexico. Neither the EDNA nor the PRISM data extend significantly into Canada or Mexico. For these areas, the HYDRO1k data (Verdin and Jenson 1996) were used to define the drainage areas originating outside of the conterminous U.S. The Global Precipitation and Temperature Climatology database (Willmott and Matsuura 2001) was used to describe the precipitation and temperature within the Canadian and Mexican portions of the drainage areas.

b. A more detailed discussion of how flow rates and power potentials in Alaska and Hawaii were calculated is provided by K. Verdin, *Estimation of Average Annual Streamflows and Power Potential for Alaska and Hawaii*, INEEL/EXT-04-01735, to be published May 2004.

c. Portions of drainage basins within Alaska receive flow from Canada. For these areas, the HYDRO1k data (Verdin and Jenson 1996) were used to define the drainage areas originating outside of the Alaska. The Global Precipitation and Temperature Climatology database (Willmott and Matsuura 2001) was used to describe the precipitation within the Canadian portion of the drainage areas.

Table 2. Exponents for regional annual mean flow rate regression equations.

Region (HUC)	Name	Exponents			
		a	**b**	**c**	**d**
1	North Atlantic	-9.4301	1.01238	1.21308	-0.5118
2	Mid-Atlantic	-2.7070	0.97938	1.62510	-2.0510
3	South Atlantic-Gulf	-10.1020	0.98445	2.25990	-1.6070
4	Great Lakes	-5.6780	0.96519	2.28890	-2.3191
5	Ohio	-4.8910	0.99319	2.32521	-2.5093
6	Tennessee	-8.8100	0.96418	1.35810	-0.7476
7	Upper Mississippi	-11.8610	1.00209	4.55960	-3.8984
8	Lower Mississippi	0.0000	0.98399	3.15700	-4.1898
9	Souris Red-Rainy	0.0000	0.81629	6.42220	-7.6551
10	Missouri	-10.9270	0.89405	3.20000	-2.4524
11	Arkansas-White-Red	-18.6270	0.96494	3.81520	-1.9665
12	Texas Gulf	0.0000	0.84712	3.83360	-4.7145
13	Rio Grande	0.0000	0.77247	1.96360	-2.8284
14	Upper Colorado	-9.8560	0.98744	2.46900	-1.8771
15	Lower Colorado	0.0000	0.8663	2.50650	-3.4270
16	Great Basin	0.0000	0.83708	2.16720	-3.0535
17	Pacific Northwest	-10.1800	1.00269	1.86412	-1.1579
18	California	-8.4380	0.97398	1.99863	-1.5319

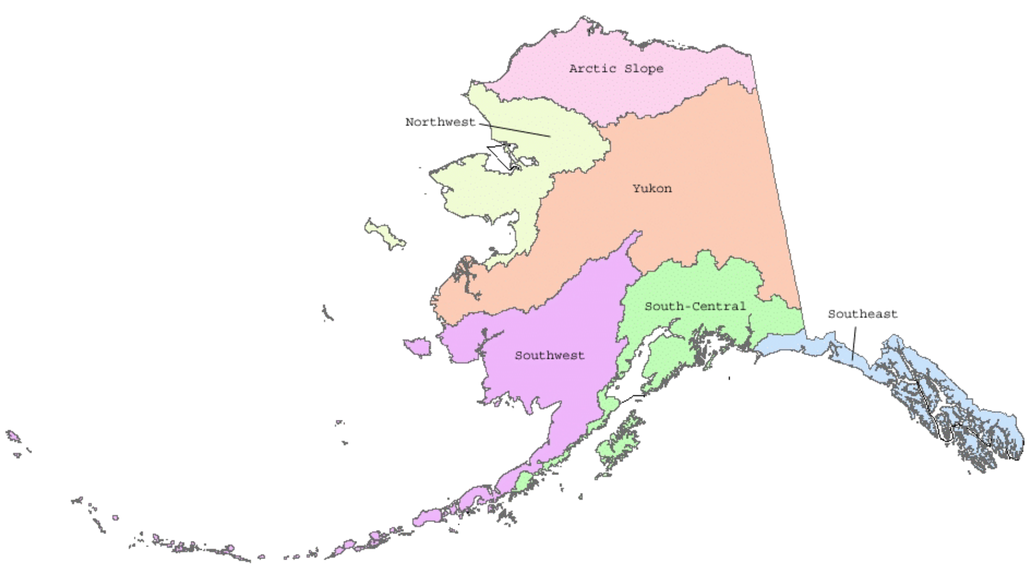


Figure 3. Alaska subregions for calculating annual mean flow rates.

Table 3. Exponents for Alaska subregion annual mean flow rate regression equations.

Subregion	Exponents		
	a	b	c
Southeast	-0.46	1.01	0.68
South-Central	-1.33	0.96	1.11
Southwest	-1.38	0.98	1.13
Yukon	-2.04	1.05	1.39
Arctic Slope and Northwest	-1.51	0.98	1.19

developed for the windward and leeward sides of the islands. For the windward areas, the significant variables were found to be drainage area, mean annual precipitation and the precipitation intensity of the 24-hour/2-year storm. The equations for the leeward areas had the same independent variables, but also included the mean elevation and the elevation range of the drainage basin. The regression equations are listed in Table 4.

Table 4. Hawaii annual mean flow rate regression equations.

	Annual Mean Flow Rate (cfs)
Windward Areas	$Q = 0.015*(A^{0.949})*(P^{0.588})*(PI^{0.850})$
Leeward Areas	$Q = 6.93E\text{-}08*(A^{0.746})*(E^{1.057}) *(R^{0.154})*(P^{2.783})*(PI^{-1.588})$

where

Q = annual mean flow rate in cubic feet/second

A = drainage basin area in square miles

P = mean annual precipitation in inches/year

PI = precipitation intensity in inches during a 24-hour period having a recurrence interval of 2 years

E = mean drainage basin elevation in feet

R = difference between minimum and maximum elevations occurring in the drainage basin in feet.

Mean annual precipitation was determined for Hawaii from the PRISM dataset (Daly et al. 1994). Precipitation intensity values were obtained from a National Weather Service isohyetal map (National Weather Service 1962). Mean drainage basin elevation was calculated using an area weighted average of the centroid elevations of each catchment in the drainage basin. The basin elevation range (R) was calculated by subtracting the elevation of the pour point node (lowest elevation in the drainage basin) from the maximum elevation occurring in the basin.

3.1.4 Calculation of Power Potential

The power producing potential (power potential) of a stream reach was calculated using the hydraulic head and estimated annual mean flow rates at the inlet and outlet of the reach. The hydraulic head associated with each stream reach was obtained using the elevation data in the EDNA dataset. The dataset provided the elevation at the upstream and downstream ends of the reach. The difference of these two elevation values was the hydraulic head for the flow in the reach. While this was the correct value for the flow that entered the reach at the upstream end and transited the reach converting potential to kinetic energy, it was not the correct value for the portion of the flow at the reach exit or downstream end that was contributed by runoff from the local catchment. This added flow had hydraulic heads varying from the total reach hydraulic head to zero depending on where the runoff entered the stream. To account for this, the following equation was used to calculate the power potential of the reach:

$$P = \kappa\,[Q_i * H + (Q_o - Q_i) * H/2];\; H = z_i - z_o$$

where

P = power in kilowatts

κ = equals (1/11.8)

Q_i = flow rate at the upstream end of the stream reach in cubic feet per second

Q_o = flow rate at the downstream end of the stream reach in cubic feet per second

H = hydraulic head in feet

z_i = elevation at the upstream end of the stream reach in feet

z_o = elevation at the downstream end of the stream reach in feet.

The first quantity in the square brackets, $Q_i * H$, is the power potential of the flow that enters and transits the entire reach. This flow experiences the full hydraulic head of the reach, H (difference between elevations at upstream and downstream ends of the reach). The quantity (Q_o-Q_i) is the part of the reach flow added by runoff from the associated catchment. For this flow, the hydraulic head varies from H to 0 depending on where runoff entered the reach. Therefore, an average value of H/2 was used for the local catchment runoff flow.

Algebraic manipulation shows that this equation reduces to:

$$P = \kappa H(Q_i+Q_o)/2$$

Thus, the reach power potential is equal to a constant times the total reach hydraulic head times the average of the flow rates at the inlet (upstream end) and the outlet (downstream end) of the reach.

The calculations described above produced a master dataset containing the following parameters for each stream reach:

- Reach characteristics
- Related catchment characteristics
- Reach outlet flow (catchment pour point flow)
- Reach hydraulic head
- Reach power potential.

This master dataset was subsequently filtered to:

1. Remove stream reaches that were not validated using the NHD
2. Identify reaches that were excluded from development because of statutory protections
3. Identify reaches having power potentials within various power classes
4. Divide low head/low power reaches into three subsets corresponding to the operating envelopes of three classes of low head/low power hydropower technologies.

These filtering operations are described in detail in the subsections that follow.

The accuracy of the power potential estimates is dependent on the accuracy of the individual stream reach power potentials that were summed to produce total values of interest. The calculated reach flow rates had standard errors ranging from ±9% to ±96%. These errors reflect sampling and measurement errors, but do not address annual flow variability (i.e., the difference between predicted annual mean flow rate and the actual mean annual rate in a specific year). The standard errors of the calculated flows for each hydrologic region in the conterminous U.S. are given in Table 5.

Standard errors of the estimated flow rates for each subregion of Alaska and Hawaii taken from the source documents for the flow rate regression equations are given in Tables 6 and 7, respectively.

The root mean square error of the elevation data that was used to determine the hydraulic head of each stream reach is ±3 m (Gesch 2003). This uncertainty in elevation is for a random discrete location. The uncertainty of the difference between two elevations in near proximity (hydraulic head) is believed by U.S. Geological Survey analysts to be much better than the elevation uncertainty for an individual location.

Because of the direct relationship of power potential and flow rate, the standard error of the reach power potential values was also at least ±9% to ±96%. The uncertainty of the calculated hydraulic head values further increases the uncertainty of the power potential values. However, if the errors are uniformly distributed, the accuracy of a total value produced by summing a large number of reach power potentials will be better than the accuracy associated with the individual values that were summed.

Table 5. Standard errors of calculated flow rates in percent by hydrologic region.

Region (HUC)	Name	Mean Std Error (%)
1	North Atlantic	9
2	Mid-Atlantic	12
3	South Atlantic-Gulf	17
4	Great Lakes	16
5	Ohio	12
6	Tennessee	14
7	Upper Mississippi	14
8	Lower Mississippi	15
9	Souris Red-Rainy	37
10	Missouri	63
11	Arkansas-White-Red	31
12	Texas Gulf	61
13	Rio Grande	55
14	Upper Colorado	44
15	Lower Colorado	96
16	Great Basin	53
17	Pacific Northwest	36
18	California	51

Table 6. Standard errors of calculated flow rates in percent for Alaska subregions.

Alaska Subregion	Mean Standard Error (±%)
Southeast	14
South-Central	16
Southwest	15
Yukon	10
Arctic Slope and Northwest	15

Table 7. Standard errors of calculated flow rates in percent for Hawaii subregions.

Hawaii Subregion	Mean Standard Error (±%)
Windward Areas	34
Leeward Areas	28

3.2 Validation of Synthetic Streams

The U.S. Geological Survey performed the processing that produced the Stage 1B version of the EDNA dataset in a consistent manner nationwide. It generally works well for areas having moderate to high relief and well-developed drainage. In certain types of terrain, however, the EDNA Stage 1B processing can create synthetic hydrography that deviates substantially from the actual hydrography.

Figure 4 shows an overlay of EDNA synthetic streams and hydrography taken from the NHD for a small part of the study area. It is clear from this comparison that some of the synthetic stream reaches are not validated by the NHD and must be removed so as not to inflate the total power potential estimate. To identify these “false” synthetic stream reaches and determine their effect on the regional, total power potential, known stream locations found in the NHD were intersected with the catchments associated with EDNA synthetic streams. This allowed the stream reaches in the master dataset to be coded effectively, creating two subsets: one containing all the reaches whose catchments contained an NHD stream segment and one containing all the reaches whose catchments did not contain an NHD stream segment. The former was considered to be a validated master dataset, while the latter was a dataset containing all the “false” stream reaches. Figure 4 illustrates false stream reaches, which show through in red in contrast to the NHD reaches shown in blue. While this approach did not guarantee exact conflation of the EDNA synthetic streams with the NHD hydrography, it did ensure that an NHD stream segment existed within the catchment area, averaging 3 square miles, that encompasses the synthetic reach.

In order to evaluate the effect of the “false” stream reaches on total power potential, the power potentials of the reaches in the false reach dataset were summed and compared to the sum of the power potentials of all the stream reaches in the master dataset. It was found that 2.7% of the total potential power calculated for the conterminous United States using all the stream reaches is

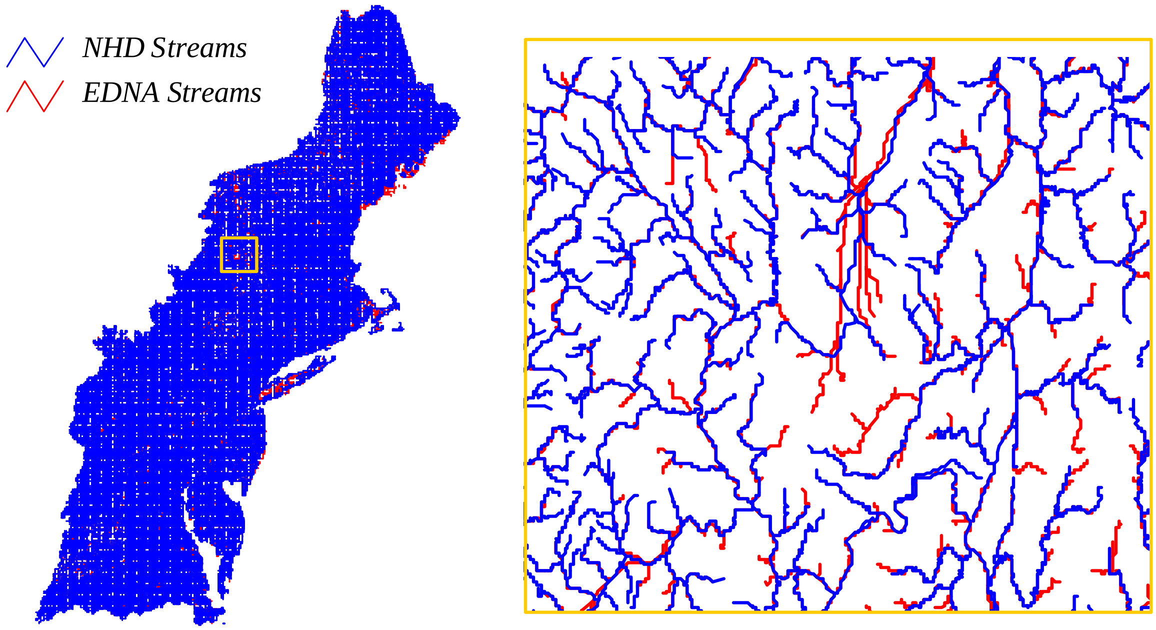


Figure 4. NHD streams overlaying EDNA synthetic streams in the study area.

associated with false stream segments, leaving 97.3% of the original total power potential in the validated master dataset for the majority of the country. The power potential associated with false stream segments in Hawaii was 36%. This large value is indicative of storm runoff channels that do not contain sustained stream flows.

Because the NHD does not cover all of Alaska and there are significant glaciated areas in the state, the process of accounting for energy resources that were not real had to be modified and extended. The Alaska dataset stream reach data were so large that the state was divided into northern and southern parts along the southern boundary of the Yukon subregion as shown in Figure 5. The same process was applied to each of these sub-datasets.

The stream reach data was intersected with a geographic information system (GIS) data layer, which is part of the NHD, that contains all the glaciated areas in the state. Stream reaches falling within glaciated areas were eliminated as potential sources of energy. Statewide, this amounted to approximately 60,000 MW of potential power. For stream reaches outside of glaciated areas, but covered by the NHD, false stream reaches were identified as described above for the rest of the country. Since collectively, there was a large area that was not covered by the NHD, it was necessary to account for the probable presence of false streams in this area. It was found that the total power potential of all the false stream reaches in the northern sub-dataset that fell within the area covered by the NHD and not in glaciated areas was 2% of the total power potential in this area. The same process applied to the southern sub-dataset resulted in a percentage reduction of 3%. Based on these results, stream reach power potentials in the northern and southern sub-datasets that were not in glaciated areas were summed to produce total power potential values in the various power classes. These values were each reduced by 3% to account for the presence of false stream reaches.

3.3 Identification of Stream Reaches Excluded from Hydropower Development

As a general rule, hydropower development is prohibited in certain protected areas, such as national parks, national monuments, or along federally designated wild and scenic rivers. Protected areas

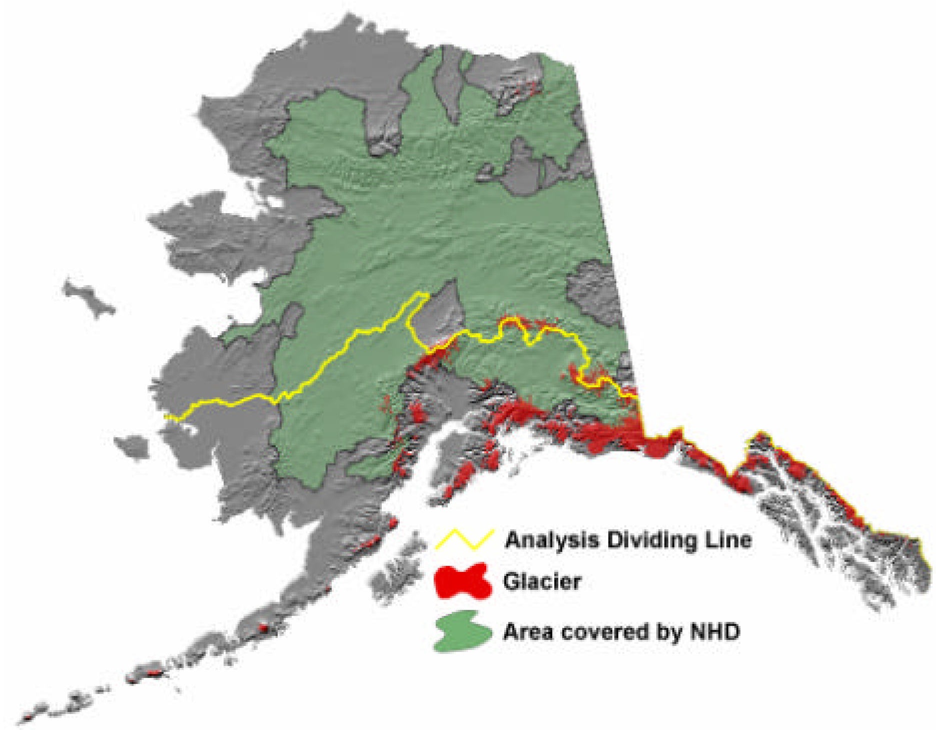


Figure 5. Map of Alaska showing dividing line between north and south sub-datasets, glaciated areas, and area covered by the National Hydrography Dataset.

such as these were designated as "exclusion areas." Catchments that overlap any portion of these "exclusion areas" were designated as "excluded catchments." The total power potential associated with the stream reaches in these excluded catchments was calculated and was subsequently subtracted from the total power potential, so that it would not contribute to available power potential.

3.3.1 Types of Excluded Areas

Two GIS data layers from the National Atlas of the United States were used to locate exclusion areas. The first layer, "Federal and Indian Lands," contains the boundaries of all federal lands in the United States, subdivided into categories such as national parks, national monuments, Indian reservations, military bases, and DOE sites. The second layer, "Parkways and Scenic Rivers," contains federally protected linear features such as National Wild and Scenic Rivers and National Parkways. Both GIS data layers are available online from the National Atlas of the United States website at *http://www.nationalatlas.gov/atlasftp.html*.

The two above-mentioned GIS data layers provide comprehensive nationwide information regarding federally protected lands. States, regional jurisdictions, and local jurisdictions have also designated protected areas that are most likely excluded from hydropower development. However, information regarding these protected areas is scattered among numerous state, regional, and local government agencies. Much of this information is not yet in digital format, and much of the digital data are not available online.

Determining the boundaries of lands protected by nonfederal agencies would have entailed contacting a large number of agencies within the study area and collecting and digitizing multiple paper datasets in a variety of formats. Such an effort was beyond the scope of the project. Therefore, only nationwide datasets of federally protected lands and rivers were used to determine the extent of exclusion areas.

The categories of federal lands listed in the GIS dataset "Federal and Indian Lands" were reviewed to determine categories corresponding to areas in which hydropower development is highly likely to be excluded. Based on this review, the following categories of federal lands were selected as exclusion areas:

- National battlefields
- National historic parks
- National parks
- National parkways
- National monuments
- National preserves
- National wildlife refuges
- Wildlife management areas
- National wilderness areas.

All the federal lands in these categories were used to create an "excluded federal lands" GIS data layer. Similarly, all national wild and scenic rivers were extracted from the National Wild and Scenic Rivers and National Parkways data layer to create a GIS data layer composed exclusively of Wild and Scenic Rivers. Because the "wild and scenic rivers data layer" contained only the rivers themselves, but no adjoining land, all land within one kilometer of a wild and scenic river reach was designated as an excluded area. These areas were combined with excluded federal lands to create a final "excluded area" GIS data layer that contains the boundaries of all lands and shorelines excluded from hydropower development.

3.3.2 Methodology for Identifying Excluded Stream Reaches

The final excluded area data layer was intersected with the catchment data layer of the master dataset to identify catchments containing stream reaches that should be excluded from consideration as sources of potential hydropower. The stream reaches in the master dataset were thus coded as being either excluded or not excluded from hydropower development.

3.4 Determining Developed Power Potential

Determining the amount of power potential within a study area that is possibly available for development requires estimating how much power potential in the area has already been developed. Use of total developed hydropower capacity within the study area as provided by the FERC's *Hydroelectric Power Resources Assessment (HPRA) Database* (FERC 1998) significantly overestimates the developed potential. Plant capacities are selected by the designer based on anticipated flow rates, which may not be natural stream flows; economic considerations; and other factors. Power capacity may be a factor of two or more higher than the average power based on average flow rate and hydraulic head where the plant is located.

In order to produce an estimate of the developed power potential that is comparable to the potential estimates based on annual mean flow rates, it was necessary to estimate the average rate at which energy was generated by each hydroelectric plant and by the aggregate of plants in the region. An estimate of this value is obtained by dividing the average annual generation of the plant or plants as listed in the HPRA Database by the total hours in a year (8,760 hr). Table 8 lists the total developed power potential (average annual mean power) for each of the 20 hydrologic regions along with the total average annual electric generation from which it was derived, the total regional hydropower capacity, and the number of plants in the region as provided by the 1998 version of the HPRA Database.

A dataset containing developed power potential corresponding to each plant and the plant's geographic coordinates from the HPRA Database was intersected with two GIS layers. The first intersection was with the exclusion area layer described in Subsection 3.3. This allowed each of the developed potentials to be coded as to whether it was inside or outside an exclusion area. The total developed power potential corresponding to plants located in exclusion areas was subsequently subtracted from the total power potential located

Table 8. Developed power potential by hydrologic region.

Region (HUC)	Name	Average Annual Mean Power (Developed Potential) (MW)	Average Annual Generation (MWh)	Developed Capacity (MW)	Number of Plants
1	North Atlantic	873	7,648,300	1,881	397
2	Mid-Atlantic	840	7,359,758	2,060	206
3	South Atlantic-Gulf	1,849	16,195,298	6,743	165
4	Great Lakes	2,852	24,986,998	4,092	288
5	Ohio	820	7,182,482	1,772	48
6	Tennessee	1,859	16,282,814	3,855	55
7	Upper Mississippi	404	3,540,641	734	119
8	Lower Mississippi	136	1,192,680	398	6
9	Souris Red-Rainy	13	110,058	22	8
10	Missouri	1,797	15,743,664	3,722	80
11	Arkansas-White-Red	696	6,100,625	2,097	33
12	Texas Gulf	127	1,115,557	428	23
13	Rio Grande	50	441,821	157	7
14	Upper Colorado	724	6,339,303	1,882	41
15	Lower Colorado	789	6,911,489	2,556	23
16	Great Basin	97	853,413	228	81
17	Pacific Northwest	16,645	145,811,168	32,365	339
18	California	4,668	40,892,958	9,450	413
19	Alaska	171	1,500,596	392	40
20	Hawaii	20	173,300	38	16
	Totals	**35,432**	**310,382,923**	**74,872**	**2,388**

in exclusion areas to avoid double counting as discussed in Subsection 3.6.3. The second intersection was with the GIS layer containing the state boundaries. This allowed each of the developed power potentials to be coded with the state name in which it is located. Standard database query techniques were used to parse the developed power potentials into power and technology classes and calculate totals for each class. The power classes and how the various totals of developed power potential were used to produce power potential totals of interest are described in the next subsection.

While the approach used to estimate developed power potential produces values that are comparable to the estimated values of total power potential, the values are recognized not to be perfectly comparable. The electricity generation figures on which the developed potential values are based are actual, average annual generation values rather than ideal values like the total power potential estimates. The actual values are less than ideal because of plant efficiency and outages. However, using average annual generation to estimate developed potential is significantly better than using developed capacity figures; although, it leads to nonconservative values of available potential.

3.5 Identification of Stream Reaches by Power and Technology Class

Stream reaches in the validated master dataset described in Subsection 3.2 with exclusion coding as described in Subsection 3.3 were filtered into three basic power classes and the operating envelopes of three classes of low head/low power technologies using standard database query techniques with power and hydraulic head as the selection criteria. The three basic power classes are:

- High head/high power
- Low head/high power
- High head/low power

where high power refers to ≥1 MW, low power refers to <1 MW, high head refers to ≥30 ft, and low head refers to <30 ft.

The boundary between the high power and low power classes defined by hydraulic head and flow rate is shown graphically in Figure 6.

The low head/low power class is defined by the following two criteria:

- All power potential less than 100 kW (microhydro)
- Power potential greater than or equal to 100 kW but less than 1 MW with hydraulic head less than 30 ft.

The low head/low power class shown in Figure 6 is divided into the operating envelopes of three classes of low head/low power technologies:

- Microhydro technologies—Power less than 100 kW
- Conventional turbines—Power greater than or equal to 100 kW, but less than 1 MW AND hydraulic head less than 30 ft, but greater than or equal to 8 ft
- Unconventional systems—Power greater than or equal to100 kW, but less than 1 MW AND hydraulic head less than 8 ft.

These operating envelopes are shown graphically in Figure 7.

3.6 Calculation of Total Power Potentials of Interest

Regional power potential totals of interest were calculated by summing the reach power

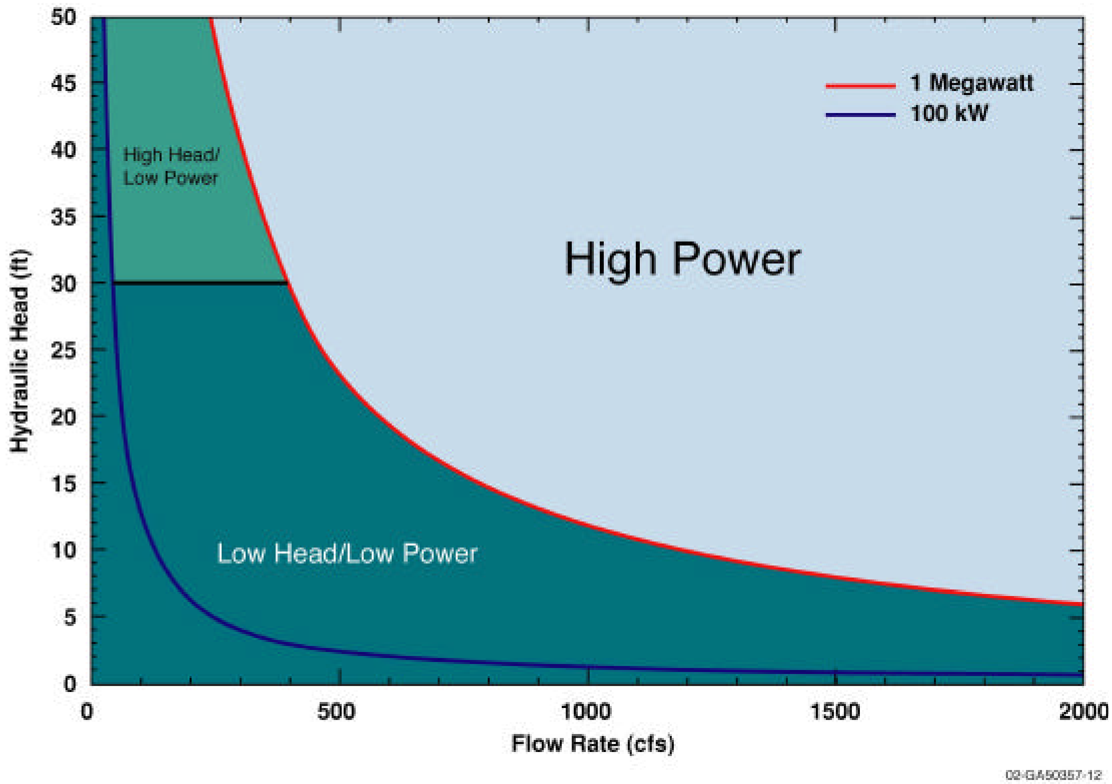


Figure 6. Boundaries of the high power and low power classes.

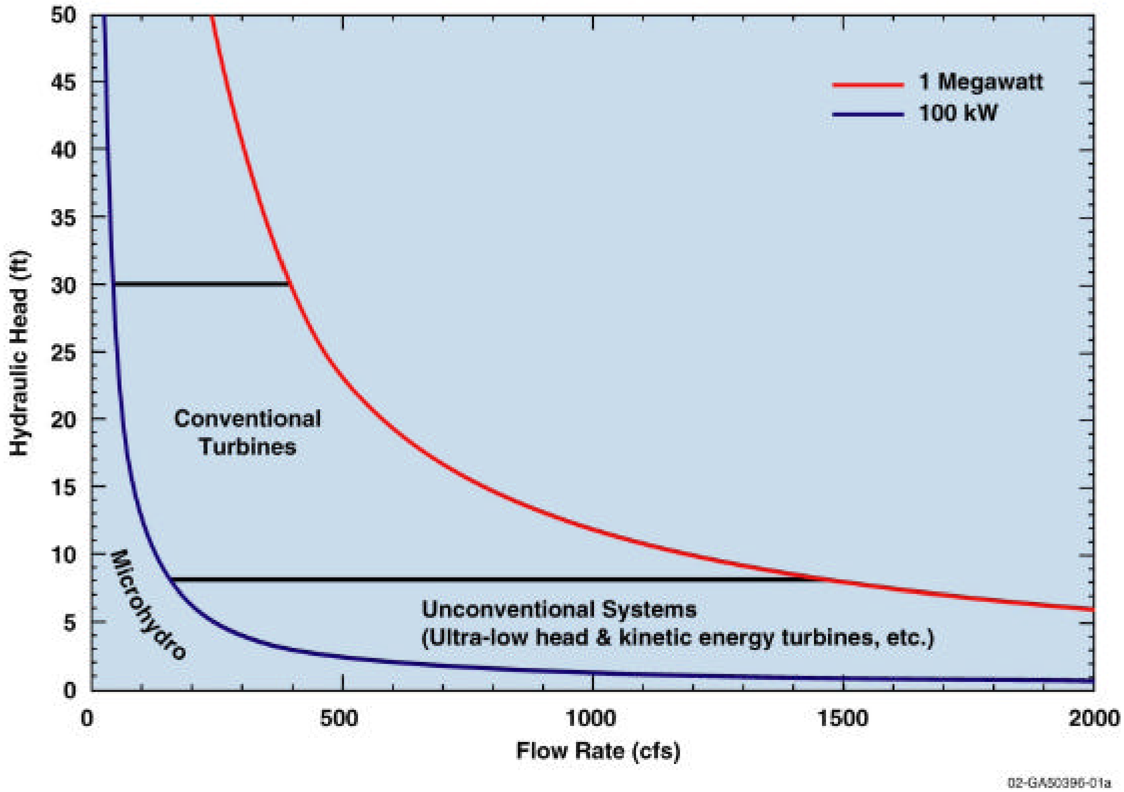


Figure 7. Operating envelopes of three classes of low head/low power hydropower technologies.

potentials within each of the three basic power classes and the three operating envelopes described in the previous subsection. Two sums were obtained for each: one using the stream reaches that were coded as excluded and one for the stream reaches coded as nonexcluded. These totals of power potential and regional developed power potential determined as described in Subsection 3.4 were used to determine total power potential in four power categories (total, developed, excluded, and available) for each of seven power classes and the three low head/low power hydropower technology classes as described below.

3.6.1 Total Power Potential

The total power potential for each of the three basic power classes and the three technology classes described in the previous subsection were calculated by adding the excluded and nonexcluded power potential totals for each power and technology class. The total power potential for four additional power classes (low head/low power, low power, high power, and total power) were obtained by rolling up constituent parts as follows:

Low Head/Low Power = ΣTechnology Classes

Low Power = High Head/Low Power + Low Head/Low Power

High Power = High Head/High Power + Low Head/High Power

Total Power = High Power + Low Power.

3.6.2 Total Developed Power Potential

Total developed power potential for each power and technology class was determined by querying the dataset of developed power potentials using annual mean power and hydraulic head selection criteria corresponding to the boundaries of the various power and technology classes. Summing the selected data produced the values for each class.

For one hydrologic region (Great Lakes [HUC 4]) and six states (Florida, Iowa, Nebraska, Nevada, North Dakota, and South Dakota), it was found that the sum of developed and excluded power potentials exceeded the total power potential in the high head/high power power class resulting in a negative value in the available power potential category in this power class. This is thought to have occurred because the developed power is actually generated using resources that are in other power classes, e.g., where a reservoir overlays resources other than those in the high head/high power class.

In order to correct these anomalies, the amount of developed power in the high head/high power class exceeding the difference between the total high head/high power power potential and the sum of the developed and excluded power potentials in this power class was "rolled down" into lower power classes. In the cases of Florida, Iowa, and Nebraska, the "excess" developed power was simply moved to the low head/high power class. If the excess developed power could not all be moved into the low head/high power class without creating a negative available power potential value, the developed power in this class was raised to the maximum value resulting in a zero available power for this class. The balance of the excess developed power was moved to the low power classes. In the cases where the region or state had developed power in the low power power classes (Great Lakes Region and Nevada), the balance of the excess developed power was apportioned to the low power classes by the amount of developed power that was originally assigned to them. In the cases of North and South Dakota where there was no developed power in the low power class, the excess developed power was rolled down into the low power classes by the maximum amount they could absorb without creating a negative value for available power potential in the power class. Data values affected by developed power redistribution are shown in yellow font on a green background in the data tables in this report.

Misdistribution of developed power among the power classes probably exists for other hydrologic regions and states, but is not detectable. This occurs because developed power is assigned to power classes solely based on the annual mean power and hydraulic head of the plant. It was beyond the scope of this study (and may not be possible) to correlate developed power with the exact corresponding resources in the various power classes that produced the developed power. However in general, we believe that there is a reasonable correlation between the power class of developed power as defined by plant annual mean power and hydraulic head and the resources in that power class.

3.6.3 Total Excluded Power Potential

Total excluded power potential in each power class was determined using the same process as described for total power potential in Subsection 3.6.1 except in this case only the sums of excluded stream reach power potentials were used. In order to avoid double counting, the total of the developed power potentials for each of the three basic power classes and three technology classes that are located in exclusion areas were subtracted from the total excluded power potential for each power/technology class.

In the case of two states, Nevada and South Dakota, the amount of developed power in exclusion zones exceeded the total excluded power potential in the high head/high power class. This may again be the result of the inability to resolve the exact power class of the resources that are producing the developed power in exclusion zones. Some of the developed power sited in exclusion zones that has been classed as all high head/high power may in fact be made up of a combination of resources in more than one power class. In order to address these anomalies, we reasoned that all the power potential in exclusion zones for this power class has been developed. Thus the excluded power potential for high head/high power class was set equal to zero. Data values affected by adjustments in excluded power potential are shown in yellow font on a green background in the data tables in this report.

3.6.4 Total Available Power Potential

The total available power potential in each power class and for each technology class was calculated using the total, developed, and excluded power potentials for the power or technology class using the equation:

$$AHP = THP - DHP - EHP$$

where

AHP = available power potential

THP = total power potential

DHP = developed power potential

EHP = excluded power potential.

3.7 Total Power Potentials for Each State

Total power potentials like those determined for each hydrologic region were produced for each of the 48 states in the conterminous United States. In order to obtain values for the states, a GIS layer containing the state boundaries was intersected with the validated master dataset of stream reaches. This allowed the stream reaches to be coded by the state in which they are located. The database queries and summing described in Subsections 3.5 and 3.6 were performed using the state name as an additional selection criterion. Because the Alaska and Hawaii hydrologic regions coincide with the states themselves, no additional processing was required to determine values for these states.

3.8 Total Power Potentials for the United States

The United States total power potentials for the various power and technology classes in the four power categories were calculated by summing the corresponding state values. The state rather than regional values were used for two reasons. First, the state boundaries were more precise in defining the boundaries of the United States. Second, because the states were smaller areas than the regions, the state data surfaced anomalies that were addressed as described in Subsections 3.6.2 and 3.6.3. This resulted in more correct values in the various power classes.

4. RESULTS

The results of the assessment process described in the previous section are presented with emphasis on four power classes:

- Total power
- High head/low power
- Low head/low power
- Low head/low power by technology

and the three classes of low head/low power hydropower technologies.

Table 9 presents a summary of the results for the United States. These results are discussed in the subsections that follow.

4.1 Total Power Potential

The sum of all the validated reach power potentials in all 20 regions and the corresponding 50 states provided an estimate of 289,741 MW of total annual mean power potential in the United States. The developed power potential corresponding to the 2,388 hydroelectric plants in the study area totals 35,429 MW of annual mean power. The sum of the power potentials of stream reaches excluded from development by federal statutes and policies is 88,761 MW of annual mean power. Subtracting the developed and excluded power potentials from the total provides an estimate of 165,551 MW of annual mean power that is available power potential because it has not been developed and is not excluded from development.

These power potential values have significant uncertainties because of the uncertainties associated with the flow rate estimates and nonconformances between the synthetic and the actual hydrography. However, they represent more comprehensive, order of magnitude estimates than have previously been achieved. Additional exclusions by state agencies that were beyond the scope of the project to research would most certainly reduce the amount of available power potential. The number would no doubt be further significantly reduced based on engineering and economic feasibility assessments of specific sites, which were not performed.

The distribution of total power potential between developed, excluded, and available power is shown graphically in Figure 8. This figure

Table 9. Summary of results of water energy resource assessment of the United States.

Annual Mean Power (MW)	Total	Developed	Excluded	Available[a]
TOTAL POWER	**289,741**	**35,429**	**88,761**	**165,551**
TOTAL HIGH POWER	**229,794**	**34,596**	**76,864**	**118,334**
High Head/High Power	**157,772**	**33,423**	**55,464**	**68,885**
Low Head/High Power	**72,022**	**1,173**	**21,400**	**49,449**
TOTAL LOW POWER	**59,947**	**833**	**11,897**	**47,217**
High Head/Low Power	**35,403**	**373**	**9,163**	**25,868**
Low Head/Low Power	**24,544**	**461**	**2,734**	**21,350**
Conventional Turbine	8,470	319	899	7,253
Unconventional Systems	3,932	43	527	3,362
Microhydro	12,142	99	1,308	10,735

a. No feasibility or availability assessments have been performed. "Available" only indicates net potential after subtracting developed and excluded potentials from total potential.

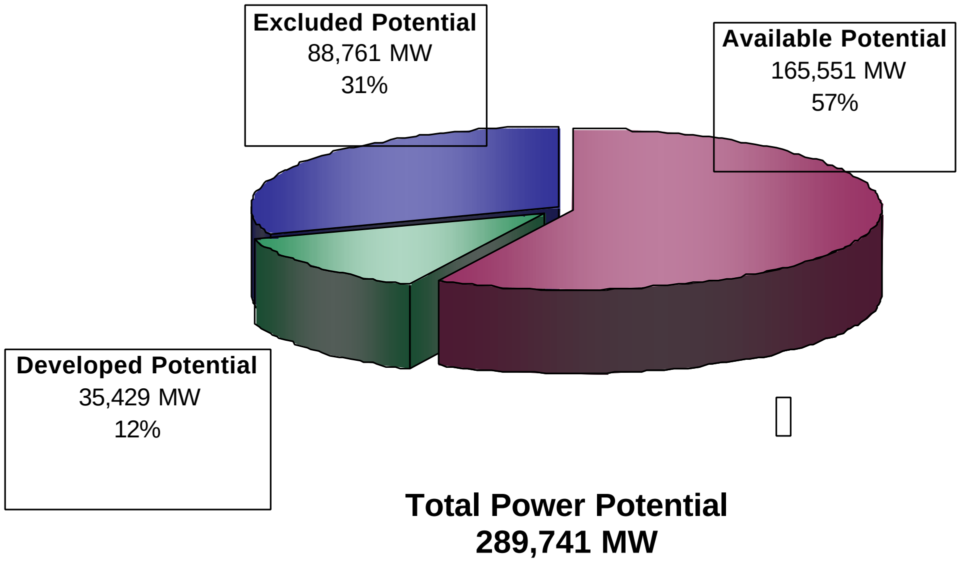


Figure 8. Power category distribution of the total potential (annual mean power) of United States water energy resources.

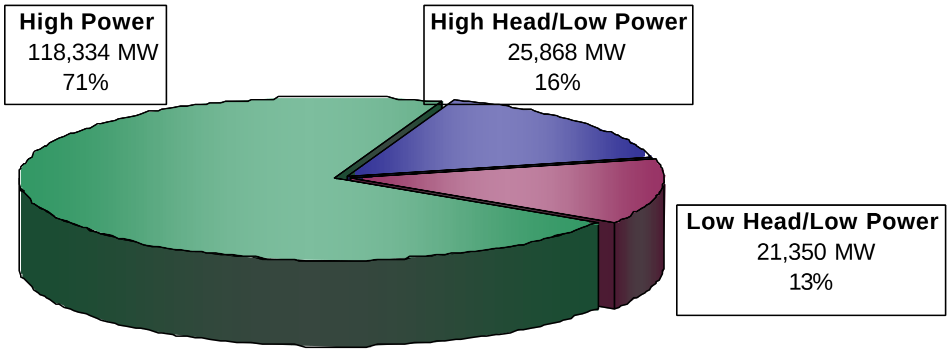
shows that only 12% of the total power potential has been developed. The power potential excluded by federal statutes and policies is 31%, leaving 57% of the potential in the United States available for possible development.

4.2 Available Power Potential

The division of the total available annual mean power potential (≈170,000 MW) between the high power (greater than or equal to 1 MW), high head/low power (power less than 1 MW and hydraulic head of 30 ft or more, excluding the microhydro operating envelope), and low head/low power (power less than 1 MW and hydraulic head less than 30 ft and including the microhydro operating envelope) is shown graphically in Figure 9. This figure shows that slightly more than 70% of the available power potential is in the high power class (120,000 MW) and slightly less than 30% is in the low power class (≈50,000 MW). The available power potential in the low power class is split roughly equally between high head (30 ft or greater) potential (15% of the available potential) and low head (less than 30 ft) potential (12% of the available potential). Considering the amount of available power potential in the high power and high head/low power classes and that in the conventional turbines technology class (discussed in Subsection 4.3) shows that 90% of the available power potential could be captured by conventional turbine technology and not require additional turbine research and development. However, deployment of the existing turbine technology to capture particularly the low power portion of the potential will likely require research and development of new system configurations.

4.3 Low Head/Low Power Potential

The sum of all the validated reach power potentials having values that fell within the low head/low power class shown in Figure 4 provided an estimate of approximately 25,000 MW of low head/low power annual mean power potential in the study area. The developed power potential that fell within the low head/low power regime amounts to 461 MW. The sum of the power potentials of the reaches that were both low head/low power and were excluded from development was approximately 2,700 MW. Subtracting the developed and excluded power potentials from the total low head/low power potential provides an estimate of about 21,000 MW



Total Available Potential
165,551 MW

Figure 9. Power class distribution of the available power potential (annual mean power) of United States water energy resources.

of low head/low power power potential that has not been developed and is not excluded from development. As mentioned in the previous subsection, this figure would be reduced by exclusions by state agencies and elimination of sites as the result of feasibility assessments.

The validated reach power potentials that have values that fall within each of the operating envelopes of the three classes of low head/low power hydropower technologies shown in Figure 7 were summed to provide an estimate of the annual mean power potential associated with each technology class. This resulted in estimates of 7,263 MW, 3,360 MW, and 10,770 MW of power potential for conventional turbines, unconventional systems, and microhydro technologies, respectively. The total power potentials that were either developed or excluded from development and corresponded to each of the operating envelopes were 1,223 MW, 568 MW, and 1,419 MW, respectively. Subtracting the developed and excluded potentials from the total potential for each technology class resulted in estimates of available power potential of 7,263 MW, 3,360 MW, and 10,770 MW, respectively. These availability estimates will be reduced because of exclusions by state agencies and feasibility assessments. However, it should be considered that portions of high power resources may be diverted to or be partially captured by low power technologies. The possibility of such diversion or partial capture means that the available power potentials for the three low head/low power technology classes are probably higher than the values given above, which were obtained considering only resources having power potentials that fell within the operating envelopes of these technology classes.

The distribution of low head/low power annual mean power potential among the three classes of technologies is shown in Figure 10. This figure shows that 34% of the available low head/low power power potential is captured by the operating envelope of conventional turbines. Half (50%) is captured by the operating envelope of microhydro technologies. The remaining 16% corresponds to unconventional systems.

The geographic locations of existing hydroelectric plants and high head/low power power potential sites in the conterminous United States are shown in Figure 11. Similarly, the geographic locations of low head/low power power potential sites in the conterminous United States are shown in Figure 12. In this figure, different color symbols are used to designate sites of power potential corresponding to each of the three classes of low head/low power technologies. Areas in which hydropower development is excluded because of federal statutes and policies are shown in both maps. The same type of information is

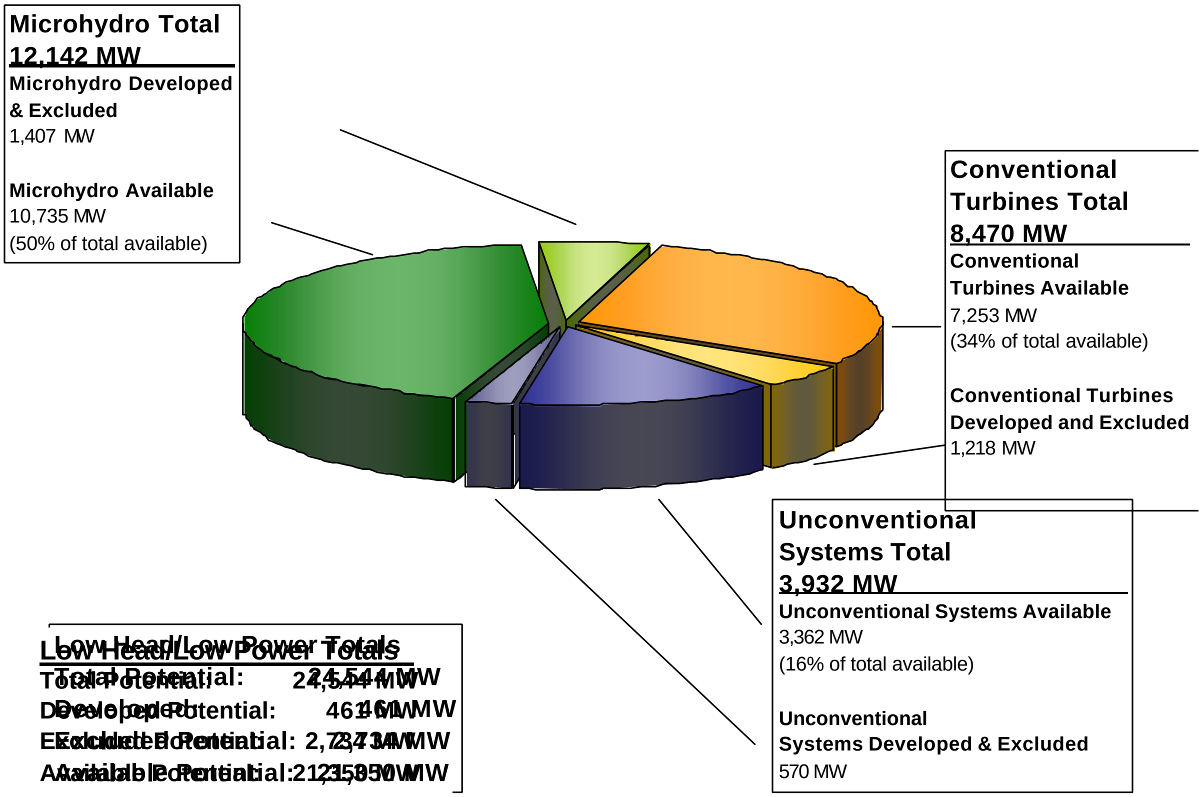


Figure 10. Distribution of the low head/low power power potential (annual mean power) of United States water energy resources among three low head/low hydropower technology classes.

shown in Figures 13 and 14 for Alaska and in Figure 15 for Hawaii. The maps are intended to show the relative density of power potential. The symbols are larger than the actual extent of the stream reach containing the potential they designate, so that the density of symbols gives a distorted image of the actual density of the stream reaches.

High head/low power potential is abundant in the mountainous areas of the country as shown in Figures 11, 13, and 15. Conventional turbine and unconventional systems sites are numerous and well dispersed in the eastern half and northern Pacific coast of the conterminous United States and throughout Alaska as shown in Figures 12, 14, and 15. These figures also show that microhydro sites are density distributed except in the central plains and other areas that have very small variations in elevation, the most arid parts of the conterminous United States, and generally in areas dominated by resources in other power and technology classes.

Because over 90% of Hawaii's available power potential is in the high power class, low power sites are not numerous as shown in Figure 15. High head/low power sites occur mainly at the lower elevations of the volcanic mountains on each island with the highest concentration being on the northeast side of the Hawaii Island. Power potential in the conventional turbine and unconventional systems power classes is almost nonexistent. Microhydro sites are thinly distributed and do not exist on the most arid parts of the islands.

Intentionally left blank to facilitate comparison of Figures 11 and 12.

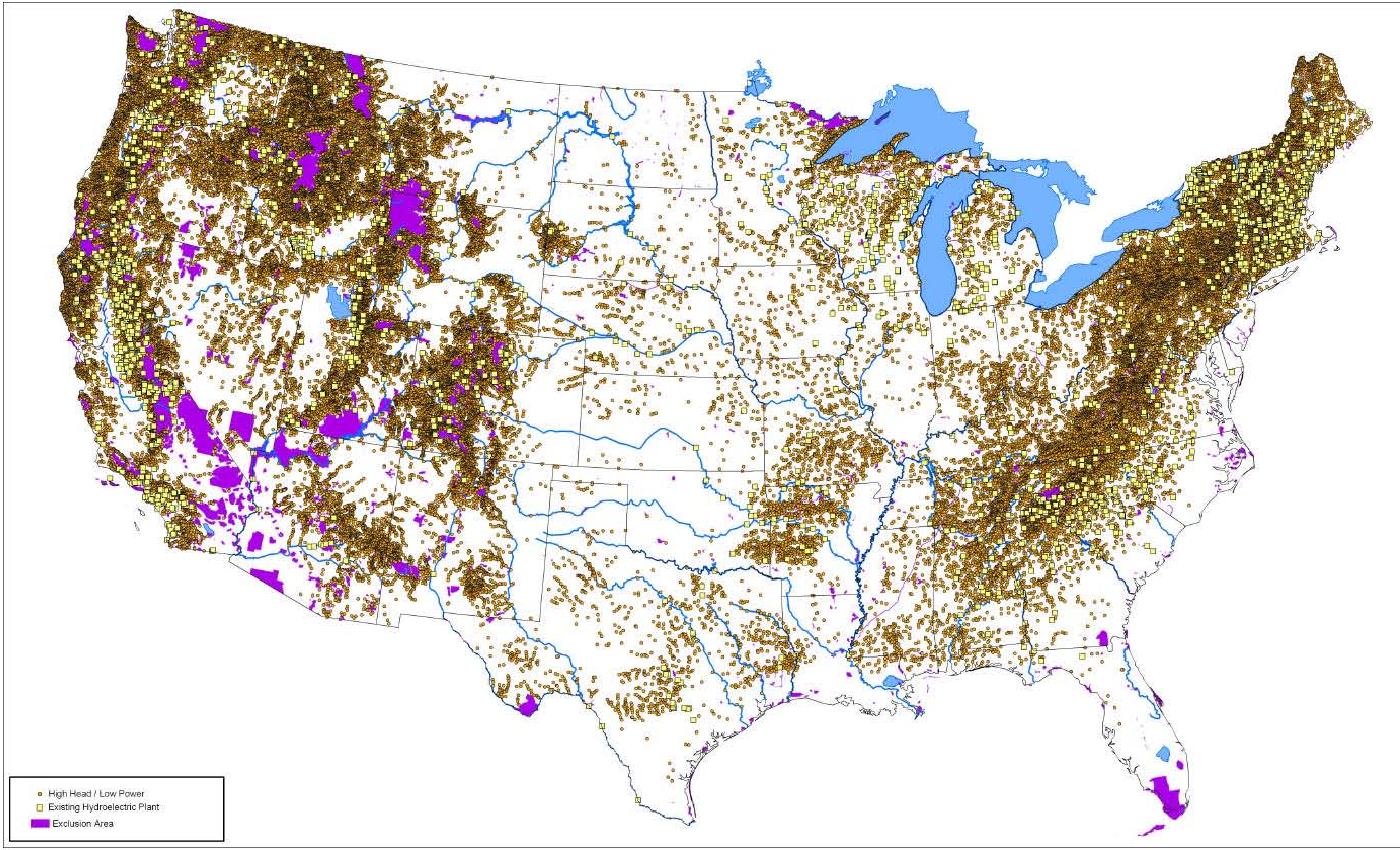


Figure 11. Existing hydroelectric plants and high head/low power water energy sites in the conterminous United States.

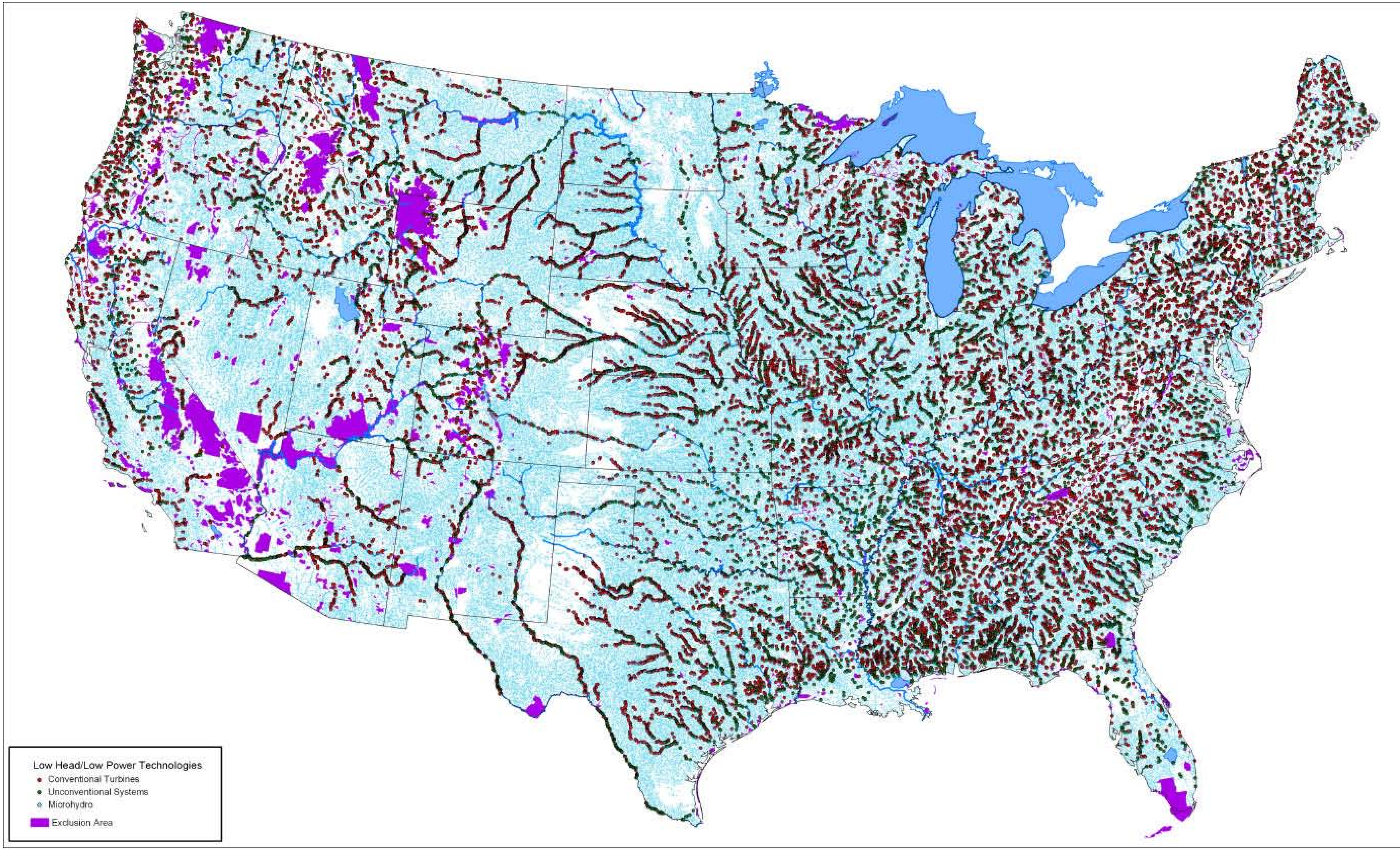


Figure 12. Low head/low power water energy sites in the conterminous United States.

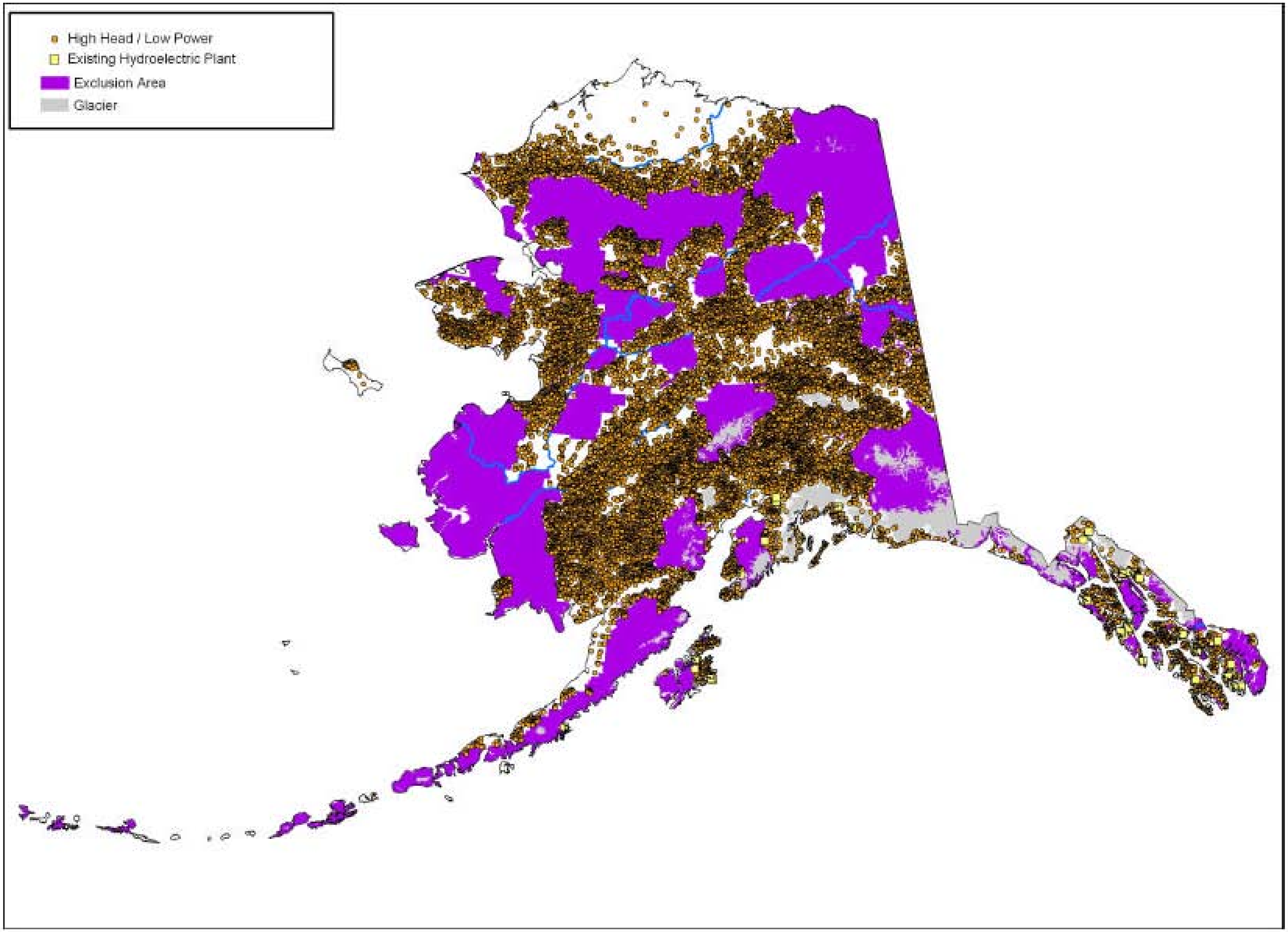


Figure 13. Existing hydroelectric plants and high head/low power water energy sites in Alaska.

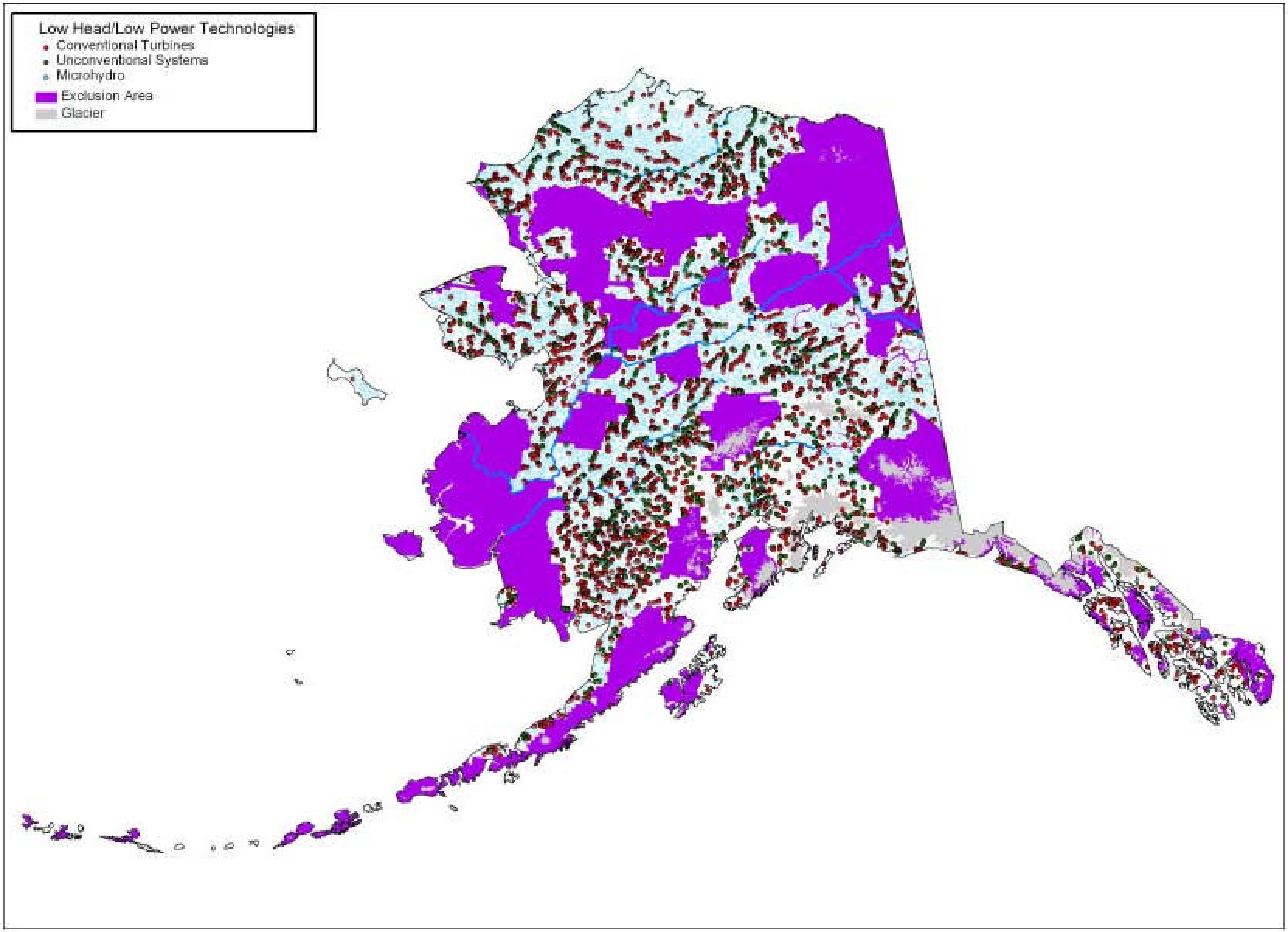


Figure 14. Low/head/low power water energy sites in Alaska.

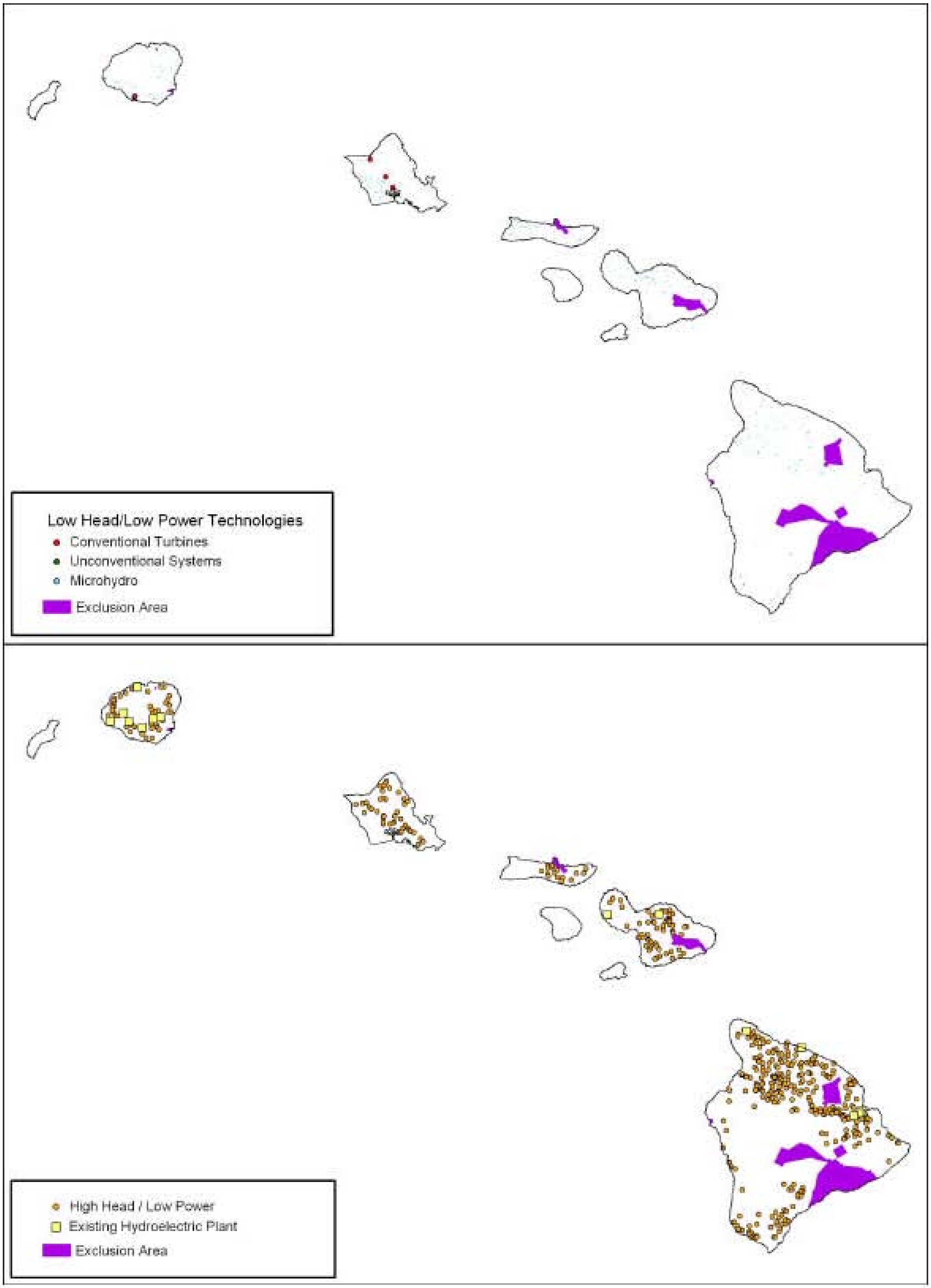


Figure 15. Low head/low power and high head/low power water energy sites and existing hydroelectric plants in Hawaii.

4.4 Comparison of Regional Power Potentials

The total annual mean power potentials of the 20 hydrologic regions subdivided into developed, excluded, and available constituents are compared in Figure 16 by presenting them in ascending order of total power potential. The Alaska Region contains the largest total potential with its slightly less than 90,000 MW of potential, which is approximately 30% of the total power potential of the United States. The Pacific Northwest Region has the second highest amount of total potential with slightly more than 76,000 MW of potential. Together these two regions contain over half (55%) of the U.S. power potential.

From the perspective of the largest percentage of total power potential that has been developed, the Great Lakes Region (66%) and the Tennessee Region (37%) are particularly noteworthy with the next highest regions being the Lower Colorado (23%), Pacific Northwest (22%), South Atlantic-Gulf (21%), and California (17%). The remaining 14 regions range in developed percentages from 15% to Alaska's less than 1%. A little over half of the regions (12 out of 20) have developed power percentages less than the national average of 12%.

Alaska and California have the highest percentages of total potential that is excluded from development by federal statutes and polices; having 49% and 45% excluded, respectively. Seven other regions [Missouri (29%), Rio Grande (28%) Upper Colorado (28%), Lower Colorado (27%), Pacific Northwest (26%), Souris Red-Rainy (23%), and Hawaii (20%)] have exclusion percentages in the 20 to 30% range with the national average being 30%.

Eight regions have outstanding percentages of their total power potential in the available category. These regions have available potential percentages equal to or greater than 80%: Lower Mississippi (92%), Texas Gulf (90%), Ohio (83%), Upper Mississippi (82%), Mid-Atlantic (82%), Great Basin (82%), North Atlantic (81%), and Arkansas-White-Red (80%). The percentage for the United States as a whole is just slightly less than 60%.

The relative amounts of power potential are distorted by the relative size of the regions. Therefore, each power potential value was normalized by dividing it by the corresponding region planimetric area yielding annual mean power densities in units of kW/sq mi. The resulting total power densities subdivided into developed, excluded, and available constituents are compared in Figure 17 by presenting them in ascending order. The ten regions with the highest power densities are located in areas of the country with the highest combinations of annual precipitation and elevation changes. The power densities of these ten regions are notably higher than the remaining 10 regions, ranging from approximately 70 to 410 kW/sq mi with the Hawaii (409 kW/sq mi) and Pacific Northwest (279 kW/sq mi) Regions being the highest, respectively. The highest ranked regions and their rankings in Figure 17 do not coincide exactly with the nine regions having notably higher total power potentials shown in Figure 16. The total annual mean power density for the United States is slightly more than 80 kW/sq mi, which corresponds to an average energy density of approximately 2,000 kWh/sq mi/day.

Comparison of the density of developed hydropower represented by the green bar segments in Figure 17 shows that hydropower development has not strictly occurred in correlation with those regions that have the greatest power potential density. Hydropower development in California has clearly been less than its total potential might indicate because of a large percentage of its potential being excluded from development. The Alaska (<1%), Hawaii (1%), and Lower Mississippi (1%) Regions have extremely small amounts of development relative to the potential. This result is understandable for the Lower Mississippi Region, because a large fraction of this potential lies in the lower Mississippi River and cannot feasibly be realized using conventional technology. On the other hand, the results indicate that Alaska and Hawaii offer significant opportunities for water energy resource development.

Because available power potential is of the greatest interest, the available annual mean power potentials of the 20 hydrologic regions subdivided into high power (≥1 MW), high head/low power (≥30 ft of head and <1 MW), and low head/low power (<30 ft of head and <1 MW) constituents are compared in Figure 18 by presenting them in ascending order of available power potential. The Alaska and Pacific Northwest Regions contain significantly more available potential than the other 18 regions. The Alaska Region with its 44,000 MW and the Pacific Northwest Region with its nearly 40,000 MW of available potential are on the order of four to five times that of the next four regions: Missouri, Ohio, California, and Lower Mississippi Regions having available potentials ranging from approximately 9,000 to 11,000 MW. Most of this available power is in the high power class. In the case of the Lower Mississippi Region, probably only a small fraction of this potential could be realized unless unconventional systems are used.

The available power potentials shown in Figure 18 were normalized to produce available annual mean power densities. The resulting available power densities that are subdivided into their three constituents are compared in Figure 19 by presenting them in ascending order. This view shows the overwhelming plurality of the Hawaii Region and shows three sets of regions based on available power density. The Hawaii Region stands alone with an available power density of 324 kW/sq mi followed by the Pacific Northwest and Lower Mississippi Regions in the range from 110 to 150 kW/sq mi, which are in turn followed by a group of seven regions in the range from 50 to 80 kW/sq mi. The remaining 10 regions are in the 5 to 25 kW/sq mi range.

The available annual mean power density for the United States is nearly 50 kW/sq mi corresponding to average energy density of approximately 1,100 kWh/sq mi/day. Eight of the ten regions shown to have the highest available power densities in Figure 19 are among the twelve regions shown to have the highest available potentials in Figure 18, but generally not in the same ranking order. Ranking by power density is a better indicator of where available potential can be found than the magnitude of the available potential.

A principal focus of this study was low head/low power potential. Therefore, the available low head/low power annual mean power potentials of the 20 hydrologic regions, which are subdivided into power classes corresponding to the operating envelopes of three classes of low head/low power hydropower technologies, are compared in Figure 20 by presenting them in ascending order of available low head/low power power potential. (See Figure 7 for the boundaries of the operating envelopes of the three classes of low head/low power hydropower technologies.) Comparison of the rankings in Figure 20 with those in Figure 18 shows that available low head/low power potential is generally not proportional to total available power potential. Therefore, it is found in some regions that do not have the largest amount of total available power potential. The Missouri Region has the highest low head/low power potential, while the Alaska Region, which has the highest total available potential, is second. Notably, the Arkansas-White-Red, Upper Mississippi, and the Texas Gulf Regions moved up into the upper nine ranks in this power class, while the Lower Mississippi, California, and Upper Colorado Regions moved out of the upper nine low head/low power rankings.

Microhydro constitutes between 42% (Arkansas-White-Red) and 89% (Hawaii) of the available low head/low power potential in the 20 regions. Conventional turbine available potential ranges from 11% (Hawaii) to 40% (Arkansas-White-Red) of the region's available low head/low power potential. The fractions corresponding to unconventional systems are relatively small ranging from less than 1% (Hawaii) to 29% (Lower Mississippi).

In order to determine the highest concentrations of available low head/low power potential among the regions, the potentials shown in Figure 20 were normalized to produce available low head/low power annual mean power densities. The resulting low head/low power power densities subdivided into their three constituents are compared in Figure 21 by presenting them in ascending order. This view gives quite a different picture of where available low head/low power potential is located. Available low head/low power power densities of about 9 kW/sq mi are indicated for the Tennessee, Ohio, Mid-Atlantic, and North Atlantic Regions. Ten regions have low head/low power power densities equal to or greater than 6 kW/sq mi for the country, which corresponds to an average energy density of 143 kWh/sq mi/day.

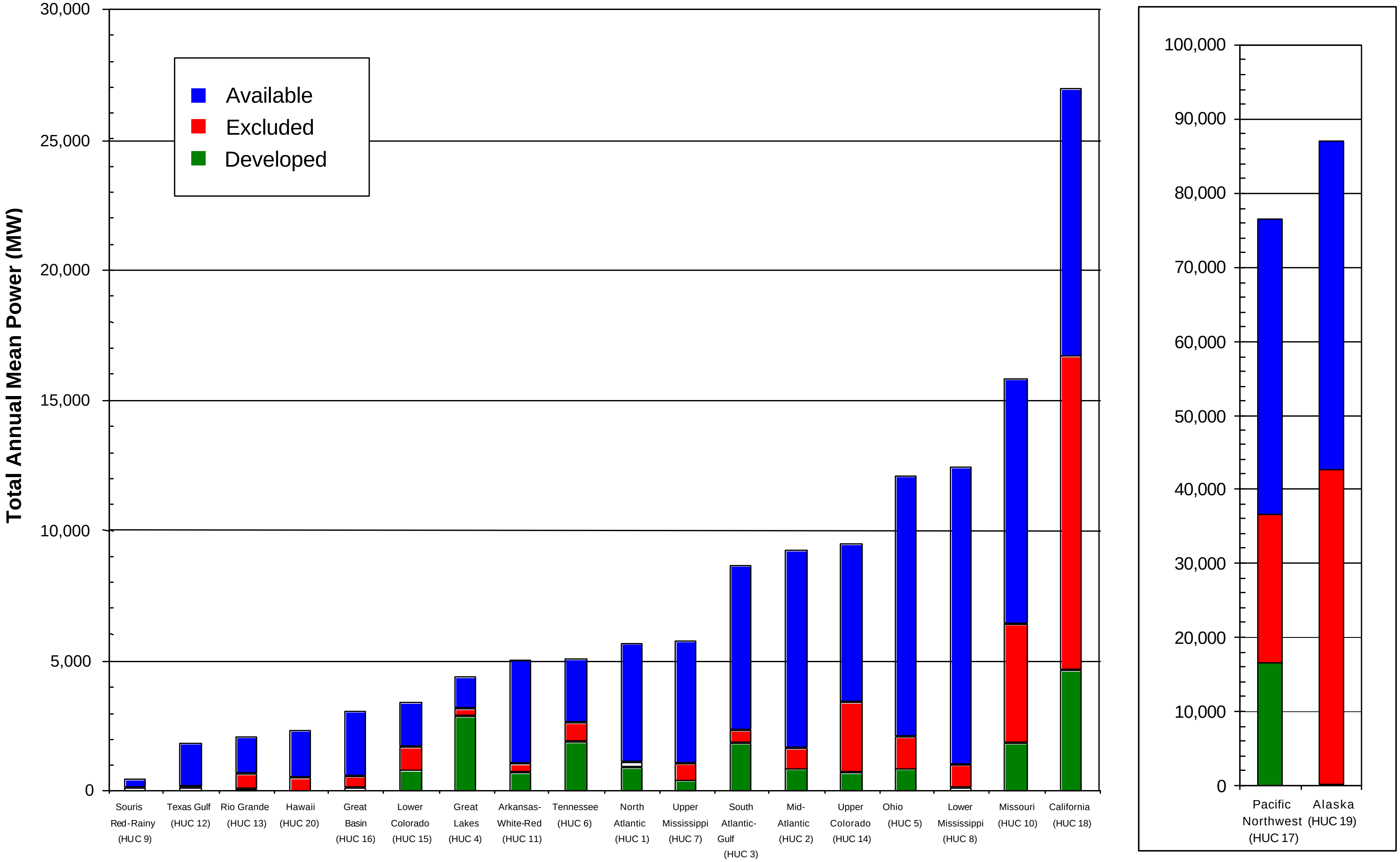


Figure 16. Total power potential of water energy resources in 20 United States hydrologic regions divided into developed, excluded, and available constituents.

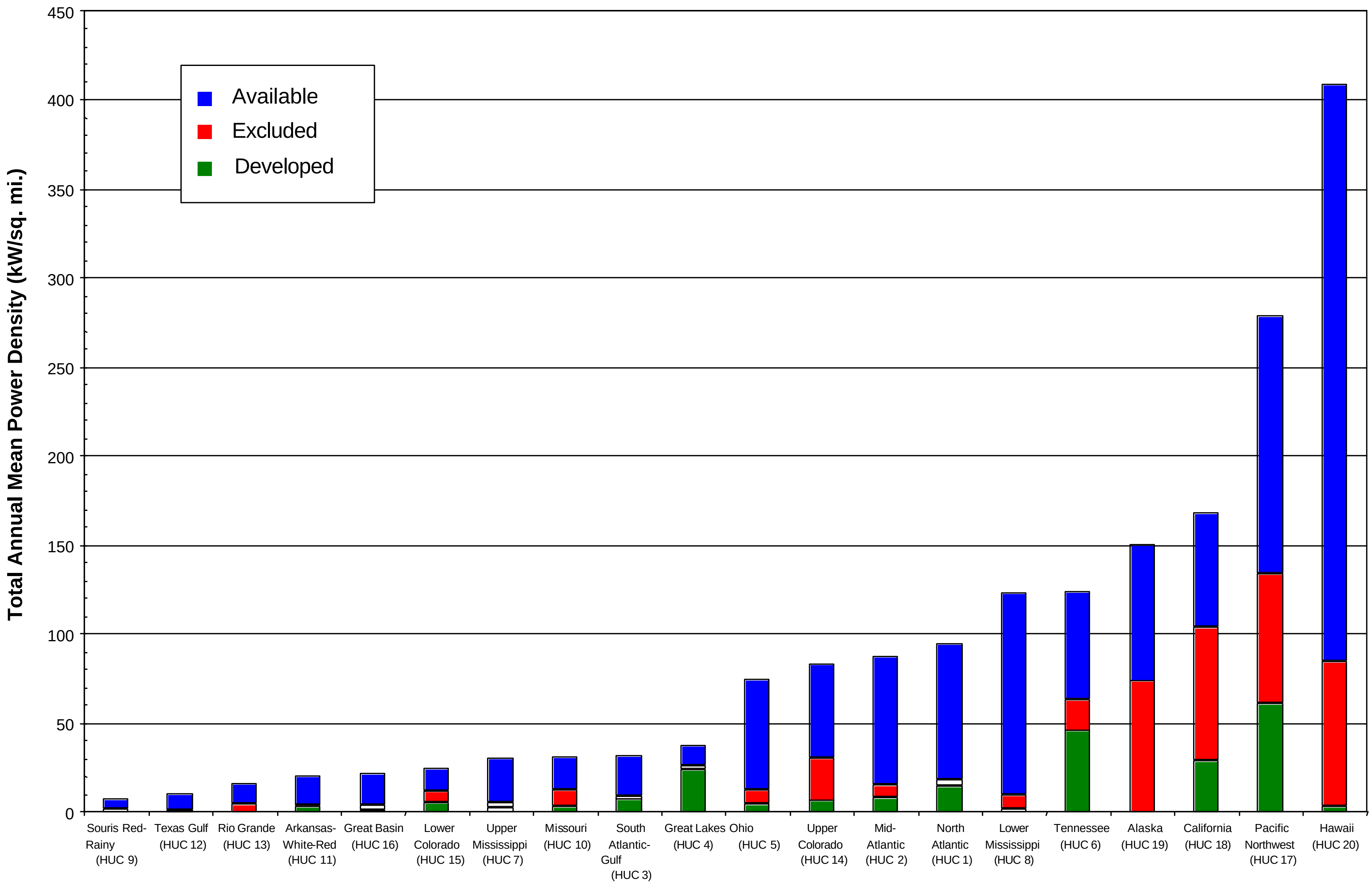


Figure 17. Total power potential density of water energy resources in 20 United States hydrologic regions divided into developed, excluded, and net constituents.

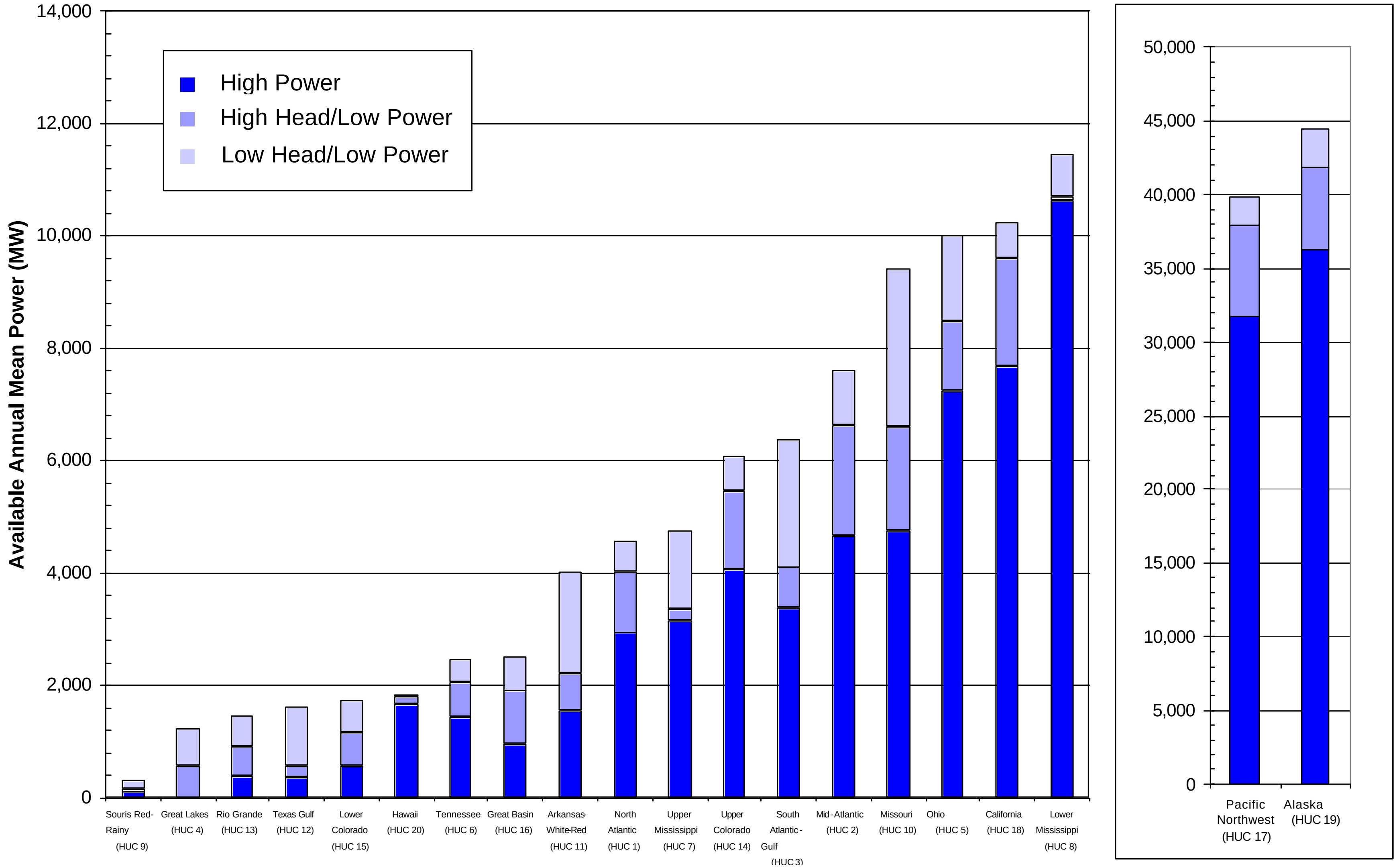


Figure 18. Available power potential of water energy resources in 20 United States hydrologic regions divided into high power, high head/low power, and low head/low power constituents.

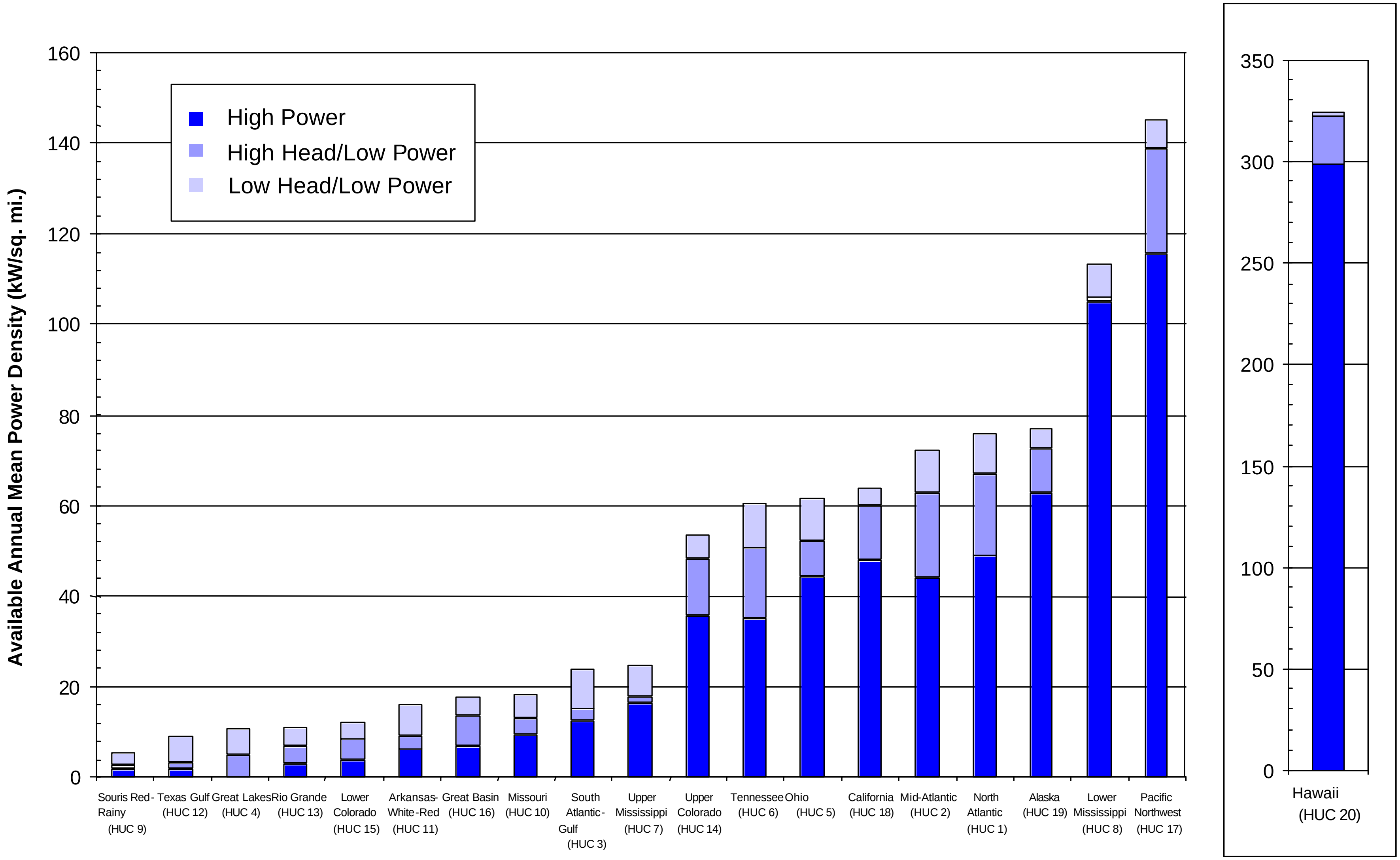


Figure 19. Available power potential density of water energy resources in 20 United States hydrologic regions divided into high power, high head/low power, and low head/low power constituents.

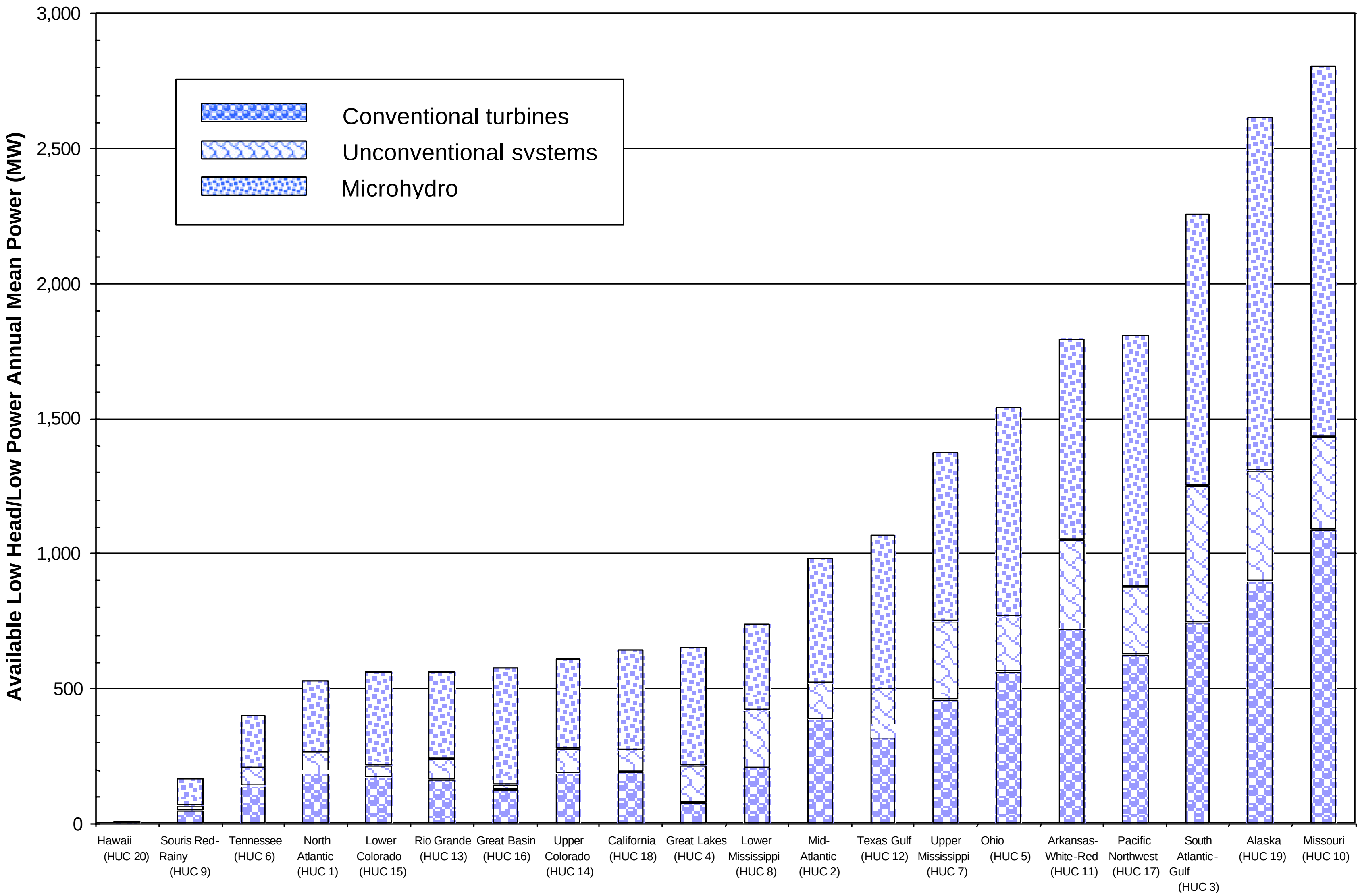


Figure 20. Available power potential of low head/low power water energy resources in 20 United States hydrologic regions divided into conventional turbines, unconventional systems, and microhydro constituents.

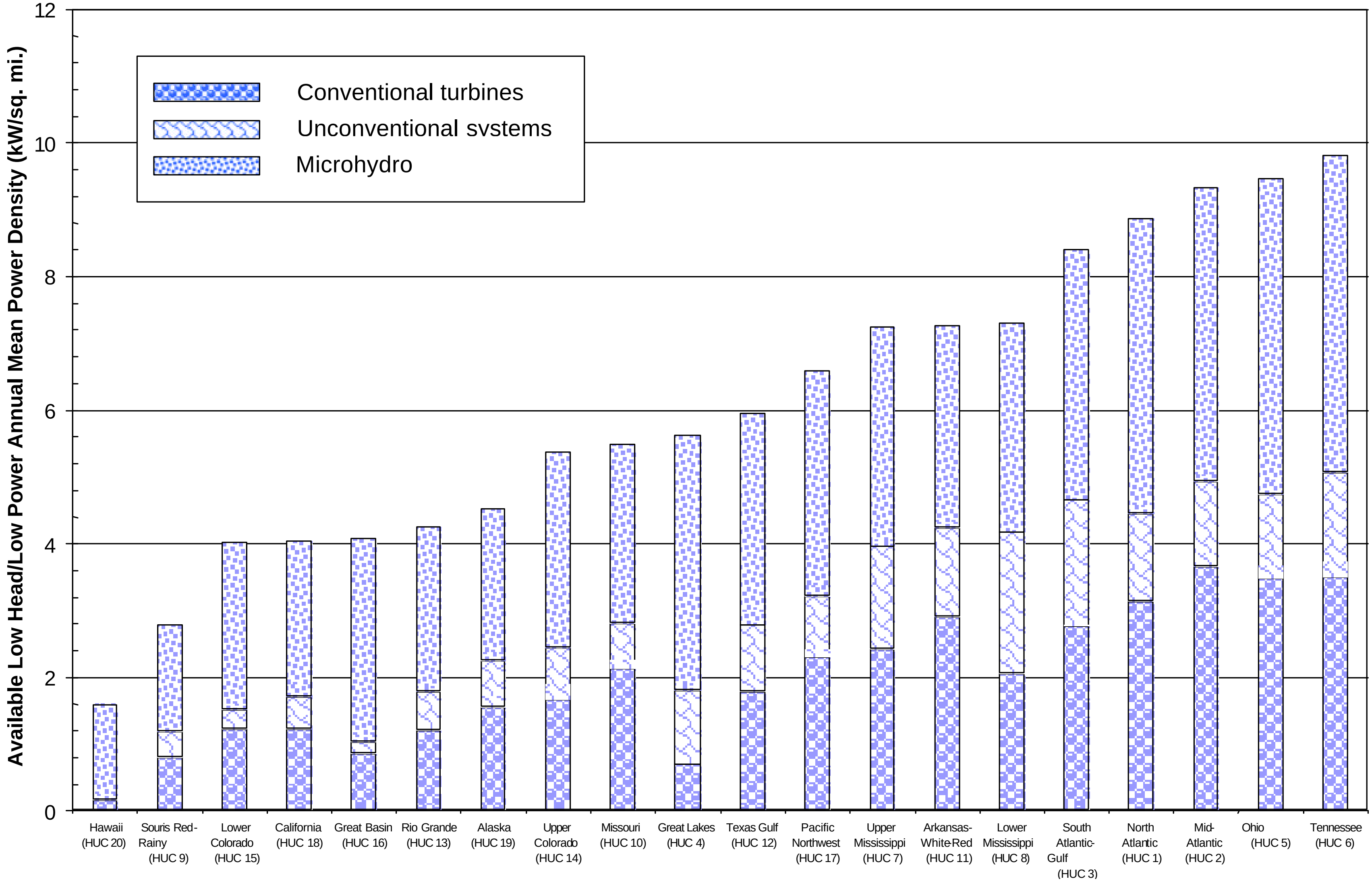


Figure 21. Available power potential density of low head/low power water energy resources in 20 United States hydrologic regions divided into conventional turbines, unconventional systems, and microhydro constituents.

4.5 Comparison of State Power Potentials

The total annual mean power potentials of the 50 states in the United States subdivided into developed, excluded, and available constituents are compared in Figure 22 by presenting them in ascending order of total power potential. Five states have outstandingly higher total power potentials than the other 45 states with their potentials ranging from approximately 18,000 MW to slightly under 90,000 MW. All these states, except Alaska which has the highest total potential, are in the western conterminous United States: Washington, Idaho, and Oregon, which are for the most part in the Pacific Northwest Region, and California, which comprises the vast majority of the California Region. These five states have the largest excluded and available potentials of all the states, but the most developed potential lies in the states of Washington, California, Oregon, New York, and Idaho.

On a percentage of total power potential developed basis, Washington is the only state with the highest amount of total potential that ranks in the top five states that have the largest percentages of developed power. These five states are: North Dakota (93%), South Dakota (72%), New York (58%), Washington (37%), and Alabama (35%). A little over half of the states (27 out of 50) have developed power percentages less than the national average of 12%. Three states have excluded potentials that exceed 40% of the state total power potential, Alaska (49%), Wyoming (46%), and California (44%). Six states have excluded potential percentages in the 30 percentiles. From the perspective of available potential as a percentage of total power potential, 21 states have available potential percentages equal to or greater than 80%. A total of 40 states have available potential percentages greater than or equal to the national percentage of 57%.

The amounts of total power potential shown in Figure 22 are distorted by the size of the states. Therefore, each power potential value was normalized by dividing it by the corresponding planimetric area of the state, which yielded the annual mean power densities in units of kW/sq mi. The resulting total power densities subdivided into developed, excluded, and available constituents are compared in Figure 23 by presenting them in ascending order. From this perspective, four of the five states having the largest total power potentials also have the highest total power densities, with Alaska slipping out of the top five and Hawaii taking second place behind Washington. The top two states, Washington and Hawaii have power densities in the range from 400 to 460 kW/sq mi. The superiority of these two states with regard to total power is accentuated by the fact that their power density is approximately twice as high as that the next closest state, Idaho. The 19 states with the highest total power densities include Alaska and Hawaii and states located east of the Mississippi or on the Pacific coast. Comparison of the density of developed hydropower represented by the green bar segments in Figure 21 shows that hydropower development has generally not occurred in correlation with those states having the greatest total power density.

The available annual mean power potentials of the states subdivided into high power, high head/low power, and low head/low power constituents are compared in Figure 24. The states are presented in ascending order of available power potential. The five states having the largest total power potentials also have the highest available power potentials ranging from approximately 9,000 to slightly over 44,000 MW. High power potential is the largest constituent of the available power potentials in 38 out of 50 states.

The available power potentials shown in Figure 24 were normalized to produce available annual mean power densities. The resulting available power densities subdivided into their three constituents are compared in Figure 25 by presenting them in ascending order. The ranking by power density is a better indicator of where available power potential can be found. The states shown to have the higher average available power densities in Figure 25 are not in all cases the same states shown to have the highest total available power potentials in Figure 24. From this perspective, three states have outstanding available power densities compared to the other states: Hawaii (324 kW/sq mi), Washington (184 kW/sq mi), and Idaho (143 kW/sq mi).

Following these three states, there is a group of 15 states having available power densities in the range of 60 to 110 kW/sq mi all of which are east of the Mississippi River with the exception of California and Oregon.

The available low head/low power annual mean power potentials of the 50 states subdivided into power classes corresponding to the operating envelopes of three classes of low head/low power hydropower technologies are compared in Figure 26. The states are presented in ascending order of available low head/low power power potential. This figure shows that because available low head/low power potential is generally not proportional to total available power potential (compare with Figure 24), Alaska and Oregon are the only states having outstanding amounts of total available potential that rank in the top five states having the largest amounts of available low head/low power potential. Alaska has the highest available low head/low power potential with slightly over 2,600 MW, while Texas has about half this amount at 1,425 MW.

Microhydro constitutes between 34% (Oklahoma) and 100% (North and South Dakota) of the available low head/low power potential in the states. Conventional turbine available potential ranges from 0% (North and South Dakota) to 51% (Nebraska) of the state total available low head/low power potential. The fractions corresponding to unconventional systems are relatively small ranging from 0% (Hawaii) to 33% (Florida).

The superiority of Alaska and Texas in possessing available low head/low power potential is largely the result of the size of the state. When viewed from a power density perspective as shown in Figure 27, a different picture emerges of where available low head/low power potential is located. From this perspective, Alaska and Texas are ranked 39th and 35th, respectively. Alabama has the highest low head/low power power density (12 kW/sq mi) with a group of the highest 21 states having this class of power densities in the range of approximately 8 to 12 kW/sq mi. Notably, all these states are in the eastern half of the United States; the vast majority being east of the Mississippi River.

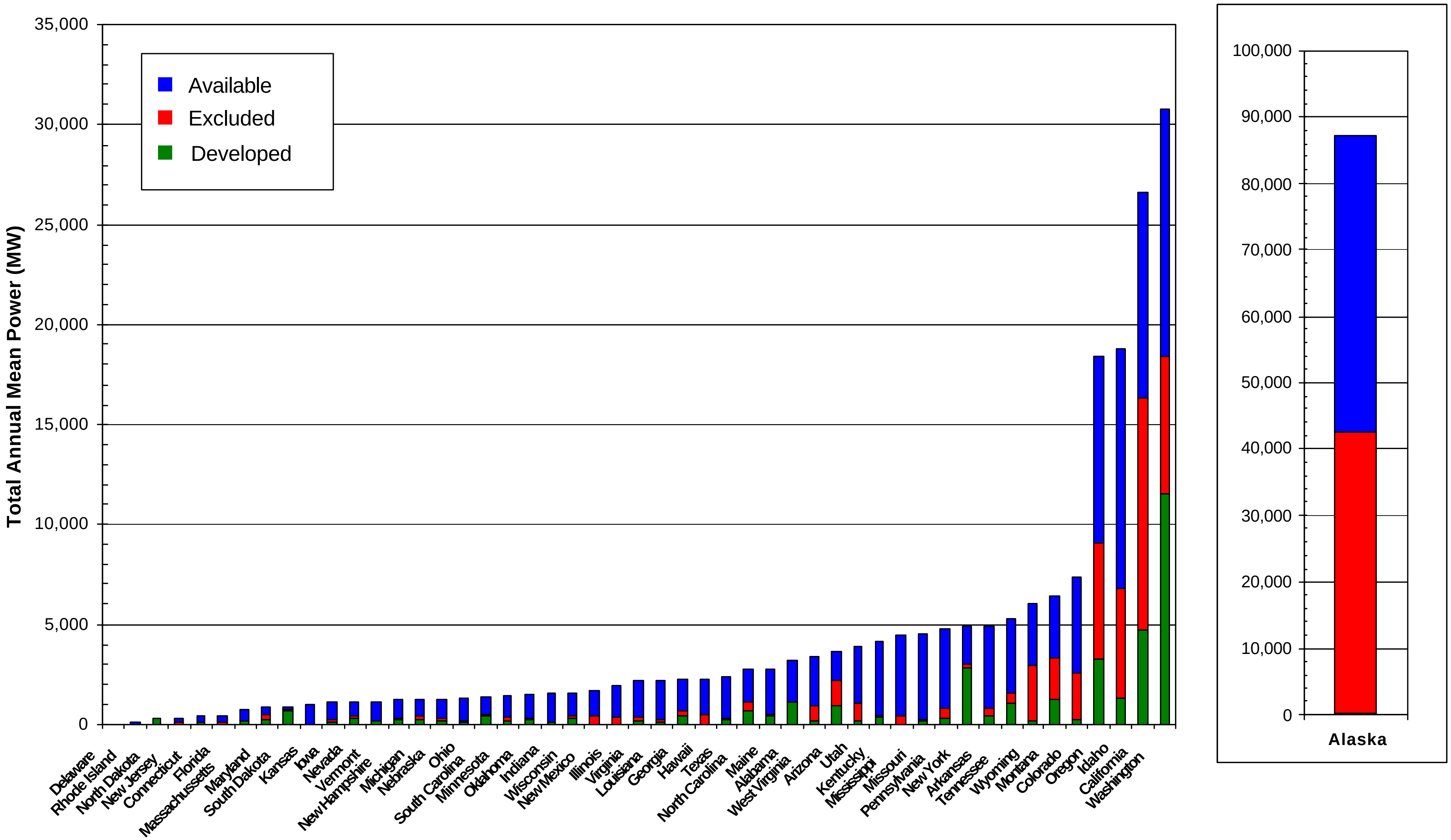


Figure 22. Total power potential of water energy resources in the 50 states of the United States divided into developed, excluded, and net constituents.

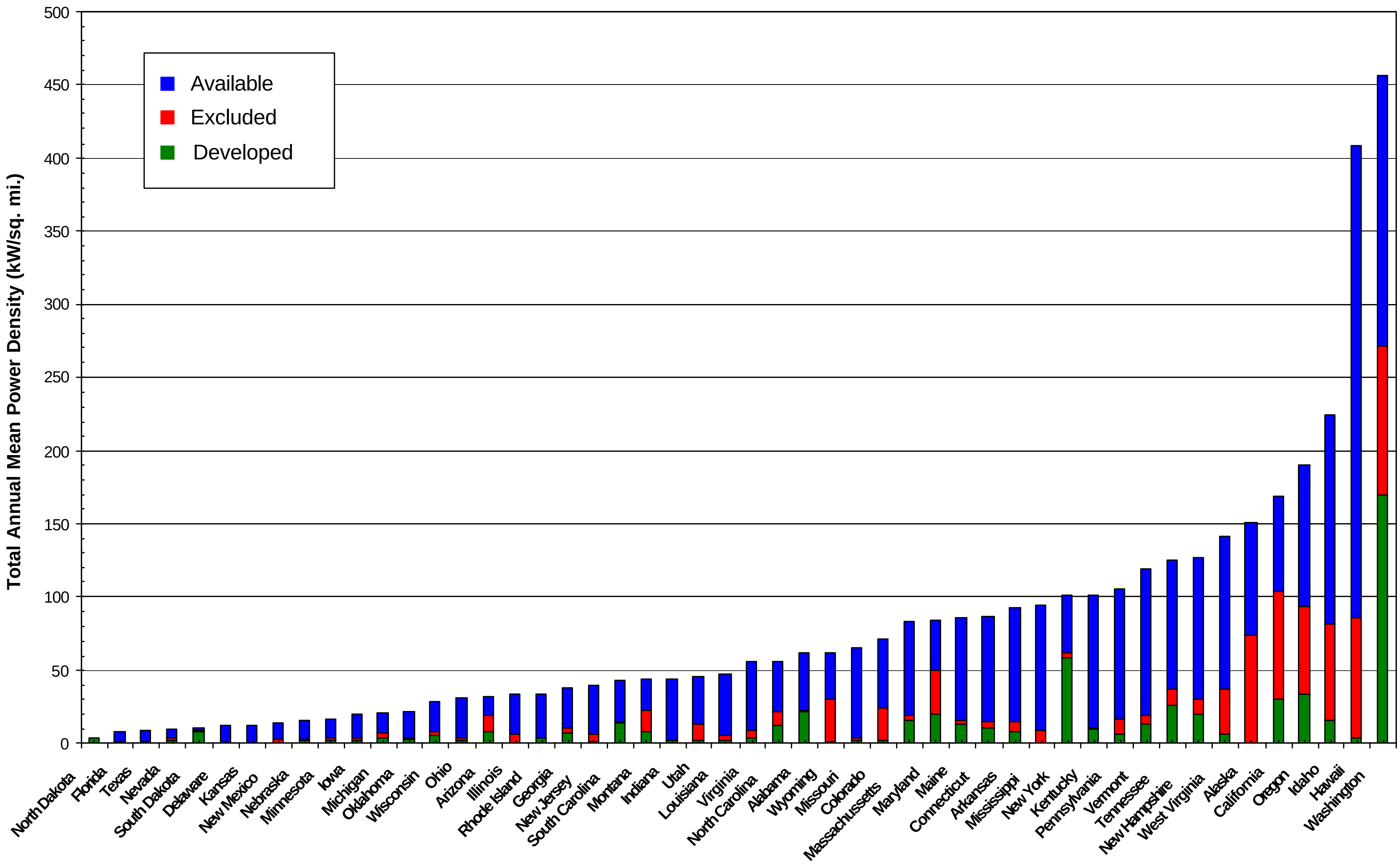


Figure 23. Total power potential density of water energy resources in the 50 states of the United States divided into developed, excluded, and net constituents.

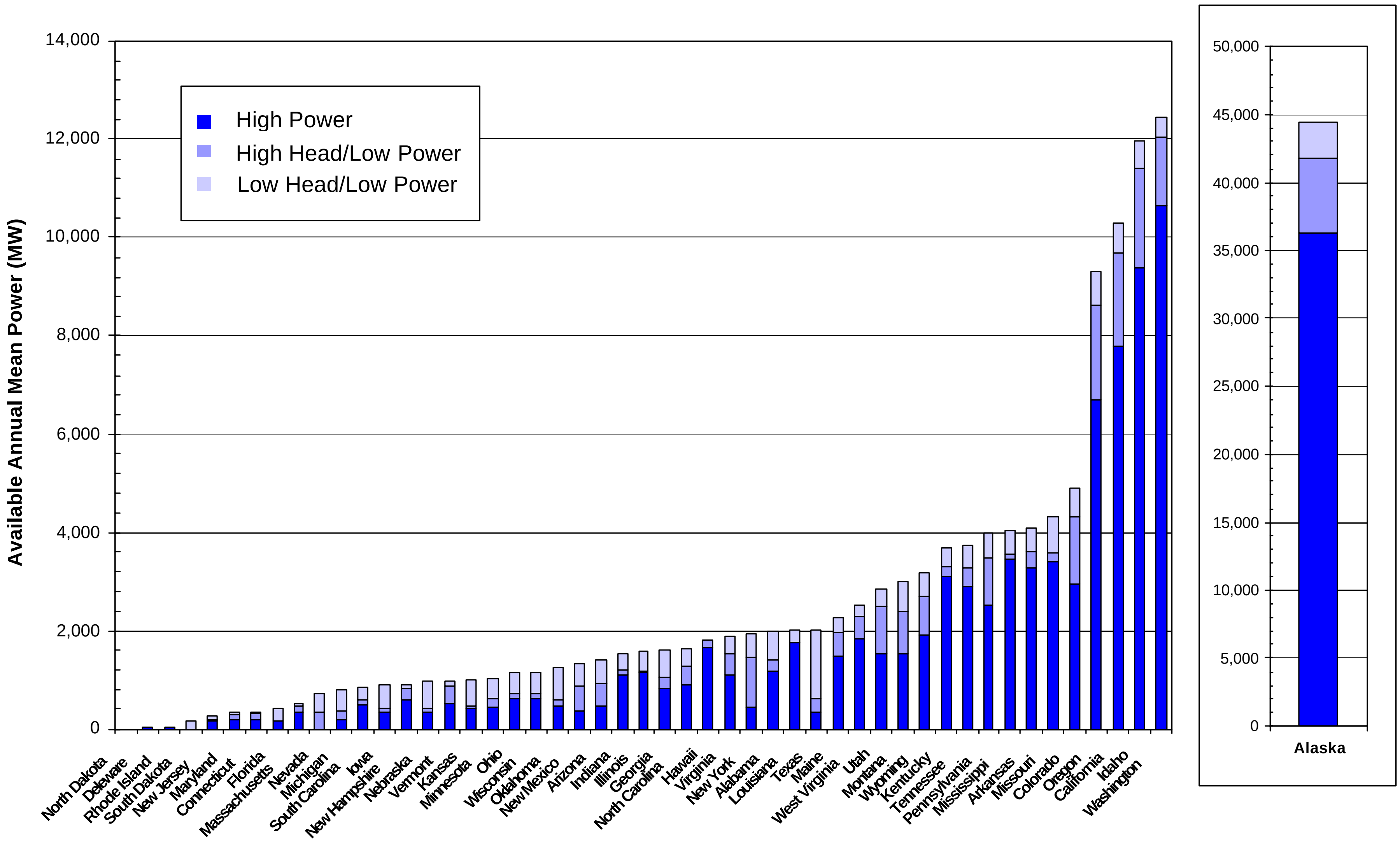


Figure 24. Available power potential of water energy resources in the 50 states of the United States divided into high power, high head/low power, and low head/low power constituents.

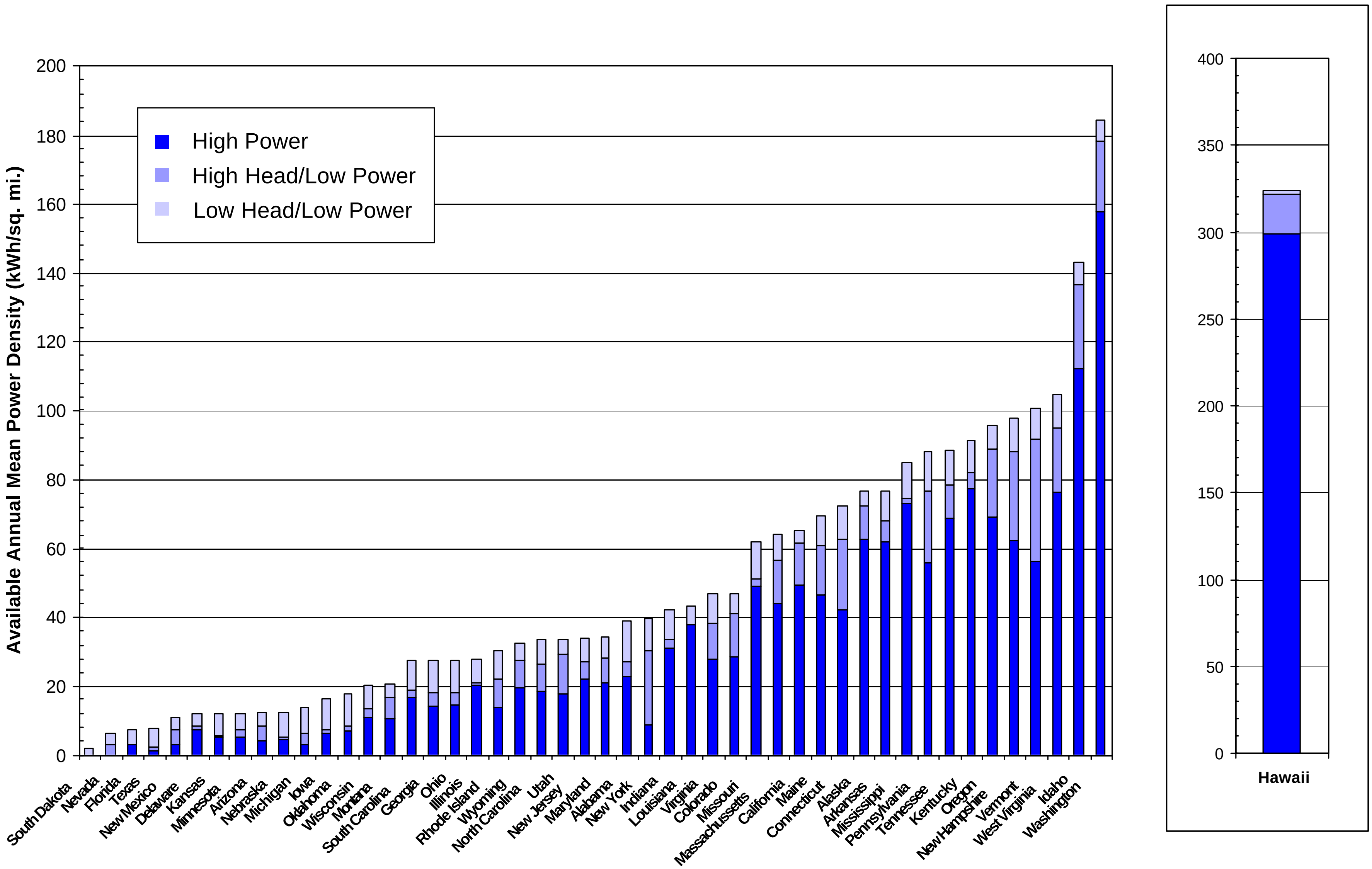


Figure 25. Available power potential density of water energy resources in the 50 states of the United States divided into high power, high head/low power, and low head/low power constituents.

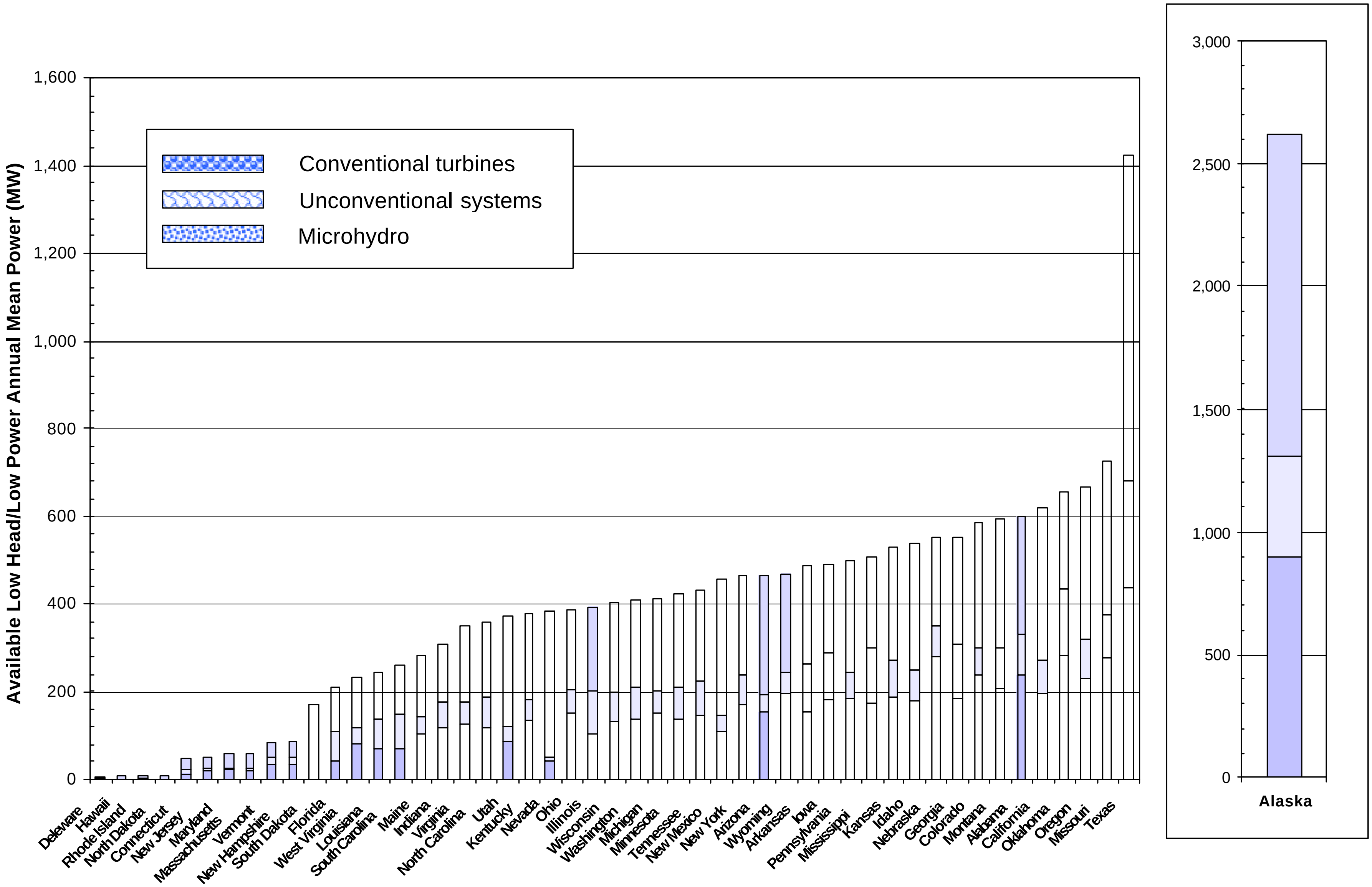


Figure 26. Available power potential of low head/low power water energy resources in the 50 states of the United States divided into conventional turbines, unconventional systems, and microhydro constituents.

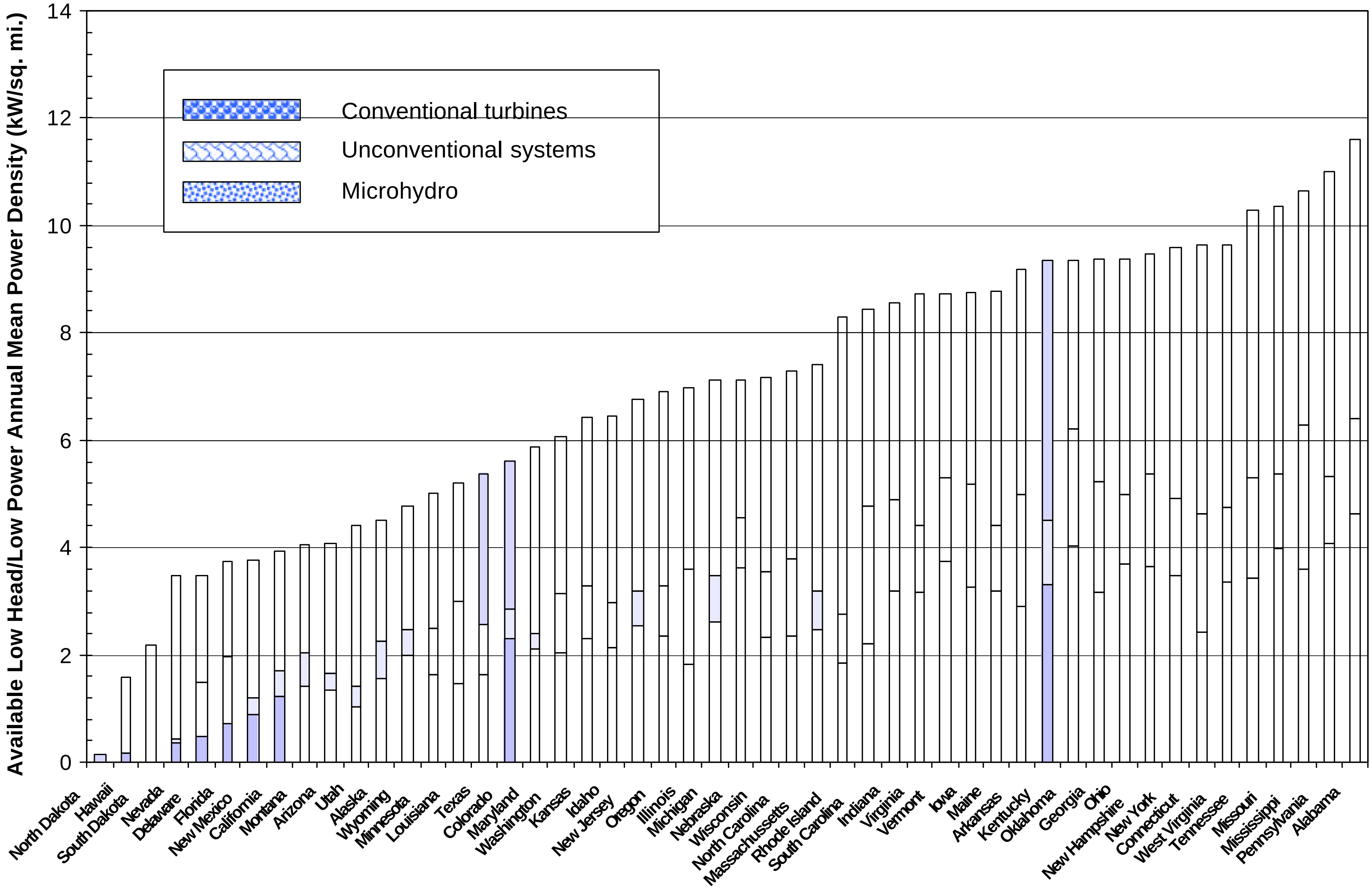


Figure 27. Available power potential density of low head/low power water energy resources in the 50 states of the United States divided into conventional turbines, unconventional systems, and microhydro constituents.

5. CONCLUSIONS AND RECOMMENDATIONS

This study has demonstrated that it is possible to estimate the power potential of the United States water energy resources based on the potentials of mathematical analogs of every stream segment in the country. Furthermore, stream segment potentials can be aggregated to determine the power potential in various power classes within geographic areas of interest and to locate the potential at discrete geographic coordinates.

The study has resulted in an estimate of the power potential of the United States water energy resources of approximately 300,000 MW corresponding to an annual energy production of 2,680,000 GWh. Of this potential, about 40,000 MW, corresponding to the approximately 80,000 MW capacity of existing hydroelectric plants, have been developed. Power potential in zones that exclude new hydropower development accounts for about 90,000 MW. This leaves approximately 170,000 MW of potential or about 60% of the total that has not been developed and is not excluded from development. This potential power corresponds to an annual energy production of 1,501,500 GWh. Ninety percent (90%) of this available potential is composed of high power potential (≥1 MW), high head/low power (head ≥30 ft and <1 MW) potential, and part of the low head/low power (head <30 ft and <1 MW) potential that could be realized using conventional turbine technology. However, the conventional turbine technology would have to be incorporated into new system configurations and not require impoundments to be determined by future research and development.

The estimated, available, low head/low power potential of approximately 21,000 MW constitutes 13% of the total available potential. High head/low power potential adds another 26,000 MW (16% of the total); therefore, low power potential is about 30% of the total available power potential. Over 90% of available power potential could be realized using conventional turbines, but perhaps in new system configurations. However, nearly two-thirds (66%) of the low head/low power potential (≈10% of total available potential) corresponds to technologies (microhydro and unconventional systems) that would require additional turbine and system configuration research and development; although, some units currently exist that could be put into service.

The study has shown that over half of the power potential of the country resides in the top two hydrologic regions: Alaska (29%) and Pacific Northwest (26%); in particular, in the states of Alaska, Washington, Idaho, and Oregon. Nearly half of the available power potential also resides in the top two regions: Alaska (26%) and Pacific Northwest (23%). Viewed from the perspective of where the greatest concentrations of available power potential are located; Hawaii, Washington, and Idaho have the highest concentrations. Oregon, Alaska, and California and 12 states east of the Mississippi make up the balance of the states in which available potential is most densely concentrated.

Because low head/low power potential is not directly proportional to the total power potential, the rankings of the states with the maximum amount and concentrations of available low head/low power potential are not the same as for total available power. For this power class, regions and states having the most potential are scattered around the country. However, from the perspective of where the highest concentrations of low head/low power potential are located, the eastern United States is the clear sector of the country having the highest concentrations with five hydrologic regions and 21 states, nearly all of them east of the Mississippi at the top of the rankings.

The average percentage of developed potential for the country is only 12%. While this is a comparison of actual to ideal power, the percentage is sufficiently low to indicate a significant opportunity to develop additional water energy resources. Because 12 of the 20 hydrologic regions and 27 of the 50 states have developed power percentages less than the national average, it is clear that most of the regions and states are underdeveloped with respect to hydroelectric power. This conclusion is further supported by the fact that 21 states have 80% or more of their total power potential available for development, and 40 states have more available than the national average (57%) of available power potential.

The estimates of available power potential produced by this study are sufficiently large to warrant further research toward realizing these additional energy resources. Such research should include at a minimum refinement of the available power potential estimates and investigation of possible locations for siting additional hydroelectric units. Low power sites are sufficiently numerous and uniformly distributed over the country to offer significant sources of distributed power without the need for reservoirs. In order to obtain a clearer estimate of the amount of power potential that can feasibly be developed and determine which sites are feasible, it is necessary to intersect the locations of potential with context parameters that govern its feasibility of development. These parameters include proximity to population centers, industry, and existing infrastructure (e.g., roads, railroads, and electric transmission lines) and locations inside or outside of nonfederal mandated exclusion areas. Because all the data generated in this project are geo-referenced and the necessary GIS tools and most of the needed context layers exist, we recommend that this research be conducted.

The power potential estimates provided in this report have large uncertainties for some hydrologic regions, because of the uncertainty in the flow rate estimation equations used to produce them. Use of flow rate prediction equations developed for smaller areas than entire hydrologic regions would probably offer increased flow rate prediction accuracy and thus increased power potential accuracy. In addition to increased accuracy in predicting annual mean flow rates, data or equations that allow flow duration to be factored into estimates of available and developable power potential are needed. Research should be conducted to locate such equations and data, and the study results and any subsequent feasibility assessment should be upgraded using them.

A limited validation study was performed and is presented in Appendix C. We recommend that results of stream reach flow rate and power potential calculations be benchmarked against a significant number of locations around the country with known, gauged flow rates and associated hydraulic heads. This validation study should be driven by the availability of EDNA synthetic hydrography that has been validated by the U.S. Geological Survey in its ongoing efforts to obtain correlation between EDNA hydrography and that provided by the more accurate NHD.

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