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Low Head/Low Power Hydropower Resource Assessment of the Pacific Northwest Hydrologic Region

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ABSTRACT

An analytical assessment of the hydropower potential of the Pacific Northwest Hydrologic Region was performed using state-of-the-art digital elevation models and geographic information system tools. The principal focus of the study was the amount of low head (less than 30 ft)/low power (less than 1 MW) potential in the region and the fractions of this potential that corresponded to the operating envelopes of three classes of hydropower technologies: conventional turbines, unconventional systems, and microhydro (less than 100 kW) technologies. To obtain these estimates, the hydropower potential of all the stream segments in the region, which averaged 2 miles in length, were calculated. 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 developed specifically for the region. Stream segments excluded from development and developed hydropower in the region were accounted for to produce estimates of available total hydropower potential. The total available hydropower potential was subdivided high power (1 MW or more), high head (30 ft or more)/low power, and low head/low power potentials. The sites of available low head/low power potentials corresponding to the three classes of technologies and high head/low power potential are displayed on maps of the region.

SUMMARY

The U.S. Department of Energy (DOE) has had an ongoing interest in assessing the hydropower potential of the United States. Previous assessments have focused on potential projects that have a capacity of 1 MW and above (Connor et al. 1998). 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 hydropower potential for low head (less than 30 feet) 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 the second in a planned series of low head/low power hydropower resource assessments. The principal objective of this study was to demonstrate that a method of estimating the hydropower potential of a large geographic area developed in the prior pilot study could be used to assess the hydropower resources of an area having a significantly different topography and climate. Where the pilot study addressed the Arkansas White Red Region (HUC 11) (much of which is at relatively low elevations), the present study addressed the Pacific Northwest (PNW) Region (HUC 17), which has extensive mountainous regions and greatly varying local climatic conditions.

The method that was used in this study uses state-of-the-art digital elevation models and geographic information system (GIS) tools to assess the hydropower potential of every stream segment within a chosen study area. Summing the estimated hydropower potential of all the stream segments in the region provided an estimate of the total hydropower of the region. Stream segments that had power potentials less than 1 MW were segregated and summed to provide an estimate of total low head/low power potential in the region. Having hydropower potential estimates in such small increments allowed the regional 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 technologies.

In order to calculate the hydropower 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 elevation data at 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. Overlaying the EDNA data with climatic data from the Parameter-elevation Regressions on Independent Slopes Model dataset provided the variables needed to calculate stream flow for each stream segment using a regression equation developed specifically for the region. Combining stream flow with hydraulic head provided the hydropower 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 hydropower potentials. A GIS layer containing streams and areas that are excluded from development by statutory regulations was used to segregate excluded and nonexcluded stream segments. The amount of developed hydropower in the region provided by the Federal Energy Regulatory Commission was subtracted from total, nonexcluded, hydropower potentials to produce estimates of available hydropower potentials.

The assessment estimated that the total hydropower potential of the PNW Region is 76,000 MW. Of this amount, 20,000 MW is excluded from development. With 32,000 MW of developed hydropower in the region, the total available hydropower potential is estimated to be about 24,000 MW. Low head/low power potential makes up 2,000 MW of the total available potential. Division of the available low head/low power potential amongst low head/low power technology classes showed that 35% fell within the operating envelope of conventional turbines, 14% fell within the operating envelope of unconventional systems, and 51% fell within the operating envelope of microhydro technologies. In addition to the low head/low power potentials, there were 6,000 MW of high head (30 ft or greater)/low power potential in the region. A map of the locations of low head/low power sites by technology class shows a significant density of sites for the conventional turbine and unconventional technology classes in the area west of the Cascade Mountains. Microhydro technology sites were located mainly in the Columbia Plateau of eastern Oregon and Washington and the Snake River Plain in southern Idaho. High head/low power sites were also mapped and found to be numerous and distributed throughout the region with the exception of the plateau and plain areas.

We concluded from this study that the technical approach is a viable method for estimating the hydropower potential of large geographic areas having diverse topography and climate. Applied to all the hydrologic regions in the continental U.S., it would provide a reasonable estimate of the total available hydropower potential of the country as well as the geographic distribution of this potential. The study showed that there is significant, available low power hydropower potential in the PNW Region most of which corresponds to the operating envelope of existing turbine technology. This significant source of distributed power could be realized without the need for water impoundments.

We recommend that similar low head/low power hydropower resource assessments be performed for the remaining 16 hydrologic regions of the conterminous U.S. and the state of Alaska. At the same time, efforts should be made to better establish and improve the accuracy of the results.

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ACRONYMS

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 US 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://mn.water.usgs.gov/uzig/eros.reed.doc)*

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.

HUC — hydrologic unit code

INEEL — Idaho National Engineering and Environmental Laboratory

NED — National Elevation Data

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 U.S. and 1:63,360-scale data for Alaska (available for the entire U.S. from USGS). *(http://gisdata.usgs.net/ned/)*

NHD — National Hydrography Dataset

A comprehensive set of digital spatial data that contains information about surface water features such as lakes, ponds, streams, rivers, springs, and wells. (http://nhd.usgs.gov)

PNW — Pacific Northwest

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)*

NOMENCLATURE

Catchment	That 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 of the catchments associated with upstream stream reaches connected to the point.
EDNA Stream Node	Starting point of an EDNA synthetic stream, a confluence, or an intermediate point on an EDNA stream defined as a result of having 5,000 National Elevation Data tiles (30 × 30 m) supplying runoff to the portion of an EDNA synthetic stream between this point and the EDNA node immediately upstream (Note: Each node has an associated catchment and is a pour point.)
EDNA Stream Reach	That portion of a EDNA synthetic stream between two EDNA stream nodes.
Pour Point Flow	The estimated flow of a stream reach equal to the runoff from the corresponding drainage basin.

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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 the energy in the United States. Past efforts to identify and measure the undeveloped hydropower capacity in the U.S. have resulted in estimates ranging from about 70,000 MW to almost 600,000 MW. The Federal Energy Regulatory Commission's (FERC's) 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 energy 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 U.S. hydropower resources.

The previous resource assessments have focused on potential projects that have a capacity of 1 MW and above. DOE identified a need to assess the U.S. hydropower resources for projects of less than 1 MW. In FY 2000, DOE initiated planning for an assessment of hydropower potential for low head (30 feet or less) and low power (1 MW or less) resources. The INEEL in conjunction with the U.S. Geological Survey recently completed the pilot low head/low power hydropower resource assessment (Hall et al. 2002). The principal objective of this pilot study was to develop and demonstrate a method of estimating the hydropower potential of 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 hydropower potential of every stream segment within a chosen study area is assessed. Summing the estimated hydropower potential of all the stream segments in the area provides an estimate of the total hydropower of the area.

The study area chosen for the study reported herein was the Pacific Northwest (PNW) Hydrologic Region, an area encompassing the entire state of Washington and nearly all of Oregon and Idaho. Having hydropower potential estimates in such small increments allowed the regional potential to be divided into total amounts of high power potential (greater that 1 MW), high head/low power potential (less than 1 MW and 30 ft of hydraulic head or greater), and low head/low power (less than 1 MW and 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.

This report is organized by presenting a description of the study area, details of the technical method that was employed to perform the resource assessment, and the results of the assessment. It ends with conclusions based on the results and recommendations for further research and refinement of the technical method.

2. STUDY AREA—PACIFIC NORTHWEST HYDROLOGIC REGION

The PNW Hydrologic Region is one of 21 hydrologic regions in the United States. The conterminous United States is divided into 18 hydrologic regions as shown in Figure 1 with the remaining three regions being Alaska, Hawaii, and Puerto Rico. The hydrologic regions have been numbered using a hydrologic unit code (HUC) of 1 through 21. The PNW Region has been assigned a hydrologic unit code of 17 and is sometimes referred to as “HUC 17.” The terms “HUC 17” and “PNW Region” are used interchangeably.

The PNW Region shown in Figure 2 was chosen for this study because of its variations in topography and climate. The region covers the entire state of Washington, most of Oregon and Idaho and part of western Montana. The region also includes small parts of California, Nevada, Utah, and Wyoming.

Geography and climate vary significantly within the PNW Region. Land elevations range from sea level to over 14,000 feet. The region includes high mountains, extensive plains and deep canyons. Climatic zones range from rain forests in the west to high deserts and steppes in the central interior.

Two major mountain systems are found in the western part of the region: the Coast Range and the volcanic mountains of the Cascade Range. Oregon's Willamette Valley and Washington's Puget Sound Lowlands separate these two mountain systems. The climate of these areas are relatively wet due to their exposure to Pacific storm systems. The Columbia Plateau, east of the Cascade Range in eastern Washington and Oregon, consists primarily of extensive basalt plains dissected in some places by deep canyons. The basalt flows also extend completely across southern Idaho forming the Snake River Plain. The Rocky Mountains cover central and northern Idaho, western Montana, and westernmost Wyoming. Basin and Range features (alternating mountains and valleys) occur along the interior southern border of the region in southernmost Idaho, northern Nevada, northern Utah, and northeastern California. Arid climates are predominate in the Columbia Plateau, Snake River Plain, and Basin and Range regions.

Two major rivers drain most of this region, the Columbia River and its largest tributary, the Snake River. The Columbia River originates in the Canadian Rockies, crossing from Canada into northern Washington. It traverses southward across the Columbia Plateau of central Washington, then bends westward to form the Oregon-Washington state line. During its westward flow to the Pacific Ocean, it crosses both the Cascade Ranges and the Coast Ranges. Numerous large hydropower projects, including the Grand Coulee Dam occur along the Columbia River.

The Snake River originates in western Wyoming near Yellowstone National Park. It traverses the entire length of southern Idaho along the Snake River Plain, then turns northward into Hells Canyon. The Snake River joins the Columbia in south-central Washington.

Other tributaries of the Columbia include the Willamette River in western Oregon, the Flathead River and Clarks Fork in western Montana, and the Pend Oreille River in northern Idaho and Washington.

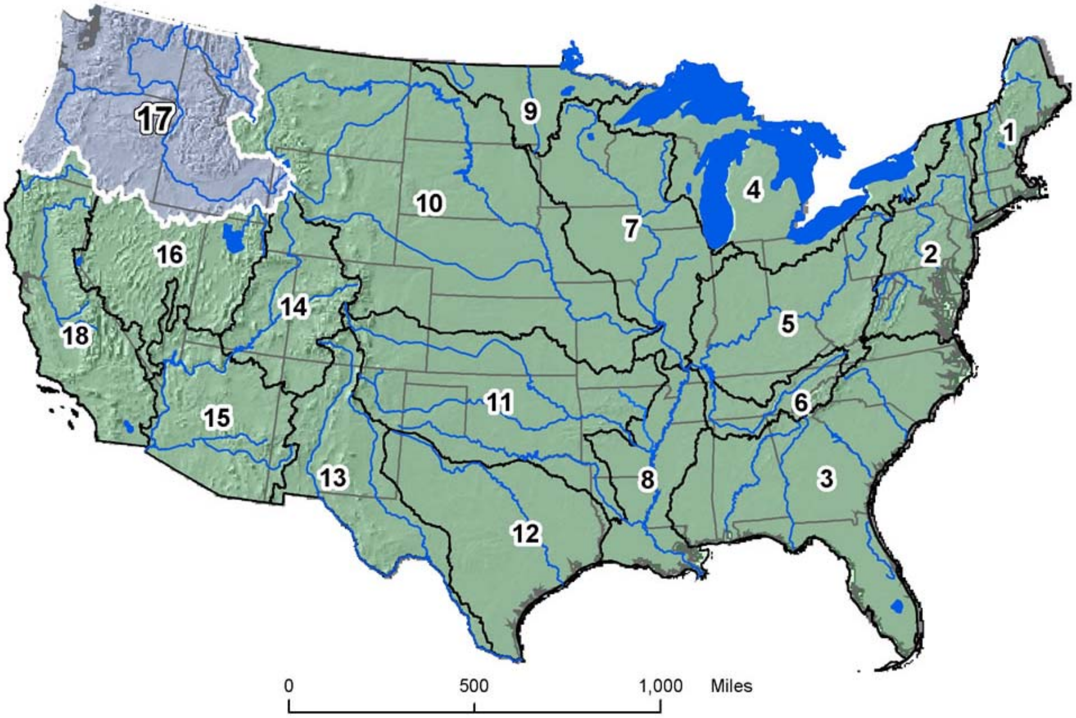

Figure 1. The 18 hydrologic units of the conterminous United States.

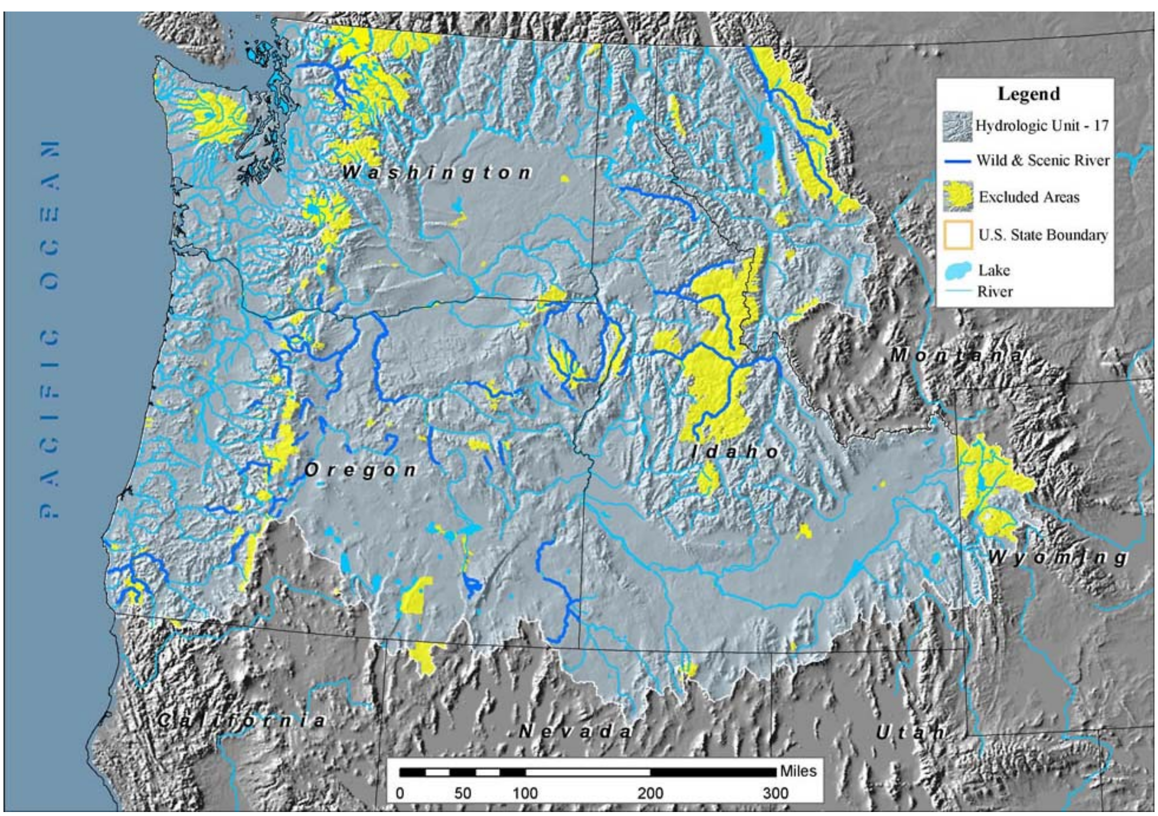

Figure 2. Pacific Northwest Hydrologic Region.

3. TECHNICAL APPROACH

The fundamental approach of this study was to calculate the hydropower potential of every stream reach within 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 filtered to account for waterways excluded from development and 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 to determine "available" power potentials. (Note: The term "available power potential" in this study simply equates to total, nonexcluded power potential minus developed power potential. No economic or development feasibility assessment was performed.)

The calculation of reach hydropower potential requires two values: the reach flow and the hydraulic head corresponding to the elevation difference between the upstream and downstream ends of the reach. The reach flow was the average of the calculated flows at the inlet and outlet of the reach. The flows were calculated using a regression equation in which drainage area, mean annual temperature, and mean annual precipitation were the independent variables. The reach hydraulic head was derived from the hydrography as defined by a digital elevation model.

The subsections that follow describe the details of the various aspects of the technical approach:

- Calculation of reach hydropower potential
- Filtering processes to validate streams, account for excluded waterways, and parse potentials between technology class operating envelopes
- Determination of available power potential based on developed hydropower.

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

The calculation of the stream flow, hydraulic head, and subsequently, hydropower 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 flows. While the National Hydrography Dataset (NHD) provides the best two-dimensional depiction of the U.S. 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 and drainage areas 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 3. 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 downstream end of each reach, which has been termed the catchment "pour point." The drainage area supplying runoff at a pour point is equal to the sum of the areas of all of upstream catchments.

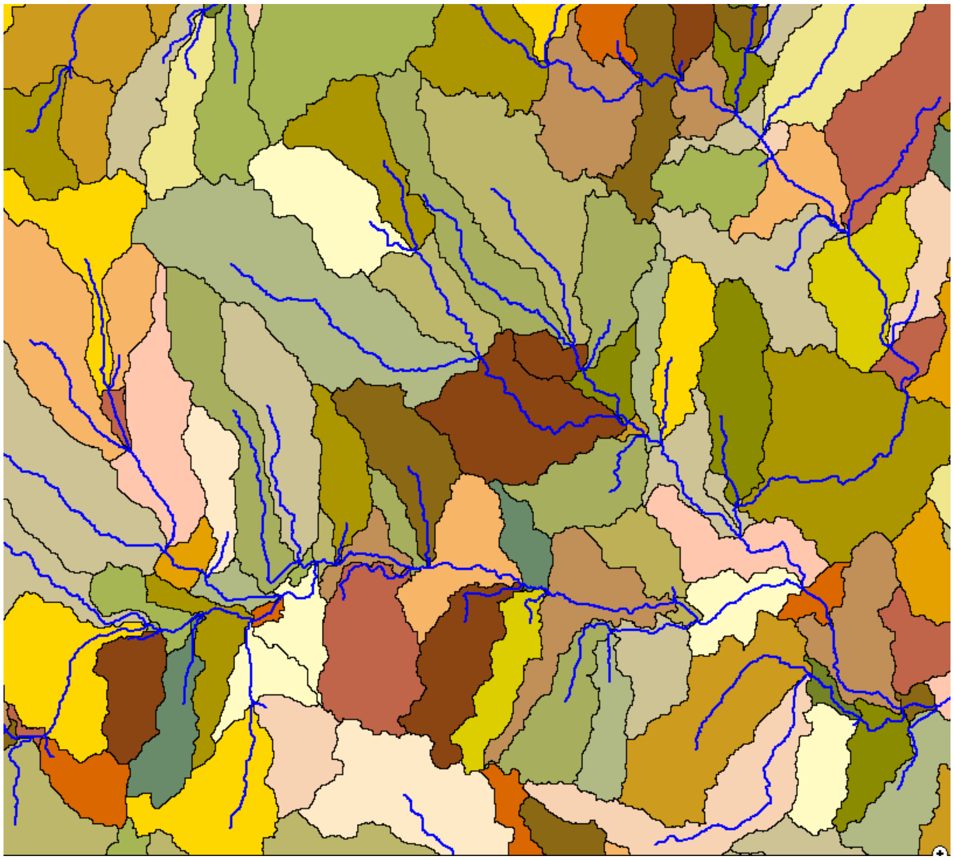

Figure 3. EDNA-derived catchments and synthetic streams.

Mean annual flow rates were calculated using a regression equation developed specifically for the PNW Region (Vogel et al. 1999).

$$Q_{11} = e^{-10.18} * A^{1.00269} * P^{1.86412} * T^{-1.1579}$$

where

Q_{11} = mean flow for a site in the PNW Region in cubic meters/second

A = drainage area in square kilometers

P = mean annual precipitation in millimeters/year

T = mean annual temperature in degrees Fahrenheit times 10.

This equation is based on gaged stream flows within the region. The drainage area used is the sum of the upstream catchment areas. The other two variables, precipitation and temperature, were derived from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (Daly et al. 1994). Both temperature and precipitation data contained in the PRISM dataset are in grid format. The cells of the grids are much larger than the cells found in the EDNA dataset; therefore, an averaging function was used to calculate the mean annual precipitation and 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 area. These values along with the drainage area were used to calculate the flow at the pour point of each catchment.

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 or potential energy 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 hydropower 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 hydropower potential of the flow at the inlet to the reach, which 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. Algrabic manipulation shows that this equation reduces to:

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

Thus, the reach hydropower 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. It is also useful to note that Q_o is the pour point flow for the catchment associated with the reach, and Q_i is equal to the sum of the pour point flows of the catchments immediately upstream of the reach (catchment) of interest.

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

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

This master dataset was subsequently filtered to:

- Remove stream reaches that were not validated using the NHD
- Identify reaches that were excluded from development because of statutory protections
- Identify reaches having hydropower potentials within the low head/low power regime
- 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.

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 the PNW Region. It is clear from this comparison that some of the synthetic streams reaches are not validated by the NHD and must be removed so as not to inflate the total hydropower potential estimate. To identify these "false" synthetic stream reaches and determine their effect on the regional, total hydropower potential, known stream locations found in the NHD were intersected with the catchments associated with EDNA synthetic streams. This allowed the master dataset to be divided into two subsets: one containing all the reaches whose catchment contained an NHD stream segment and one containing all the reaches whose catchment 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 showing through in red as illustrated in Figure 4. 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 encompassed the synthetic reach.

In order to evaluate the effect of the "false" stream reaches on total hydropower potential, the hydropower potentials of the reaches in the false reach dataset were summed and compared to the sum of the hydropower potentials of all the stream reaches in the master dataset. It was found that 3% of the total potential power calculated for the PNW Region using the master dataset is due to false stream segments.

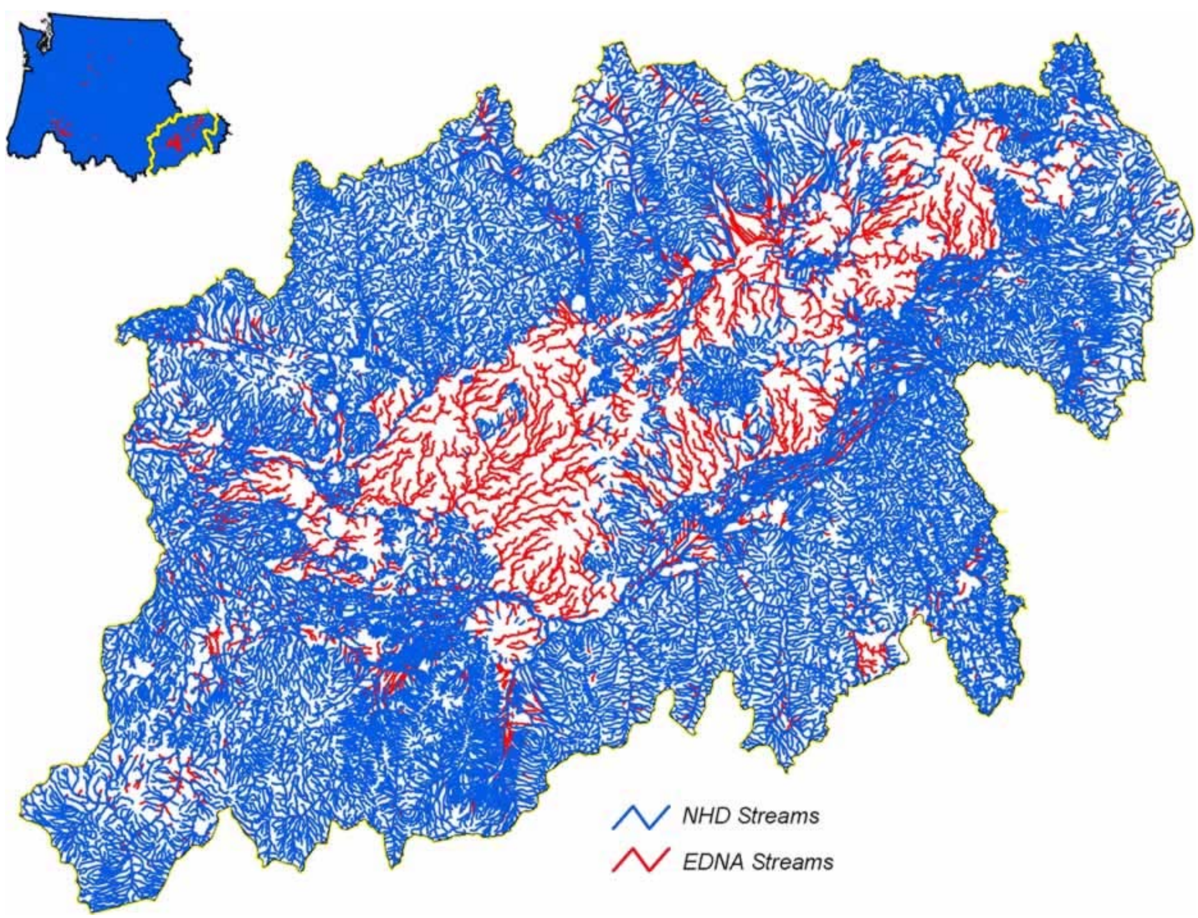

Figure 4. NHD streams overlaying EDNA synthetic streams for the PNW Region.

3.3 Identification of Excluded Waterways and Hydropower Potential

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 such as these were designated as “excluded areas.” Catchments that overlap any portion of these "excluded areas" were designated as “excluded catchments.” The hydropower potential associated with the stream reaches in these excluded catchments was calculated and was subsequently subtracted from the hydropower potentials of interest for the PNW Region, so that it would not contribute to available hydropower potential.

3.3.1 Classes of Excluded Waterways

Two geographic information system (GIS) data layers from the National Atlas of the United States were used to locate excluded 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 is not available online. Determining the boundaries of lands protected by nonfederal agencies would have entailed contacting a large number of agencies within the eight states in 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 federal lands were used to determine the extent of excluded areas.

The categories of federal lands listed in the GIS dataset “Federal and Indian Lands” were reviewed to determine categories that defined excluded areas. Based on this review, the following categories of federal lands were selected as excluded 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 to be excluded from hydropower development.

3.3.2 Methodology for Identifying Excluded Stream Reaches

The final excluded area data layer was intersected with the EDNA catchment data layer to identify catchments containing stream reaches that should be excluded from consideration as sources of potential hydropower. Two data subsets resulted: one containing data for reaches that were excluded from hydropower development and one containing data for reaches that were not excluded.

3.4 Determining Developed Hydropower Capacity in the PNW Region

The developed hydropower capacity within the PNW Region was taken from Federal Energy Regulatory Commission's *Hydroelectric Power Resources Assessment (HPRA) Database*. The developed capacities of plants in the PNW Region were summed to determine the total developed hydroelectric capacity in the region.

3.5 Identification of Low Head/Lower Power Stream Reaches

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

- All hydropower potential less than 100 kW (microhydro)
- Hydropower 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 regime is shown graphically in Figure 5.

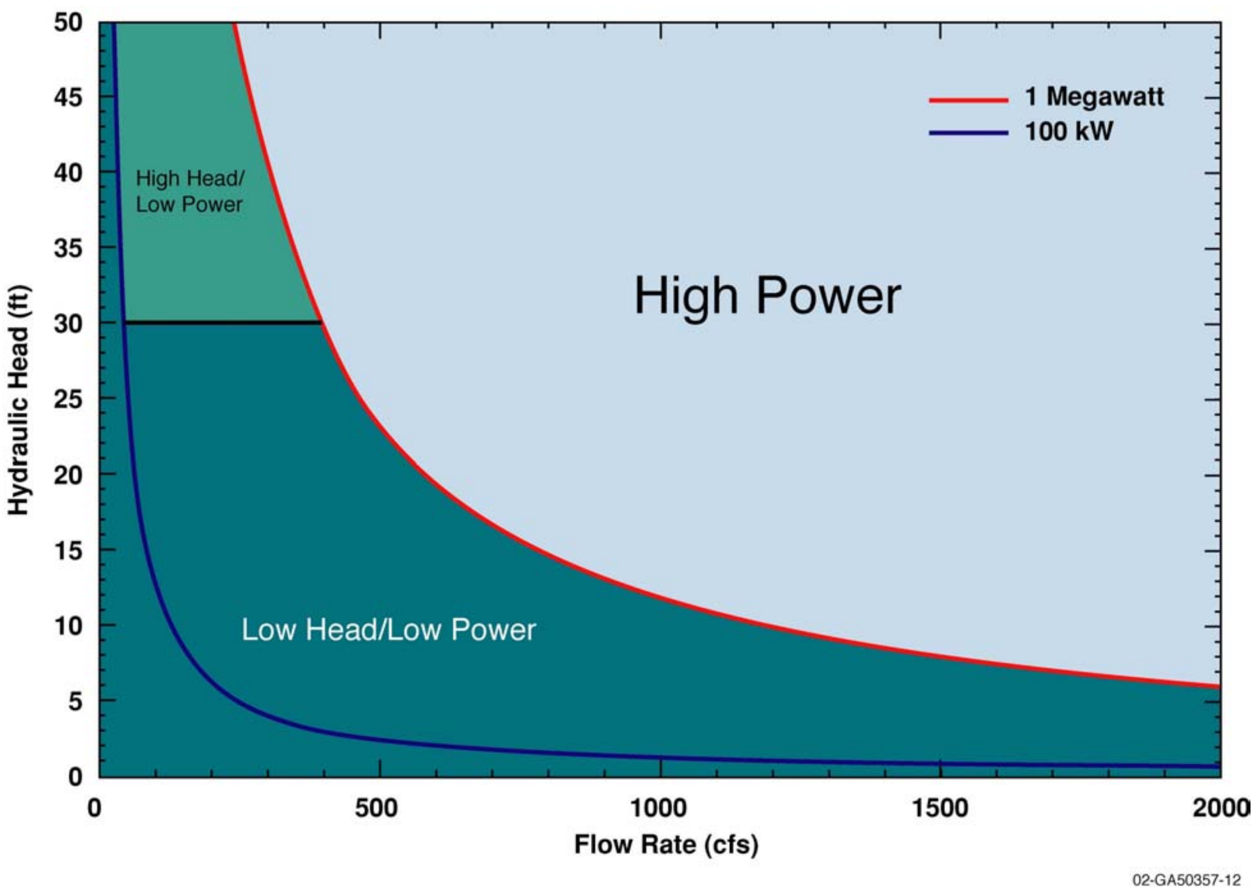

Figure 5. The low head/low power regime.

Standard database query techniques were applied to the validated master dataset described in Subsection 3.2 using the criteria for low head/low power as the selection criteria. This resulted in the identification of stream reaches having hydropower potentials within the boundaries of the low head/low power region. These reaches were also filtered as described in Subsection 3.3 to identify the low head/low power reaches that were excluded and not excluded from development.

3.6 Identification of Stream Reaches Corresponding to the Operating Envelopes of Three Classes of Low Head/Low Power Hydropower Technologies

The low head/low power regime shown in Figure 5 has been divided into the operating envelopes of three classes of low head/low power technologies:

- Microhydro technologies—Power less than to100 kW
- Conventional turbines—Power greater than or equal to 100 kW, but less than 1 MW AND hydraulic head greater than or equal to 8 ft, but less than 30 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 6.

Standard database query techniques were applied to the dataset containing low head/low power reaches identified as described in Subsection 3.5. The criteria for defining each of the technology class operating envelopes were used as the selection criteria. This resulted in the identification of stream reaches having hydropower potentials within the boundaries of the operating envelopes. These reach subsets were also filtered as described in Subsection 3.3 to identify the reaches that were excluded and not excluded from development.

3.7 Calculation of PNW Region Total Hydropower Potentials of Interest

Total hydropower potentials of interest were calculated by summing the reach hydropower potentials within each of the datasets that were determined as described in the previous subsections. "Available" hydropower potential was determined by accounting for the corresponding amount of developed hydroelectric capacity. No feasibility analysis was performed to further refine the estimates of available hydropower potential.

3.7.1 Total Hydropower Potential

Summing of the reach hydropower potentials in the validated master dataset described in Subsection 3.2 yielded the estimated total hydropower potential for the region.

3.7.2 Total Excluded And Nonexcluded Hydropower Potential

Summing of the reach hydropower potentials in the excluded and nonexcluded reach datasets described in Subsection 3.3 yielded the estimated total, excluded, and nonexcluded hydropower potentials for the region.

3.7.3 Total Available Hydropower Potential

The total available hydropower potential was determined by subtracting the total developed hydroelectric capacity in the region from the total nonexcluded hydropower potential.

3.7.4 Low Head/Low Power Hydropower Potentials

The total, excluded, nonexcluded, and available hydropower potentials for the low head/low power regime were calculated using the same processing as described above to obtain the total values. However, in this case the dataset containing all low head/low power reaches and the excluded and nonexcluded subsets of this dataset were used. The available potential was equal to

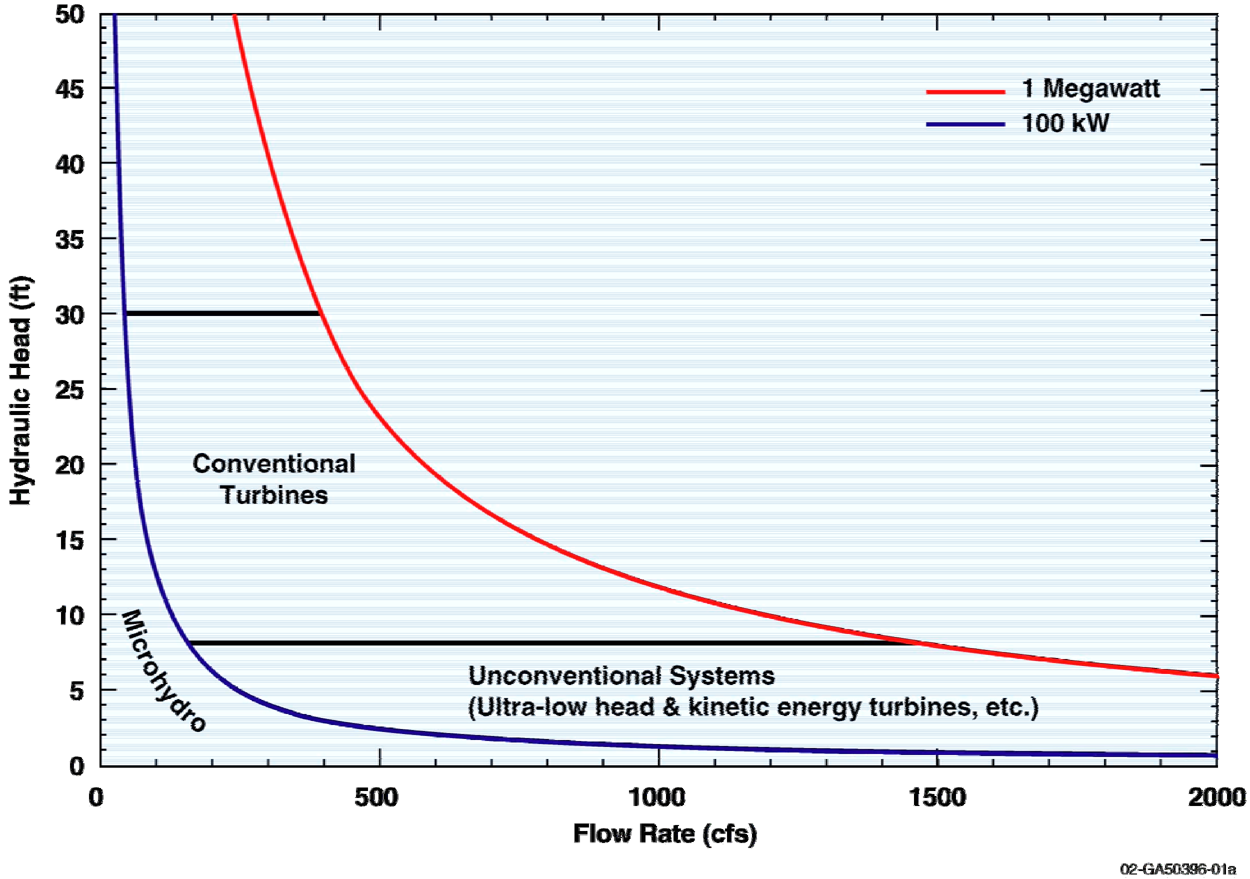

Figure 6. Operating envelopes of three classes of low head/low power hydropower technologies.

the nonexcluded potential, because no developed hydroelectric capacity in the low head/low power regime was listed in the FERC reference.

3.7.5 Hydropower Potentials By Hydropower Technology Class

The total, excluded, nonexcluded, and available hydropower potentials for each hydropower technology class were also calculated using the same processing as described above to obtain the low head/low power values. Each set of hydropower potentials for the three classes was calculated using a set of reach hydropower potentials corresponding to the technology class operating envelope and the excluded and nonexcluded subsets. Available hydropower potential for each technology class was equal to the nonexcluded value because of the absence of developed hydroelectric capacity in the low head/low power regime.

4. RESULTS

The results of the calculations described in Subsection 3.7 are presented in this section. The results are presented in four sets of total hydropower potentials of interest for the PNW Region:

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

The accuracy of the hydropower potential estimates is dependent on the accuracy of the individual stream reach hydropower potentials that were summed to produce total values of interest. The calculated reach flow rates had a standard error of ± 36%. Because of the direct relationship of hydropower potential on flow rate (see Subsection 3.1), the standard error of the reach hydropower potential values was also at least ± 36%. If the errors are uniformly distributed, the accuracy of a total value produced by summing a large number of reach hydropower potentials may be better than the accuracy associated with the values that were summed.

Table 1 presents a summary of the results with each set of results that are discussed respectively in the subsections that follow.

4.1 Total Hydropower Potential

The sum of all the validated reach hydropower potentials provided an estimate of 76,425 MW of hydropower potential in the PNW Region. FERC has cataloged 32,430 MW of developed hydroelectric capacity in the region. The total hydropower potential of stream reaches excluded from development was 20,294 MW. Subtracting the developed and excluded hydropower potentials from the total provides an estimate of 23,701 MW of hydropower in the region that has not been developed and is not excluded from development. A previous hydropower resource assessment (Conner et al. 1998) that focused on sites with greater that 1 MW of undeveloped capacity resulted in a combined undeveloped capacity of the states of Idaho, Montana, Oregon, and Washington of approximately 22,000 MW. This number lends credence to the approximately 24,000 MW of available potential estimated by the present study considering that the PNW Region does not include all of Montana, but addresses every stream segment in the region.

This available hydropower potential figure is an upper limit and provides an indicator of whether further investigation is warranted. Additional exclusions by state agencies that were beyond the scope of the project to research would most certainly reduce this number. The number would no doubt be further significantly reduced based on the engineering and economic feasibility of specific sites.

The distribution of total hydropower potential between developed, excluded, and available power is shown graphically in Figure 7. This figure shows that only approximately 40% of the hydropower potential in the region has been developed. The hydropower potential excluded by federal statute is approximately 30% of the total, regional hydropower potential. This leaves approximately 30% of the regional potential undeveloped.

4.2 Available Power Potential by Regime

The distribution of the total, available hydropower potential in the region (≈24,000 MW) between the high power (greater than or equal to 1 MW), high head/low power (hydraulic head of 30 ft or more and power less than 1 MW, excluding the microhydro operating envelope), and low head/low power is shown graphically in Figure 8. This figure shows that two-thirds (66%) of the available hydropower potential is in the high power regime and one-third (34%) is in the low power regime with 27% being high head/low power potential, and 7% being low head/low power potential. This result is not surprising given the extent of the mountainous terrain in the region.

Table 1. Summary of results of hydropower resource assessment of the Pacific Northwest Hydrologic Region.

Power in MW	Total	Developed	Excluded	Available
TOTAL POWER	**76,425**	**32,430**	**20,294**	**23,701**
TOTAL HIGH POWER	**66,664**	**32,400**	**18,662**	**15,602**
High Head/High Power	**57,046**	**32,270**	**16,000**	**8,776**
Low Head/High Power	**9,618**	**130**	**2,662**	**6,826**
TOTAL LOW POWER	**9,761**	**31**	**1,632**	**8,098**
High Head/Low Power	**7,769**	**25**	**1,429**	**6,315**
Low Head/Low Power	**1,992**	5	**203**	**1,784**
Conventional Turbine	695	3	71	621
Unconventional	310	1	59	250
Microhydro	987	2	73	912

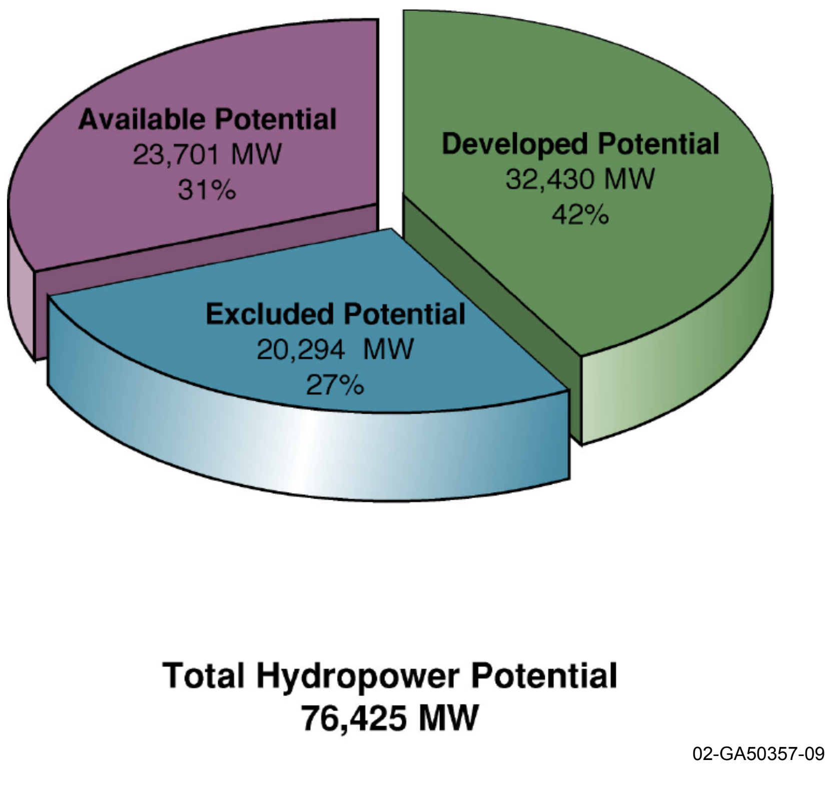

Figure 7. Distribution of total hydropower potential in the Pacific Northwest Hydrologic Region.

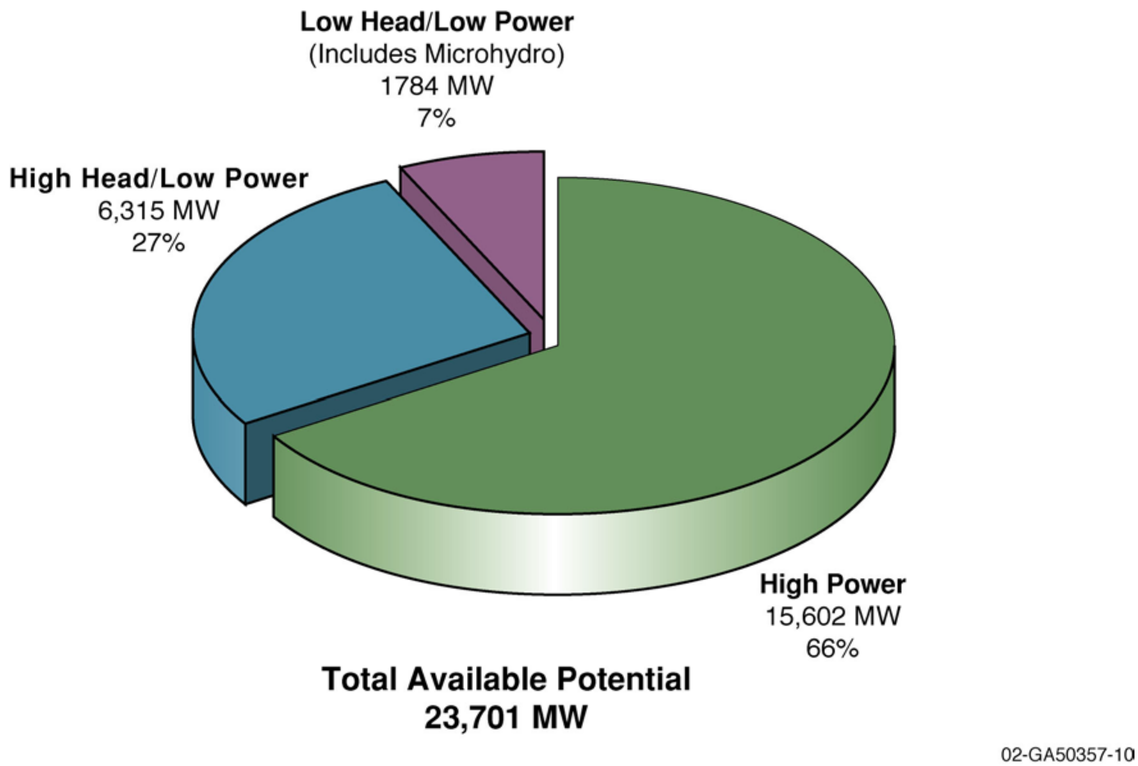

Figure 8. Distribution of available hydropower potential in the PNW Region.

4.3 Low Head/Low Power Potential

The sum of all the validated reach hydropower potentials having values that fell within the low head/low power regime shown in Figure 5 provided an estimate of 1,992 MW of low head/low power hydropower potential in the PNW Region. FERC listed 5 MW of developed hydropower capacity that fell within the low head/low power regime. The total hydropower potential of the reaches that were both low head/low power and were excluded from development was 203 MW. Subtracting the developed and excluded hydropower potentials from the total low head/low power potential provides an estimate of 1,784 MW of low head/low power hydropower in the region that has not been developed and is not excluded from development. As mentioned in the previous subsection, this figure is an upper limit and is subject to reductions due to exclusion by state agencies and feasibility assessments.

The validated reach hydropower potentials having values that fell within each of the operating envelopes of the three classes of low head/low power hydropower technologies shown in Figure 6 were summed to provide an estimate of the total hydropower potential associated with technology class. This resulted in estimates of 695 MW, 310 MW, and 987 MW of hydropower potential for conventional turbines, unconventional systems, and microhydro technologies, respectively. The total hydropower potentials that were either developed or excluded from development and corresponded to each of the operating envelopes were 74 MW, 60 MW, and 75 MW, respectively. Subtracting the developed and excluded potentials from the total potential for each technology class resulted in estimates of available hydropower potential of 621 MW, 250 MW, and 912 MW, respectively. As stated in the previous two subsections, these availability estimates do not account for exclusions by state agencies or reductions resulting from feasibility assessments.

The distribution of low head/low power hydropower potential amongst the three classes of technologies is shown in Figure 9. This figure shows that approximately 35% of the available low head/low power hydropower potential is captured by the operating envelope of conventional turbines, which would require relatively little development. Half (51%) is captured by the operating envelope of microhydro technologies. The remaining 14% corresponds to unconventional systems.

The geographic locations low head/low power potential sites by technology class are shown in Figure 10. This figure shows a significant density of sites for conventional turbines and unconventional systems in coastal areas west of the Cascade Mountains. It also shows that microhydro sites are located principally in the Columbia Plateau of eastern Oregon and Washington, and the Snake River Plain in southern Idaho.

Because of the extent of the mountainous terrain in the PNW Region, most of the approximately 8,000 MW of available low power potential (less than 1 MW) is high head (30 ft or greater) potential. This hydropower potential totals more than 6,000 MW and is distributed over the region as shown in Figure 11. This figure shows that only the plateau and plain areas do not contain a significant number of these sites.

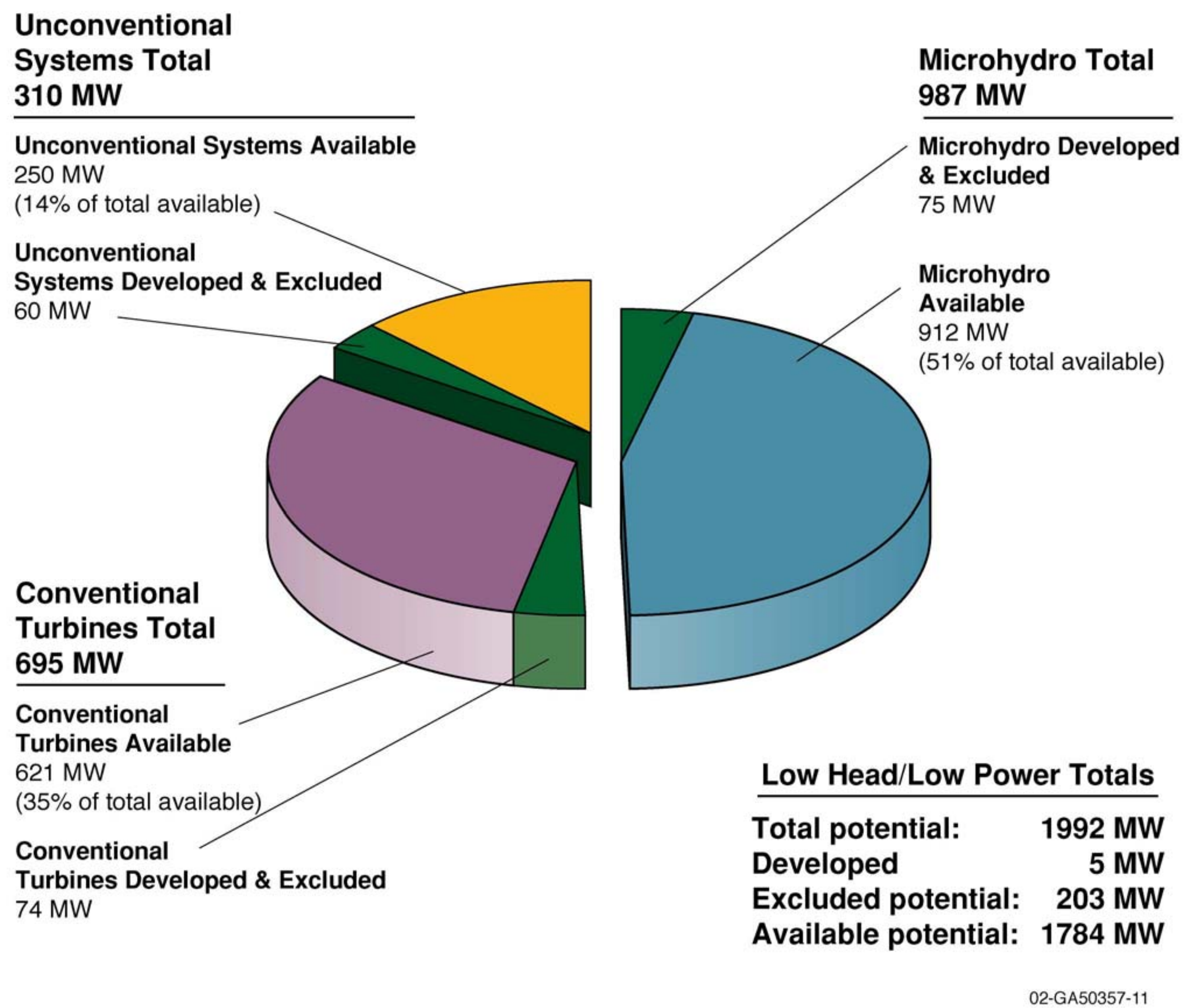

Figure 9. Distribution of low head/low power hydropower potential in the PNW Region amongst three low head/low power hydropower technology classes.

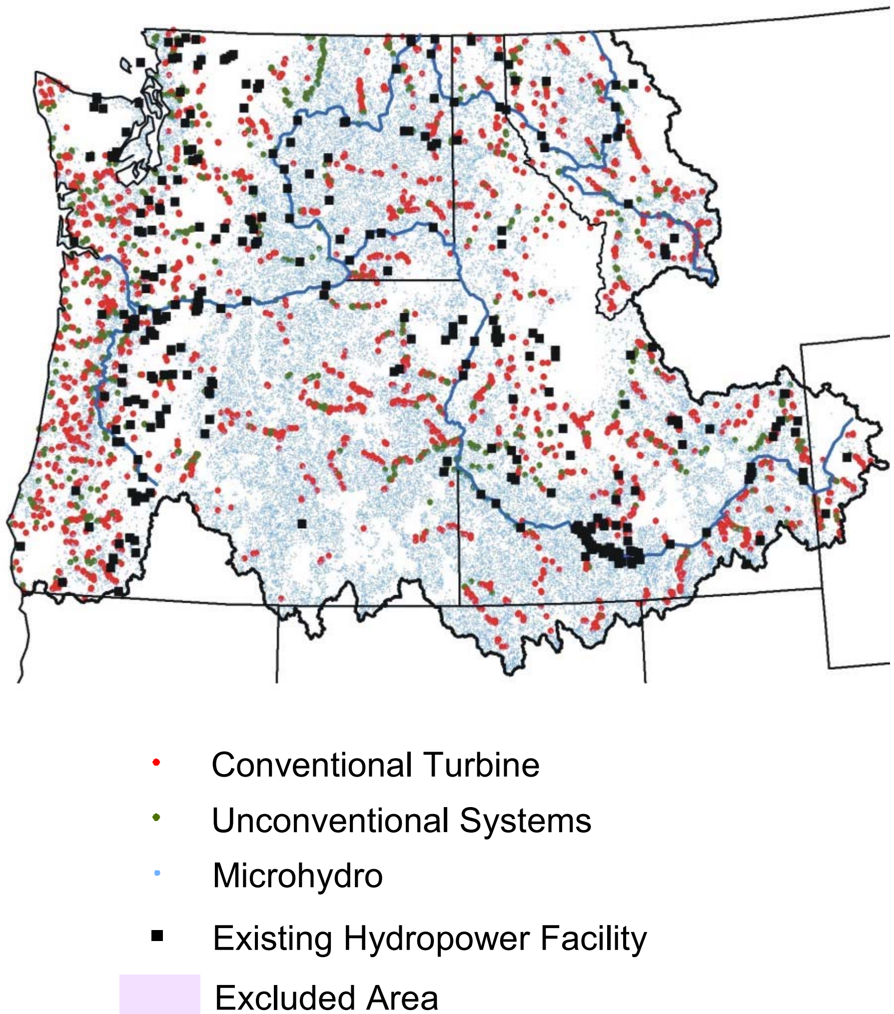

Figure 10. Location of low head/low power hydropower potential sites in the Pacific Northwest Region by technology class.

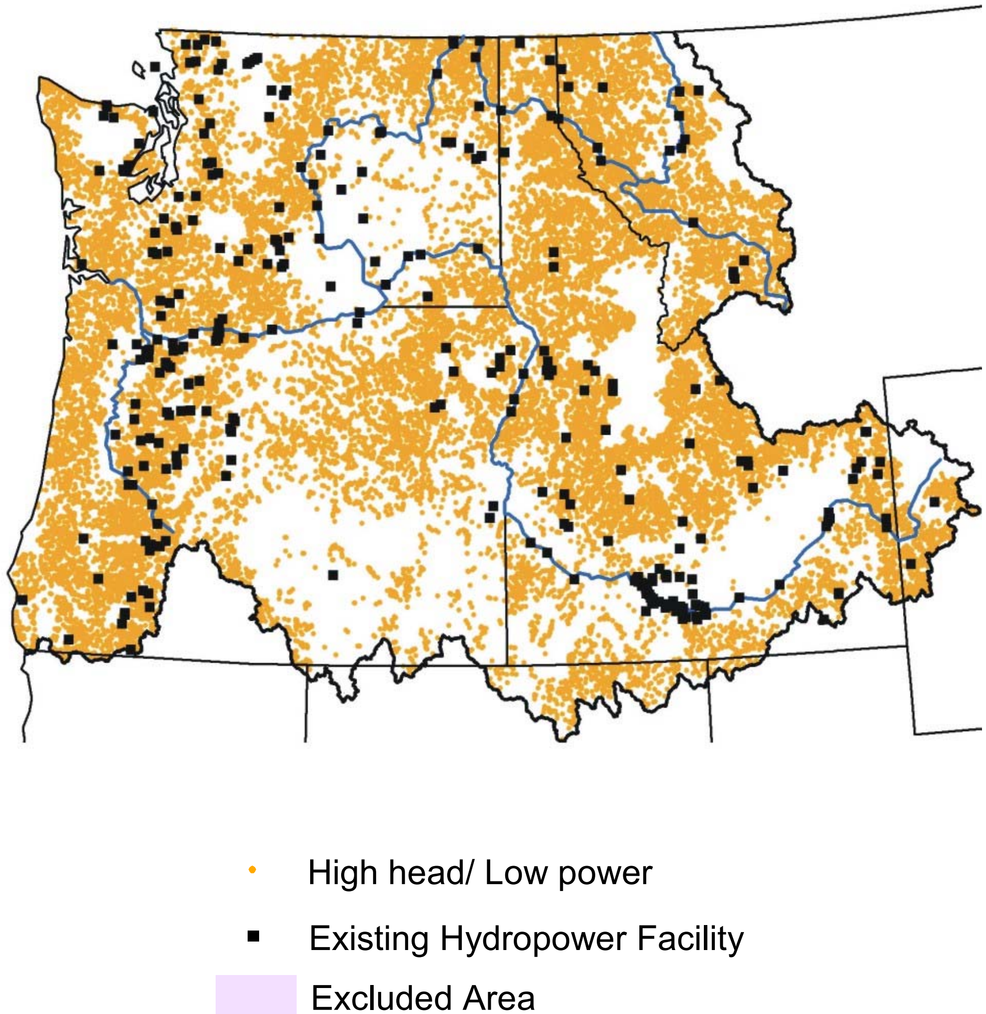

Figure 11. Location of high head/low power hydropower potential sites in the Pacific Northwest Region.

5. CONCLUSIONS AND RECOMMENDATIONS

This study has resulted in an estimate of approximately 24,000 MW of available hydropower potential in the PNW Region. One-third or 8,000 MW is low power hydropower potential of which approximately 2,000 MW is low head potential. These estimates are sufficiently large to warrant further research regarding possible siting of low power hydropower installations in the region. Low power sites are sufficiently numerous and uniformly distributed over the region to offer significant sources of distributed power without the need for reservoirs.

The study has shown that 6,000 MW of available high head/low power potential and an additional 621 MW or 35% of available low head/low power hydropower potential fall with the operating envelope of existing, conventional turbine technology. Thus this fraction of the available hydropower potential could be realized without investments in basic research. Sixty-five percent of the available low head/low power hydropower potential corresponds to technologies (microhydro and unconventional systems) that would require additional research and development; although, some units currently exist that could be put into service.

This study and the previous, pilot study (Hall, et al. 2002) have shown that it is possible to obtain an estimate of the hydropower potential of the entire United States that is based on minutely detailed hydrography. Application of the technical approach used in this study to each of the 18 hydrologic units in the conterminous U.S. and ultimately the State of Alaska will allow assessment of the available hydropower potential of each region and identification of the type of technology best suited to realize that potential. A composite of these regional results will provide a spatial distribution of available hydropower potential in the conterminous U.S. as well as an estimate of total available U.S. potential. Given the demonstrated possibility of obtaining this important, fundamental information, we recommend the hydropower potential of the 16 remaining hydrologic regions in the conterminous U.S. and the State of Alaska be assessed using the same technical approach. Figure 12 shows the two regions that have been assessed to date and the 16 regions in the conterminous U.S. that remain to be assessed.

Early in the expanded study, we recommend that results of stream reach flow rate and hydropower potential calculations be benchmarked against known, gauged flows and installed hydropower capacity. The 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. If possible, equations that predict median rather than mean annual stream flow should be used to obtain better temporal estimates of hydropower potential.

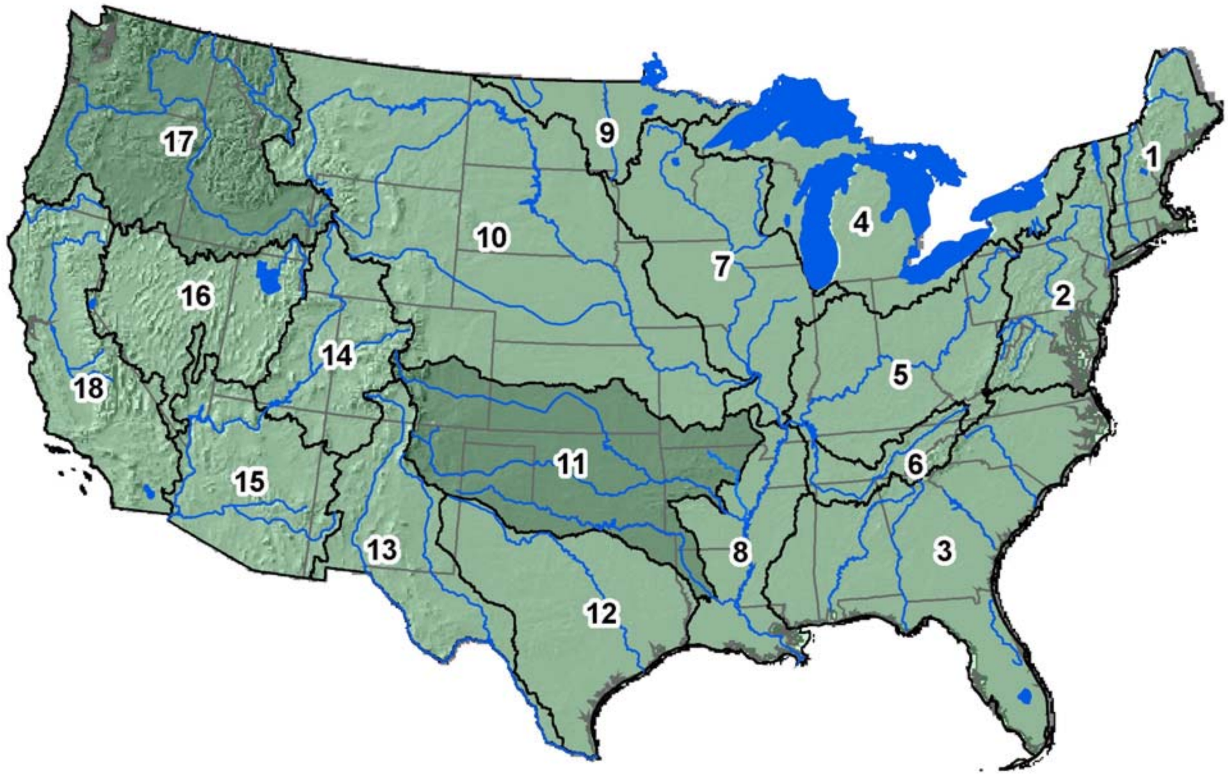

Figure 12. Location of the Arkansas White Red Hydrologic Region (HUC 11) and the Pacific Northwest Hydrologic Region (HUC 17), which have been assessed, and the remaining 16 hydrologic regions in the conterminous U.S. to be assessed.

6. REFERENCES

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