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June 2015

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

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Summary

The Basin-Scale Opportunity Assessment (BSOA) Initiative, led by the U.S. Department of Energy's (DOE's) Water Power Program, established an integrative, three-phase approach for assessing complementary hydropower-environmental opportunities at the scale of a river basin. Phase 1 of this approach is a scoping assessment process for a given river basin that is intended to provide initial identification, classification, screening, and integration of possible hydropower and environmental opportunities for DOE and basin stakeholders to consider carrying forward as appropriate. Phases 2 and 3 involve greater stakeholder engagement and technical analysis pertaining to potential opportunities identified during Phase 1. Pacific Northwest National Laboratory (PNNL) and Oak Ridge National Laboratory (ORNL) developed a technical approach and methodology for BSOA Phase 1 assessments and performed assessments for the Bighorn, Connecticut, and Roanoke River basins. This report summarizes the Phase 1 assessment for the Bighorn River basin.

The scoping assessment for the Bighorn River basin identified *complementary* hydropower-environmental opportunities for powering non-powered dams (NPDs), new stream-reach developments (NSDs), in-canal small hydropower, and efficiency improvements at existing hydroelectric facilities. A complementary hydropower-environmental opportunity was defined as a situation where an existing environmental issue can be improved, either directly or indirectly, in conjunction with a hydropower action. Situations where there may be potential cause-effect benefits of a hydropower action on an existing environmental issue were assessed at the individual project scale for NPD opportunities. Opportunities for indirect environmental improvements, for example through compensatory mitigation, were assessed by quantifying hydropower opportunities (NPD, NSD, in-canal small hydropower, and existing facility improvements) and environmental issues at the sub-basin scale (eight-digit hydrologic unit code drainages). Hydropower opportunity data were obtained from ORNL's National Hydropower Asset Assessment Program (NHAAP) database and other government or private hydropower assessments, where available.

The assessment of potential hydropower capacity that could be added by powering NPDs identified 4 of 143 (5.6%) NPDs in the Bighorn River basin that meet our criteria for a potential opportunity; i.e., the NPDs have ≥0.1 megawatt (MW) capacity, do not intersect lands protected from development, are not found in river segments protected under the National Wild and Scenic Rivers Act, and do not feature habitats of species protected under the federal Endangered Species Act. These four opportunities represent a combined capacity of 9.6 MW, although most of that capacity is attributed to one location. Three of the four NPD sites were associated with potential direct complementary environmental opportunities, including opportunities to reduce hydrologic disturbance, improve water quality, and increase instream flow in high-quality trout fisheries.

A total of 204 potential NSD locations were identified in the basin, representing a total capacity of 463 MW. Of these 204 potential NSD locations, 159 meet the criteria for a potential opportunity and represent a total capacity of 368.7 MW. Although each site is treated as an opportunity in our analysis, some sites would be mutually exclusive from actual development because of their proximity to each other. Therefore, we aggregated NSD potential from individual sites to the sum of sites within 12-digit hydrologic unit drainages in the Bighorn River basin (N = 44) to represent NSD potential by reach rather than site. Areas with the greatest raw potential for NSD include the lower Wind River near Riverton and

Thermopolis, Wyoming, the Shoshone River near Cody and Lovell, Wyoming, and the lower Bighorn River near Hardin, Montana.

A total of 120 in-canal/conduit hydropower opportunity sites were identified from previous assessments by the U.S. Bureau of Reclamation (USBR) and Wyoming Water Development Commission. Of these 120 sites, 48 have a potential individual capacity of ≥0.1 MW and represent a combined total capacity of 32.9 MW. These opportunities are concentrated primarily on USBR infrastructure for the Shoshone Project (N = 30) and Pick-Sloan Missouri Basin Program Riverton Unit (N = 10). The remaining eight sites are located on infrastructure in Greybull Valley and Cody Canal Irrigation districts.

Hydropower production at some of the four existing hydropower dams in the basin (representing a total installed capacity of 297.1 MW) might be increased by replacing generation machinery or improving operational efficiency. Improvements at existing hydropower facilities, however, will necessarily be site-specific and dependent on the age of the plant, cost-effectiveness of the improvements, any required mitigation, and other factors. To provide a point of comparison to other hydropower opportunities in the Bighorn River basin, we applied a modest 1% increase in capacity (i.e., approximately 3 MW of additional generating capacity). Such improvements could be linked with flow enhancements or minimum flow requirements at existing sites. Low flow turbines could be installed where there are none presently or hydropower turbines could be used in lieu of excess spill or to provide flow in bypass reaches. Both could result in greater minimum flows to benefit aquatic resources. More detailed examination of flow enhancement related to turbine or operational improvements at existing facilities would be appropriate in a Phase 3 Technical Analysis.

Indirect opportunities were quantified by summarizing and comparing the total number of each hydropower opportunity type (i.e., powering NPDs, NSDs, in-canal small hydropower, and efficiency improvements at existing powered dams,) and environmental issue type at the scale of eight-digit hydrologic unit code drainages in the Bighorn River. The Lower Bighorn drainage ranked the highest in raw potential for hydropower in terms of additional capacity (125.7 MW). However, most (92%) of this additional capacity is attributed to NSDs, which likely have more environmental impediments than other hydropower opportunity types and would require greater compensatory mitigation. Improving water quality or recreational access where high-quality fisheries exist emerged in our analysis as a potential indirect complementary opportunity of NSD development in the Lower Bighorn drainage, although such development could exacerbate hydrologic disturbance in the drainage. The Shoshone drainage of the Bighorn River basin has a more balanced set of in-canal (13.5 MW) and NSD hydropower opportunities (58.9 MW) that could add considerable hydropower capacity if fully developed. Analysis of existing environmental issues in the Shoshone drainage revealed a mix of opportunities for environmental improvement, including minimizing/reducing hydrologic disturbance, preventing canal entrainment, securing instream flow, and maintaining/improving high-quality trout fisheries. The more diverse suite of hydropower opportunity types and environmental issues in the Shoshone drainage may provide a more tractable set of win-win scenarios than drainages with a lower diversity of hydropower opportunity types and environmental issues.

Acknowledgments

We thank Hoyt Battey and Thomas Heibel (DOE); members of the BSOA national steering committee, including Linda Church-Ciocci (National Hydropower Association), Julie Keil (Portland General Electric), Jeff Leahy (National Hydropower Association), Kerry McCalman (USBR]), Lisa Morales and Kamau Sadiki (U.S. Army Corps of Engineers), Jeff Opperman (The Nature Conservancy [TNC]), Mike Pulskamp (BOR), Richard Roos-Collins (Water and Power Law Group), and John Seebach (Low Impact Hydropower Institute).

We are grateful for the guidance provided by Clark Bishop with the USBR Renewable Energy Program Office. We also appreciate the local knowledge of Bighorn basin issues and key contacts provided by Clayton Jordan and Hilaire Peck with the Montana and Wyoming area Bureau of Reclamation Offices.

Acronyms and Abbreviations

ac	acre(s)
BSOA	Basin-Scale Opportunity Assessment
cfs	cubic (foot) feet per second
DO	dissolved oxygen
DOE	U.S. Department of Energy
DOM	dissolved organic matter
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
ft	foot (feet)
FY	fiscal year
GAP	Gap Analysis Program
GIS	geographic information system
HUC	hydrologic unit code
km	kilometer(s)
km^2	square kilometer(s)
m	meter(s)
mi	mile(s)
MOU	Memorandum of Understanding
MW	megawatt(s)
NABD	National Anthropogenic Barrier Dataset
NCAT	Northeast Aquatic Connectivity Tool
NFHAP	National Fish Habitat Action Plan
NHD	National Hydrography Dataset
NHAAP	National Hydropower Asset Assessment Program
NOAA	National Oceanic and Atmospheric Administration
NMFS	National Marine Fisheries Service
NPD	non-powered dam
NSD	new stream-reach development
NPD	non-powered dams
NWSR	National Wild and Scenic River
ORNL	Oak Ridge National Laboratory
T&E	threatened and endangered
TNC	The Nature Conservancy
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey
WBD	Watershed Boundary Dataset

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1.0 Introduction

The Basin-Scale Opportunity Assessment (BSOA) Initiative originated as an action item in the 2010 Memorandum of Understanding (MOU) for Hydropower among the U.S. Departments of Energy (DOE), Interior (Bureau of Reclamation [USBR]), and Defense (U.S. Army Corps of Engineers [USACE]) (DOE et al. 2010). The purpose of the Hydropower MOU is to "…help meet the Nation's needs for reliable, affordable, and environmentally sustainable hydropower by building a long-term working relationship, prioritizing similar goals, and aligning ongoing and future renewable energy development efforts…" among the three signatory federal agencies. The MOU agencies, while recognizing that hydropower is the largest source of renewable energy in the nation, emphasized that efforts to increase hydropower generation must avoid, mitigate, or improve environmental conditions in our nation's rivers and watersheds. Accordingly, a goal of the BSOA Initiative is to develop and implement an integrative approach for the assessment of hydropower and environmental opportunities at a basin scale. Another goal is to identify commonality among the sometimes disparate goals of regional stakeholders and increase the possibility that development can proceed with fewer conflicts and environmental consequences. Thus, information from BSOAs is intended to encourage subsequent dialog among regional stakeholders about potential actions that can be taken to increase hydropower generation while protecting and improving environmental values, within the context of existing uses.

By exploring specific pathways through which integrated hydropower and environmental opportunities might be feasible, the BSOA Initiative complements other DOE assessments of hydropower, such as small hydropower (Hall et al. 2006), powering non-powered dams (Hadjerioua et al. 2012), and new stream-reach development (i.e., constructing a new hydropower dam; Pasha et al. 2013). The BSOA Initiative provides a framework with national applicability to identify, investigate, synthesize, and visualize "win-win" scenarios for hydropower development and environmental improvement at the scale of a river basin. The BSOA Initiative defines these scenarios as complementary opportunities, which are situations where an existing environmental issue can be directly or indirectly alleviated as a result of, or in conjunction with, a hydropower action.

The MOU agencies established a national steering committee to advise research team members from the Pacific Northwest National Laboratory (PNNL) and Oak Ridge National Laboratory (ORNL) during implementation of the BSOA Initiative. The national steering committee consists of representatives of the MOU agencies, hydropower industry, the environmental community, and other key stakeholders. During fiscal year (FY) 2010, the national steering committee selected the Deschutes River basin in Oregon for a pilot BSOA. During the pilot BSOA, researchers developed a multidisciplinary toolbox to conduct opportunity assessments using geographic information system (GIS) models, hydrology modeling, water management operational modeling, hydropower technology evaluation, data visualization, and stakeholder engagement (Geerlofs et al. 2011; Larson et al. 2014a).

Based on the pilot BSOA experience, PNNL, ORNL, and the BSOA steering committee agreed on a three-phased approach to improve the cost-effectiveness, identify research priorities, and increase the impact of future assessments. Progression from one phase to the next requires a conscious go/no go decision on the part of DOE and the national steering committee, and would take place as follows:

- Phase 1 Scoping Assessment − rapid (approximately 6-month duration), initial classification, screening, and identification of potential complementary hydropower-environmental opportunities;

- Phase 2 Stakeholder Engagement − stakeholder-driven opportunity identification, prioritization, and scenario building;
- Phase 3 Technical Analysis − detailed analysis of interactions and tradeoffs between hydropower and environmental opportunities in the context of other water uses.

During FY 2012, PNNL and ORNL began developing a technical approach and methodology for conducting a Phase 1 Scoping Assessment. Initially, two river basins were selected for piloting Phase 1 assessments: the Connecticut River basin in northeastern United States and Roanoke River basin in the eastern United States. These assessments were completed in October 2014 (Larson et al. 2014b; Bevelhimer et al. 2014). In FY 2014, the Bighorn River basin in central Wyoming and Montana was selected for a Phase 1 Scoping Assessment to broaden and refine the methodology.

This report describes the methods (Section 2.0) and preliminary results (Section 3.0) of the BSOA Scoping Assessment for the Bighorn River basin. A brief description of the BSOA stepwise approach that was piloted in the Connecticut and Roanoke River basins is included for context. For more detailed descriptions of the methodology, readers should refer to previous reports for the Connecticut and Roanoke River basins (Johnson et al. 2013; Larson et al. 2014b; Bevelhimer et al. 2014) available at http://www.basin.pnnl.gov.

2.0 Methods

The project team developed a stepwise technical approach to conducting Phase 1 Scoping Assessments (Figure 2.1). The approach includes an analytical methodology for identifying complementary hydropower-environmental opportunities (Steps 5−7), which are defined as situations where an existing environmental issue can be directly or indirectly alleviated as a result of or in conjunction with a hydropower action. Other environmental opportunities, such as ecosystem restoration, are possible but are not considered in a Phase 1 Scoping Assessment because of the complexity and site specificity that is typically involved with such opportunities.

The BSOA approach starts with planning and organizing personnel, resources, technical needs, milestones, and selecting a basin for the assessment (Steps 1−2). Key stakeholders in the basin are then identified and contacted for coordination purposes (Step 3) and information pertaining to potential hydropower opportunities and relevant environmental issues is then obtained (Steps 4−6). The data are then catalogued and analyzed according to a data model designed to identify potential complementary relationships between hydropower opportunities and existing environmental issues (Step 7). Following an initial analysis and report of opportunities for the basin (Step 8), feedback is then solicited from key stakeholders (Step 9) and any further analyses are conducted to finalize the assessment (Step 10).

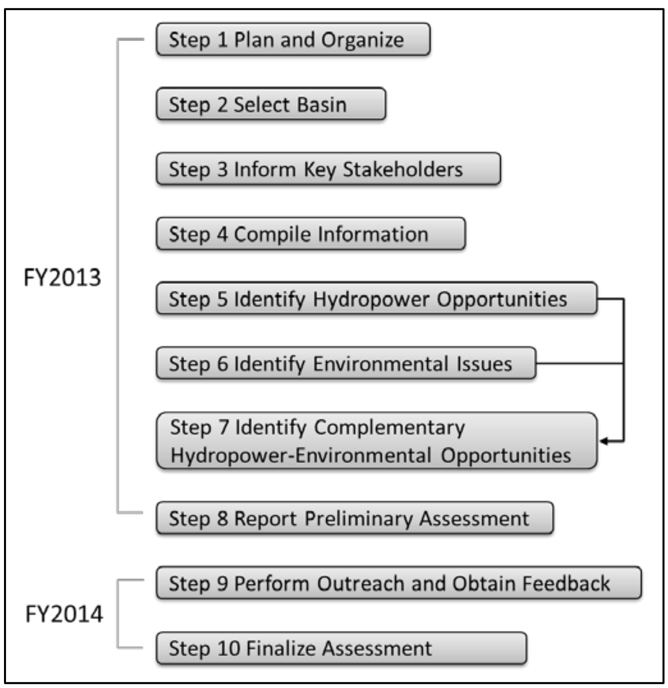

Figure 2.1. Stepwise technical approach for conducting Phase 1 Scoping Assessments.

This section contains a brief description of the methods for Steps 3−7 of the BSOA Phase 1 Scoping Assessment for the Bighorn River basin. The information presented here is intended to give readers a general understanding of the process, data, and analytical procedures used in the assessment. More detailed descriptions of these aspects are presented in previous reports (Johnson et al. 2013; Larson et al. 2014b; Bevelhimer et al. 2014).

2.1 Stakeholder Contact

By design, stakeholder interaction during Phase 1 is limited to a small number of stakeholders in the basin who represent local hydropower, state and federal regulatory branches, leading environmental organizations, and Native American tribes. The purpose of this step is to inform stakeholders of the assessment, ask about key sources of information for the basin, coordinate future feedback on the preliminary assessment, and answer any questions they may have regarding the assessment. The project team initially contacted the USBR Senior Hydropower Advisor who identified the USBR lead for renewable resources and contacts at the Wyoming and Montana field offices. Through these channels the project team made contact with representatives in the basin from the USBR; Bureau of Land Management; National Parks Service; Wyoming State Engineers Office; Montana Fish, Wildlife, and Parks; Crow Tribe; and the Bighorn River Alliance.

2.2 Information Compilation

The project team obtained and reviewed information regarding hydropower opportunities and environmental issues from reports, planning documents, publicly available data sets, and the Federal Energy Regulatory Commission (FERC) eLibrary website. We used the U.S. Environmental Protection Agency (EPA) web site “Surf Your Watershed” to help identify organizations that may have information relevant to the project, and created a broad list of environmental issues pertaining to water resources to guide research on potential environmental opportunities (Table 2.1). When applicable, information gathered was documented in a bibliographic database.

Table 2.1. List of common environmental issues applicable to Phase 1 Scoping Assessments.

Issue	Subcategory
Fish Interactions	Injury
	Barriers
	Entrainment
	Harvest
	Competition/predation
	Population augmentation
	Other
Aquatic Habitat Loss/Degradation	Life cycle habitat
	T&E species habitat
	Critical habitat
	Sensitive habitat
	Riparian condition
	Inundation or dewatering
	Habitat condition
	Other
Socio-Concerns	Wild and Scenic River Designation
	Protected areas
	Recreational importance
	Cultural importance
	Aesthetic preservation
	Other

Issue	Subcategory
Water Quality	Temperature
	Dissolved gases
	Pollution
	Turbidity/erosion
	pH/acidification
	Bacteria
	DOM/nutrients
	Salinity
	Other
Hydrology & Hydraulics	Surface, sub-surface input
	Hydraulic modification
	Morphological changes
	Sediment/nutrient export
	Land cover changes
	Precipitation changes
	Other

DOM = dissolved organic matter;
T&E = threatened and endangered.

2.3 Identify Hydropower Opportunities

Information from the National Hydropower Asset Assessment Program (NHAAP) database (ORNL 2014) was used to identify non-powered dams (NPDs) and potential new stream-reach development (NSD) sites in the Bighorn River basin. NPDs were evaluated for their potential to accommodate the installation of turbines and generation of power. NSD sites were evaluated for dam installation within the context of factors such as annual flow, estimated head, potential generating capacity, and 100-year floodplain boundaries. Opportunities for increasing capacity at existing powered dams (e.g., improving the efficiency of operations, increasing head, replacing existing turbines) and installing small in-canal or in-conduit hydropower were also considered in this assessment. Because opportunities for increasing power at existing facilities are complex and depend on a suite of site-specific factors, we applied a 1% increase in capacity to give an approximation of this opportunity type and provide a point of comparison for other hydropower opportunities. Information about opportunities for in-canal/conduit hydropower was obtained for many of the USBR canals in the basin and several private canal systems (Aqua Engineering 2006; Hutton Consultants 2006; A&H Consultants 2003; Bergquist et al. 2003; USBR 2011, 2012).

For each hydropower opportunity (with the exception of in-canal opportunities), the upstream and downstream extents of the project were delineated for subsequent analysis of direct complementary hydropower-environmental opportunities. Where available, water bodies (i.e., reservoirs/lakes/ponds) from the high-resolution National Hydrography Dataset (NHD) that are greater than 25 ac (0.1 km^2) and located within 300 ft (~90 m) of the associated project were used to delineate the upstream extent of the project. For projects where NHD water bodies were not available, the NHD flowline segment immediately upstream of the project was used. NHD flowline segments extending approximately 10 mi downstream of each project were used to delineate the downstream extent of each project.

Geographic locations of dams and their associated upstream and downstream extents were loaded into the GIS database supporting the BSOA data model (see Section 2.5.1). Descriptive information about each hydropower opportunity was also loaded into the database.

2.4 Identify Environmental Issues

We identified and mapped key environmental issues in the basin that may interact with potential hydropower development. Information about environmental issues was assembled from discussions with stakeholders and publicly available resources such as watershed planning documents, stakeholder reports, environmental impact statements, water-quality certifications, regulatory filings for hydropower projects, and nationally available environmental data. Geographic locations of environmental issues were derived from existing geospatial data or manually georeferenced from information in literature sources. Ecological, cultural, or aesthetic issues representing potential public resistance to or negative impacts caused by hydropower development were also identified and used to screen hydropower opportunities from the analysis. Geographic data for environmental issues were compiled from multiple sources, including the NHAAP database, federal and state geospatial clearinghouses, and by georeferencing data from location descriptions of environmental issues in the literature. It should be noted that all of these data sources were evaluated but only those relevant to documented environmental issues were used in subsequent analysis. Environmental data used in the Bighorn River assessment are further described in Table 2.2 and the ensuing sections.

Table 2.2. Environmental data sets obtained for Bighorn River assessment.

Issue Category Subcategory	Description	Data Set(s)
Fish Interactions		
Barriers	Physical barriers (i.e., dams, weirs, culverts) preventing migratory movements of fish	NABD
Injury/ Entrainment	Injury or mortality resulting from entrainment through dam, turbine strike, and associated hydropower operations	FERC Orders; USACE NID; NABD
Water Quality		
Temperature	Abnormal temperatures (too low or too high)	EPA 303d Listed Waterbodies
Dissolved gases	Low dissolved oxygen	same
Pollution	High pollution or contaminant levels	same
Turbidity/ erosion	High erosion and turbidity levels	same
pH/ acidification	Low pH	same
Bacteria	Elevated pathogen and bacteria concentrations	same
DOM/nutrients	Elevated nutrients and DOM	same
Salinity	Increased total dissolved solids and salinity	same
Aquatic Habitat Loss/Degradation		
T&E species habitat	Areas containing state or federally listed species excluded from critical habitat designations	NatureServe
Critical Habitat	Critical habitat designation areas for federally listed threatened and endangered species	USFWS Critical Habitats
Sensitive habitats	Areas designated by federal or state government as having high biodiversity or conservation value (e.g., wetlands, diverse habitats)	State-specific conservation data sets
Habitat condition	Degree of anthropogenic disturbance (e.g., urbanization, upstream dams) in watershed or stream segments	NFHAP
Hydrology & Hydraulics		
Hydraulic modification	Degree of hydrologic disturbance of stream flows. Presence of infrastructure, such as canals and penstocks, known to modify natural hydrologic processes.	NHD 1:24,000 scale canals, penstocks, pipelines; USGS stream gages; NFHAP
Other Water Resource Issues		
Wild and Scenic River	Rivers protected under the Wild and Scenic River Act	NWSRS
Protected Areas	Areas owned and protected for conservation, recreation, or aesthetic purposes	National GAP Protected Areas Data Portal
Recreational Importance	Areas of known recreational value, such as fishing or boating.	DeLorme fish and boat access; American Whitewater National Whitewater Inventory
Aesthetic preservation	Areas of aesthetic value, such as waterfalls, geologic formations, or landmarks.	NHD waterfalls

FERC = Federal Energy Regulatory Commission; GAP = Gap Analysis Program; NABD = National Anthropogenic Barrier Dataset; NFHAP = National Fish Habitat Action Plan; NHD = National Hydrography Dataset; NID = National Inventory of Dams; NWSR = National Wild and Scenic River System; T&E = threatened and endangered; TNC = The Nature Conservancy; USFWS = U.S. Fish and Wildlife Service; USGS = U.S. Geological Survey.

2.4.1 Fish Interactions

Entrainment in irrigation canals has been identified as a concern for some native fish species in the Bighorn River basin (Cotnatzer 2014; Burckhardt 2011; Smith 2008; A&H Consulting 2003) and can be quite significant in some canal systems. Studies by the Wyoming Game and Fish Department revealed that tens of thousands of fish can enter a canal system during an irrigation season, of which only 1−10% are estimated to return to the river during electroshock and recapture campaigns (Smith 2008). Information about where entrainment may occur is either incomplete or is not readily available. There is some record of the location of diversions in the Wyoming portion of the basin, but we were not able to find location information for diversions in the Montana portion of the basin or for irrigation returns in either state. In addition, there is a lack of information to determine which diversions or returns are screened or where fish entrainment has been documented. For this assessment, we inferred potential locations for fish entrainment by identifying known diversions within 50 m of a stream and intersections of canals and streams in the NHD.

Barriers to fish movement can include natural (e.g., falls, debris jams, insufficient flow) and man-made obstacles (e.g., dams, culverts, diversion infrastructure), and can affect factors such as habitat use, reproduction, immigration and emigration, and genetic diversity. Opportunities to improve fish movement and habitat connectivity may be made more feasible at man-made obstacles by creating or improving passage, either through design modification or removal. Impairments of fish movement and/or fish passage have been documented in the Bighorn River basin (Montana Fish Wildlife and Parks 2012), although our review indicated that barriers were used as a management tool to keep certain species out of a reach of river. We supplemented information from our review with data from the National Anthropogenic Barrier Dataset (USGS 2013) to identify potential opportunities to improve fish passage and habitat connectivity.

2.4.2 Water Quality

Water-quality issues were considered if they could be mitigated by modifying dam operations, altering design, or by trapping pollutants within reservoirs. Spatial information about water-quality issues was obtained from the EPA’s 303d Listed Impaired Waters data set (EPA 2013) and by manually georeferencing information from literature sources. Water-quality concerns that were deemed most relevant for this assessment included waters exceeding state or federal standards for water temperature, metals pollution, excessive sedimentation, and high turbidity.

2.4.3 Aquatic Habitat Loss and Degradation

Areas containing habitats of sensitive species or habitats of conservation importance may pose constraints on hydropower development as well as potential opportunities for habitat restoration, mitigation, and protection. Several sources of habitat information were considered in this assessment including federally and state-listed threatened and endangered (T&E) species’ habitat areas, designated Critical Habitat (USFWS 2014) areas, state-designated sensitive habitats, and National Fish Habitat Partnership habitat condition index (Esselman et al. 2011). Hydropower opportunities that are spatially coincident with T&E species’ habitat or Critical Habitat are removed from consideration in a Phase 1 Scoping Assessment. There are no federally listed threatened or endangered aquatic species within the Bighorn River basin, but there is concern for Yellowstone cutthroat (*Oncorhynchus clarki bouvieri*), Burbot (*Lota lota*), and Sauger (*Sander canadensis*). All three species are considered Species of Greatest Conservation Need in Wyoming and therefore warrant special consideration by the state.

2.4.4 Hydrologic Disturbance

Certain hydropower opportunities (e.g., powering an NPD, improving efficiency at existing powered dams) may provide opportunities to improve the timing and amount of flow in reaches where hydrologic disturbance is high. We identified areas of high hydrologic disturbance using methods described by McManamay et al. (2012) to calculate an index of hydrologic disturbance. The index is a composite score for USGS gaged streams based on seven factors for each entire basin: major dam density, change in reservoir storage from 1950 to 2006, freshwater withdrawal, artificial paths (canals, ditches and pipelines), road density, distance to major National Pollutant Discharge Elimination System sites, and the fragmentation of undeveloped land. Index values in the top 25th percentile value of all index values in the basin were considered “high” in this assessment.

2.4.5 Other Water Resource Issues

Several other categories of issues related to water resources and hydropower opportunities were considered, including lands protected from development and areas of recreational, cultural, or aesthetic importance. New hydropower was assumed unlikely to occur on reaches designated as Wild and Scenic Rivers and lands identified in the National Gap Analysis Program (GAP) Protected Areas Database as having some level of permanent protection from development and/or being managed primarily for the purpose of conservation or preservation (i.e., GAP Status 1 and 2; USGS 2014). Areas known for recreational importance may represent potential barriers to hydropower development if recreation is compromised. However, certain types of recreation may be improved in conjunction with hydropower development if the development includes creating or improving public access sites, or maintaining flows needed for recreation. For this assessment, we considered reaches classified as either high-quality (i.e., Blue Ribbon) trout fisheries by the states of Wyoming and Montana or important whitewater recreation reaches by American Whitewater, as locations where recreational access or value could potentially be improved in conjunction with hydropower development.

2.5 Identifying Complementary Hydropower-Environmental Opportunities

Potential hydropower opportunities were evaluated in the context of existing environmental issues to identify where complementary opportunities or potential conflicts might occur. Recall, an environmental “opportunity” was defined as a situation in which an existing environmental issue can be alleviated, either directly or indirectly, as a result of or in conjunction with a hydropower action. Other environmental opportunities, such as ecosystem restoration, are possible but are not considered in a Phase 1 Scoping Assessment because of the complexity of addressing such opportunities. Environmental opportunities can result *directly* from a hydropower action, e.g., installing a turbine at a NPD may trigger regulatory drivers to mitigate impaired water quality via improved flow management, or *indirectly* from a hydropower action, e.g., modifying or removing a nearby dam to improve habitat connectivity as part of development elsewhere. The relationship between hydropower potential and environmental issues is defined by two sets of criteria: one set that describes conditions that may preclude development and another set that describes positive hydropower-environmental interactions. In this section, we explain the data model and geodatabase, and the process for identifying direct and indirect complementary hydropower-environmental opportunities.

2.5.1 BSOA Data Model and Geodatabase

A geospatially driven data model was developed to examine interactions between hydropower opportunities and environmental issues to identify possible complementary hydropower-environmental opportunities (Figure 2.2). The BSOA data model involves core data elements, relationships between data elements, and rules by which interactions can be explored and opportunities identified. The data model enables a rapid, flexible, and robust method for assessing interactions between data elements that are spatially disparate but functionally linked. Core data elements of the BSOA data model include hydropower opportunities, environmental issues, and hydrologic units from the national Watershed Boundary Dataset (WBD) and NHD. Hydrologic units were chosen as a common spatial unit for associating hydropower and environmental data because they provide a natural, functional linkage and are nested within each other, allowing for multi-scale associations to be drawn. For the Bighorn River basin (as defined by the 6-digit HUC boundary), this includes 8-, 10-, and 12-digit HUCs from the WBD, and hydrologic catchments from NHD, which are the smallest hydrologic units used in the analyses.

The data model is implemented in a geospatial database (geodatabase), a key function of which is to maintain the spatial relationships among the data elements. The geodatabase also maintains non-spatial relationships among data elements and tables containing descriptive attributes for each element that were used to examine interactions in greater detail. By using this type of relational structure, the geodatabase provides considerable flexibility in examining interactions between hydropower opportunities and environmental issues under a variety of scenarios.

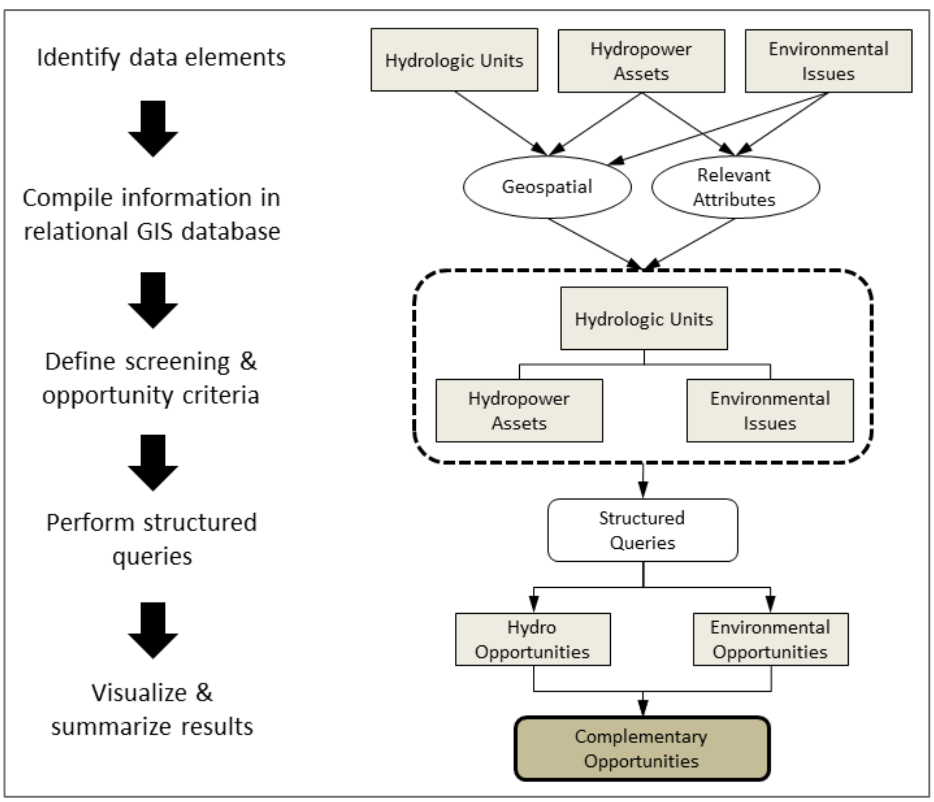

Figure 2.2. BSOA data model and process flow for identifying complementary hydropower-environmental opportunities in Phase 1 Scoping Assessments.

2.5.2 Direct Complementary Hydropower-Environmental Opportunities

In this assessment, *direct* complementary hydropower-environmental opportunities are defined as those in which there is a direct cause-and-effect relationship between a hydropower action and environmental improvement (e.g., construction of a fish ladder, operational changes to improve water quality, meeting environmental flow requirements, or improving recreation) within the upstream and/or downstream extents of a project. Direct opportunities may have indirect effects (e.g., increased productivity of aquatic populations, improved ecosystem processes and services), which we define differently from indirect complementary hydropower-environmental opportunities (see Section 2.5.3).

Direct opportunities were identified by examining relationships between hydropower opportunities and environmental issues within hydrologic catchments (the smallest hydrologic unit in the BSOA data model) that intersect the upstream and downstream extents of a given project. Relationships were defined by two sets of criteria: one set that describes conditions that may preclude development and another set that describes positive hydropower-environmental interactions. The criteria are then used to structure queries of the geodatabase to locate and view complementary hydropower-environmental opportunities. The six-step process for identifying direct complementary hydropower-environmental opportunities is as follows:

1. Select a hydropower opportunity type. Powering an NPD was the only hydropower opportunity type considered with respect to direct complementary hydropower-environmental opportunities in the Bighorn River basin. Other types of hydropower opportunities that could be included in future assessments are modifying an existing site, developing new sites, powering a water conduit, or developing hydrokinetic energy.
2. List relevant environmental issues that might be affected by the selected hydropower opportunity. This list necessarily should include conditions that may preclude development as well as positive hydropower-environmental interactions to create a broad characterization of possible effects from which opportunities can be identified.
3. Identify environmental issue(s) that could be affected in a positive manner if hydropower development was conducted in a particular fashion; an example is the environmental issue of low dissolved oxygen.
4. Describe what and how environmental improvements could be realized during hydropower development. For example, installing a turbine at an NPD could be done in a way (e.g., with aerating turbines) that increases dissolved oxygen levels in a downstream reach that has a low dissolved oxygen issue.
5. Define criteria to identify sites where the selected hydropower opportunity might be realized, as well as criteria where the hydropower opportunity might create a mutual environmental opportunity. In addition to identifying sites that may be positively associated with development opportunity, we can also screen out sites that do not meet certain criteria. Screening criteria include attributes or issues (environmental and other) that we deemed would likely preclude development at a particular location, as follows:
    - Generating capacity <0.1 MW for NPD
    - GAP status = 1 or 2

- Wild and Scenic River designation
- Other Protected Area designation
- Presence of threatened/endangered species habitat.

6. Identify data sets needed to analyze spatial interaction between hydropower and environmental opportunities. This includes the locations of projects, environmental issues, hydrologic units, and extent of each project (i.e., upstream and downstream). In the example presented above, the opportunity to improve dissolved oxygen is within the downstream extent of the dam.

The criteria established in Steps 5 and 6 above were used to construct queries of the geodatabase to identify locations where the hydropower opportunities and environmental issues of interest interact in both positive and negative ways. The locations identified provide a starting point for further analysis and discussion, but uncertainty remains about how a given opportunity would be realized. For example, for the opportunities strongly tied to flow management, it is assumed that powering a NPD would provide some mechanism(s) for managing flows to better meet environmental objectives like improving water quality or recreation. Ultimately, the exact mechanism or manner in which a hydropower opportunity addresses a specific environmental issue depends on a suite of factors that would be examined in later phases (i.e., Phase 2 Stakeholder Engagement and Phase 3 Technical Analyses). The results of this assessment are intended to narrow the scope of possible locations where such assessments would be needed to identify the mechanism(s) for realizing an opportunity.

2.5.3 Identifying Indirect Complementary Hydropower-Environmental Opportunities

An indirect complementary hydropower-environmental opportunity is defined as an opportunity to improve an environmental condition in the basin that is not directly affected by the hydropower project of interest. We define these opportunities differently from indirect effects of direct opportunities, such as increased population productivity, species health, and ecosystem services. Examples of indirect opportunities can include direct-effect actions elsewhere in the basin (e.g., installing or improving fish passage at another dam, dam removal, providing recreational access) as well as compensatory mitigation such as high-quality land acquisition, wetland restoration, and habitat or fisheries enhancement. As information about compensatory mitigation projects becomes available, it can be added to the Bighorn River database and included in future analyses of indirect opportunities.

Because indirect opportunities are not linked to any one particular hydropower opportunity type or location, we quantified them as independent opportunities so that stakeholders could assess possible combinations of opportunities at multiple scales. We used guidance from the USACE's' Final Compensatory Mitigation Rule (73 FR 19594) to choose an appropriate spatial scale for summarizing indirect opportunities. The Rule states that compensatory mitigation should be located within the same watershed as the impact site, and it should be located where it is most likely to successfully replace lost functions and services. For the Bighorn River basin assessment, we chose to use sub-basin eight-digit HUC drainage areas (roughly equivalent to drainages of major tributaries to the Bighorn River) to quantify the number of indirect complementary hydropower-environmental opportunities. This approach could be expanded to multiple scales to allow stakeholders to determine which portions of the basin present the most potential for "win-win" hydropower development and environmental improvement scenarios.

The data model for identifying indirect opportunities is similar to that for identifying direct opportunities in that it uses the same core data elements, spatial relationships, hydrologic units, and criteria that describe conditions that may preclude development. However, the indirect opportunity data model does not include criteria that describe direct hydropower-environmental interactions because each environmental issue is treated as an independent opportunity for improvement. Indirect opportunities are also assessed at a larger scale (eight-digit HUC drainage) than direct opportunities (hydrologic catchments within an individual project extent). The following process describes how indirect complementary hydropower-environmental opportunities were identified in this assessment:

1. Select a hydropower opportunity type. Hydropower opportunity types considered with respect to indirect complementary hydropower-environmental opportunities in the Bighorn River basin included powering an NPD, constructing an NSD, efficiency improvements at existing powered dams, and in-canal small hydropower.
2. List relevant environmental issues that might be affected by hydropower development. This list necessarily should include more than what might be considered opportunities for environmental improvement to create a broad characterization of possible effects from which opportunities can be identified.
3. Identify environmental issue(s) in the affected watershed that could be addressed to offset the impact of hydropower development; an example would be land purchase or riparian restoration.
4. Define criteria to identify sites where the selected hydropower opportunity might be realized (same as Step 5 for identifying direct opportunities).
5. Identify data sets needed to spatially analyze interaction between hydropower and environmental opportunities. This includes the locations of projects, environmental issues, and hydrologic units.
6. Catalogue environmental issues by hydrologic catchments and quantify the number of affected catchments in each eight-digit HUC drainage in the basin for each issue. Similarly, quantify the number of hydropower opportunities in the watershed that meet criteria in Step 4.

In the case of either a direct or indirect complementary opportunity there is inherent uncertainty in how an opportunity may be realized because there may be multiple ways to address the issue. However, it is presumed there are more potential mechanisms for indirect opportunities because they are not tied directly to any particular hydropower development action. In the example of improving fish passage at a given dam, dam removal would not be an option if there was interest in hydropower development at that dam, whereas removal could be an option if the hydropower opportunity was elsewhere.

3.0 Results

The Phase 1 Scoping Assessment for the Bighorn River basin entailed identifying hydropower opportunities and environmental issues, then integrating them geospatially to reveal potential complementary hydropower-environmental opportunities. This section describes the hydropower and environmental opportunities and their direct and indirect linkages.

3.1 Hydropower Opportunities

We considered the following hydropower opportunities for the Bighorn River basin: powering NPDs, developing NSDs and in-canal small hydropower, and increasing efficiencies at existing hydropower plants. With the exception of in-canal opportunities, other hydropower information (location and potential capacity) was derived from NHAAP. Most in-canal opportunities considered were derived from USBR assessments of small hydropower on USBR infrastructure (USBR 2011, 2012). Eight additional in-canal opportunities were identified from available literature (Aqua Engineering 2006; Hutton Consultants 2006; A&H Consultants 2003; Bergquist et al. 2003).

The assessment of potential hydropower capacity that could be obtained by powering NPDs identified 8 of 143 (5.6%) NPDs in the Bighorn River basin that have a potential capacity of ≥0.1 MW. Four of these eight NPDs meet the additional criterion for a potential opportunity; i.e., they do not intersect lands protected from development [GAP Status 1 or 2 lands, Critical Habitat, Wild and Scenic River segment] or Threatened/Endangered species habitat (Figure 3.1). These four opportunities represent a total capacity of 9.6 MW, although most of that capacity (9.2 MW) is attributed to Yellowtail Afterbay Dam. The Crow Tribe retains exclusive rights to develop and market power generation at Yellowtail Afterbay Dam until 2025 (Public Law 111-291); therefore, it is not considered a generally available opportunity.

A total of 463 MW of potential NSD capacity was identified at 204 locations in the basin. Of these 204 potential NSD locations, 159 meet the criteria for a potential opportunity for NSD and represent a total capacity of 368.7 MW. Although each site is treated as an opportunity in our analysis, some would be mutually exclusive from actual development because of their proximity to each other. Therefore, we aggregated NSD opportunities to the scale of 12-digit HUC drainages to better represent NSD potential (Figure 3.2). Together, these 159 sites lie within 44 individual 12-digit HUC drainages. Areas within the basin with the greatest raw potential for NSD include the lower Wind River near Riverton and Thermopolis, Wyoming, the Shoshone River near Cody and Lovell, Wyoming, and lower Bighorn River near Hardin, Montana.

A total of 120 in-canal/conduit hydropower opportunity sites were identified from existing assessments conducted by the USBR and Wyoming Water Development Commission. Of these 120 sites, 48 have a potential individual capacity of ≥0.1 MW and represent a total capacity of 32.9 MW (Figure 3.3). These opportunities are concentrated primarily on USBR infrastructure for the Shoshone Project (N = 30) and Pick-Sloan Missouri Basin Program Riverton Unit (N = 10). The remaining eight sites are located on infrastructure in Greybull Valley and Cody Canal Irrigation districts.

Hydropower production at some of the four existing hydropower dams in the basin (representing a total installed capacity of 297.1 MW) might be increased by replacing generation machinery or improving operational efficiency. Improvements at existing hydropower facilities, however, will necessarily be site-specific and dependent on the age of the plant, cost-effectiveness of the improvements, any required mitigation, and other factors. To provide a point of comparison with other hydropower opportunities, we applied a modest 1% increase in existing hydropower capacity in the Bighorn River basin, which equates to approximately 3 MW of additional generating capacity. Such improvements could be linked with flow enhancements or requirements at existing sites. Minimum flow turbines could be installed where none are present or hydropower turbines could be used in lieu of excess spill or to provide flow in bypass reaches. Both improvements could result in greater minimum flows to benefit aquatic resources. More detailed examination of flow enhancement related to generation equipment or operational improvements at existing facilities would be appropriate in a Phase 3 Technical Analysis.

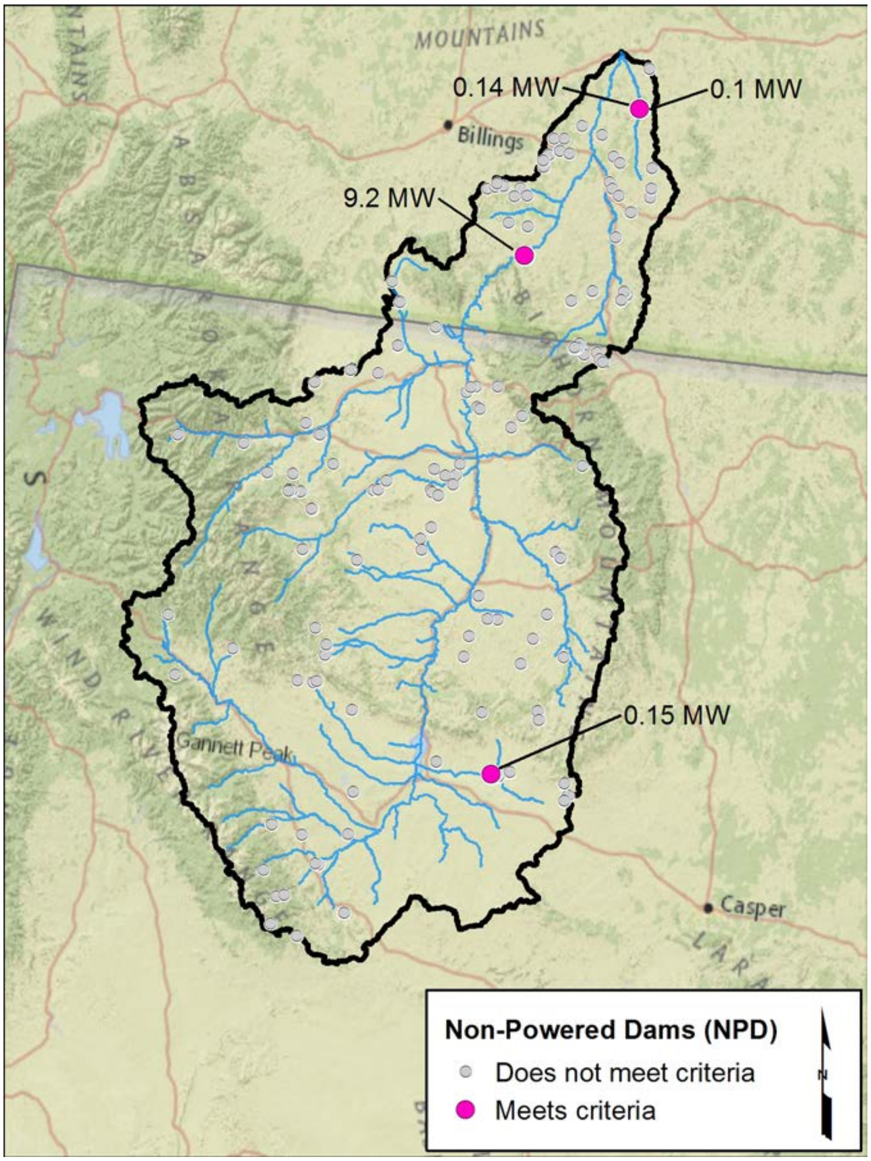

Figure 3.1. Non-powered dam sites in the Bighorn River basin that meet screening criteria for potential hydropower development opportunities (N = 4). Sites that do not meet criteria are also shown for reference. (Note: Some sites may not be visible due to overlap at the scale shown.)

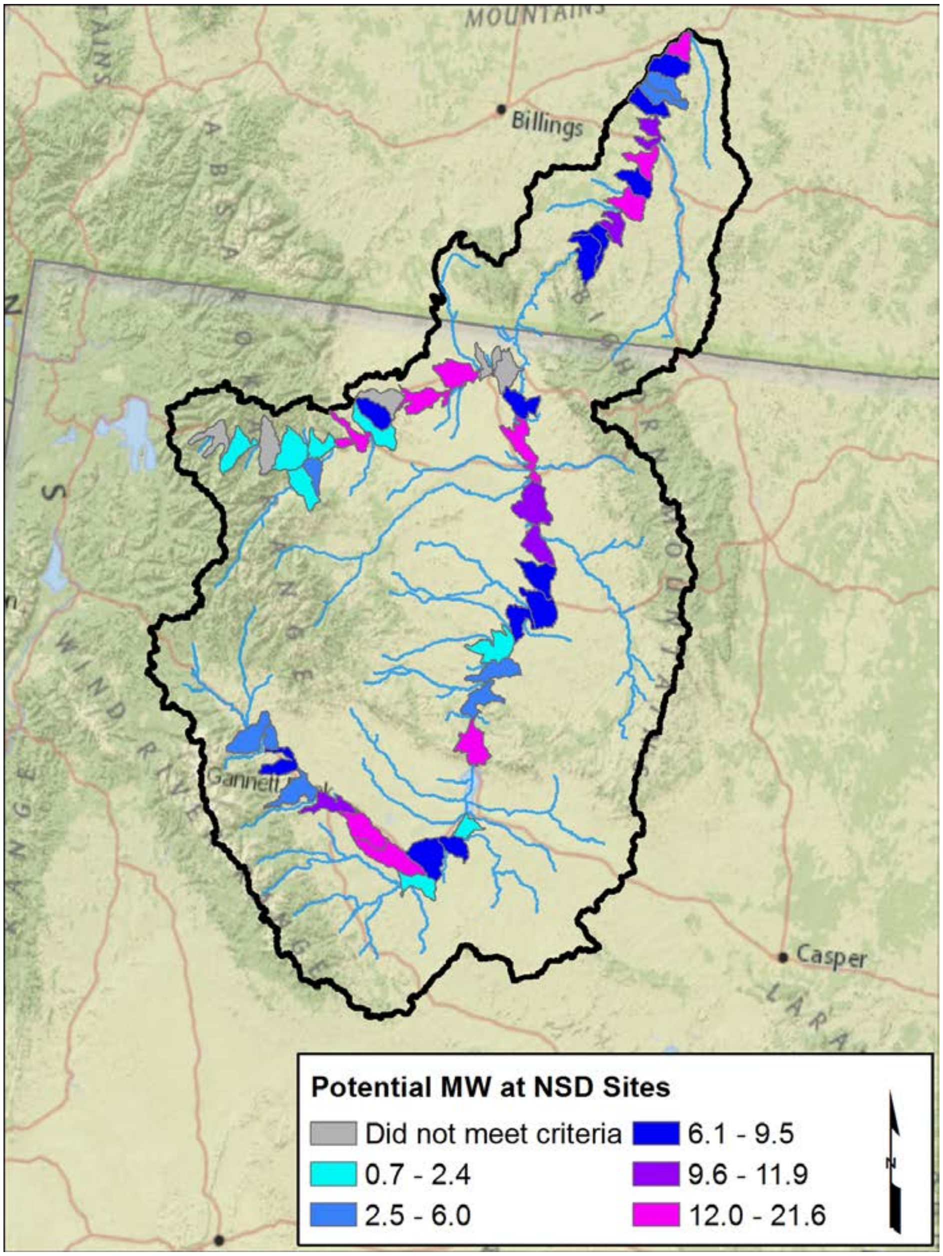

Figure 3.2. New stream-reach development sites in the Bighorn River basin that meet screening criteria for potential hydropower development opportunities (N = 44 12-digit hydrologic unit drainages, or 159 individual sites). Sites that do not meet criteria are also shown for reference.

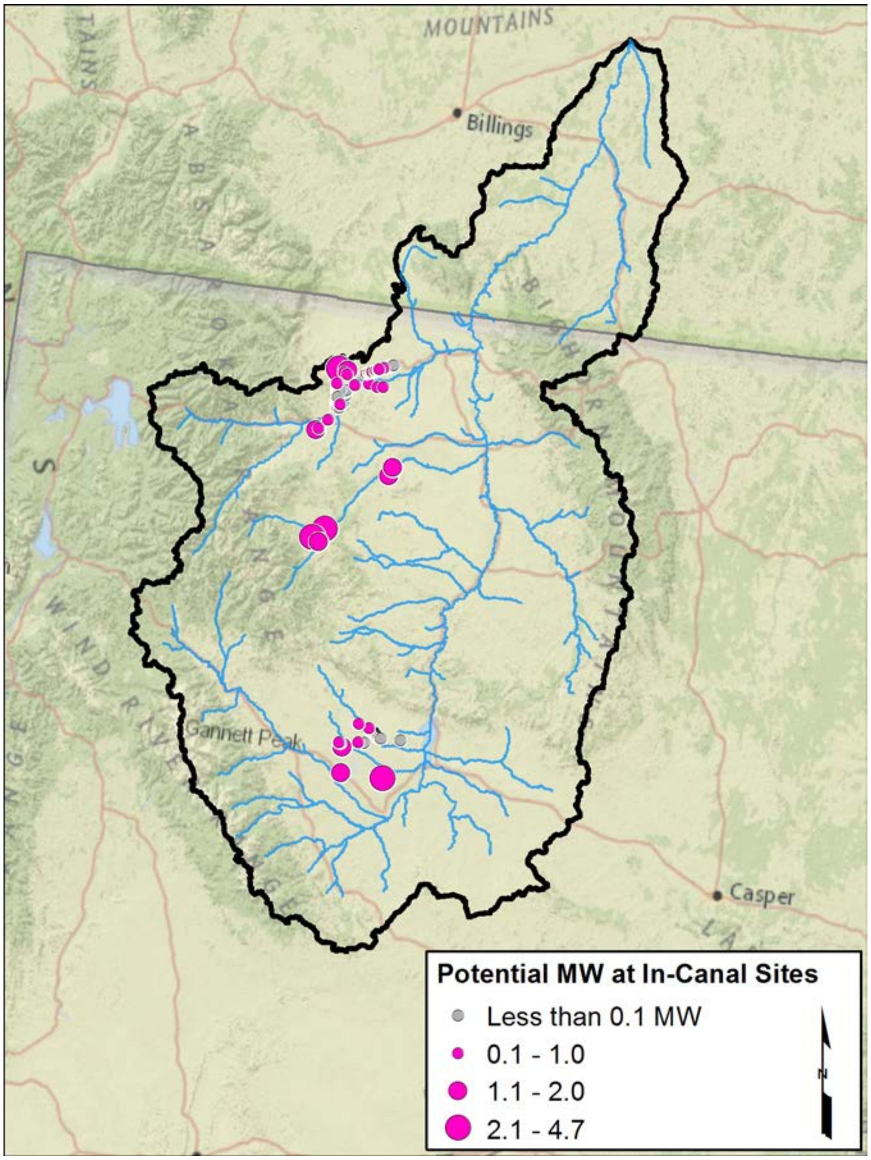

Figure 3.3. Potential in-canal small hydropower sites with greater than 0.1 MW generating capacity in the Bighorn River basin (N = 48). Sites less than 0.1 MW are also shown for reference. (Note: Some sites may not be visible due to overlap at the scale shown.)

3.2 Environmental Issues

Of the 20,220 hydrologic catchments in the Bighorn River basin, 29% (N = 5862) contained at least one of the environmental issues we examined for potential complementary opportunities. In general, the occurrence of environmental issues we examined increased with stream order; i.e., they were less abundant in headwaters and more abundant along the Bighorn River and major tributaries. Hydrologic disturbance was the most geographically extensive issue of those we examined, affecting 25% of the catchments in the basin. Impaired water quality and potential canal entrainments were the second- and third-most common issues, each affecting 5% of the catchments in the basin.

The distribution of catchments classified as having high hydrologic disturbance in the basin is closely tied to the distribution of dams, diversions, and other water-control infrastructure. This corresponds to our expectations based on the primary use of water in the basin, and the manner in which hydrologic disturbance was calculated. The primary use of water in the basin is storage and delivery for irrigation (Wyoming Water Development Office 2010) and the hydrologic disturbance index generally increases with larger departures from natural flow regimes and proximity to water-control infrastructure (McManamay et al. 2012). The index also considers other factors affecting hydrology, such as road density and fragmentation of undeveloped land.

Impaired water quality was the second-most common environmental issue in terms of catchments affected (N = 1013). Water quality is affected by both natural and anthropogenic factors such as seasonal runoff, geology, mining, livestock, wastewater return, and others. The most common water-quality impairments in the basin include excessive bacteria levels, methyl mercury contamination in reservoir sediments, and excessive sedimentation.

Potential locations for entrainment of fish in canals was the third-most common environmental issue in terms of catchments affected (N = 930). We inferred these locations from known diversions within 50 m of a stream and intersections of canals and streams, which does not necessarily reflect locations where entrainment occurs or could occur. Information where entrainment may occur or where measures have been taken to prevent entrainment (e.g., screening, bypass, removal) is generally lacking; thus, it was difficult to validate our results. However, review of existing literature and discussions with experts in the basin do suggest that our results reflect the broad nature of the issue, which is significant concern for native fish species in some canal systems (Cotnatzer 2014;, Burckhardt 2011; Smith 2008; A&H Consulting 2003; Sam Hochalter 2015 personal communication; Robert Capron 2015 personal communication).

Recreation was another important issue we examined in the Bighorn River basin. Predominant recreational uses of water in the basin include fishing and whitewater rafting (Wyoming Water Commission 2010). We examined the occurrence of two types of recreationally important areas related to these two uses (Blue Ribbon trout fisheries and whitewater boating reaches); combined they were present in 3% of the catchments in the basin (N = 597).

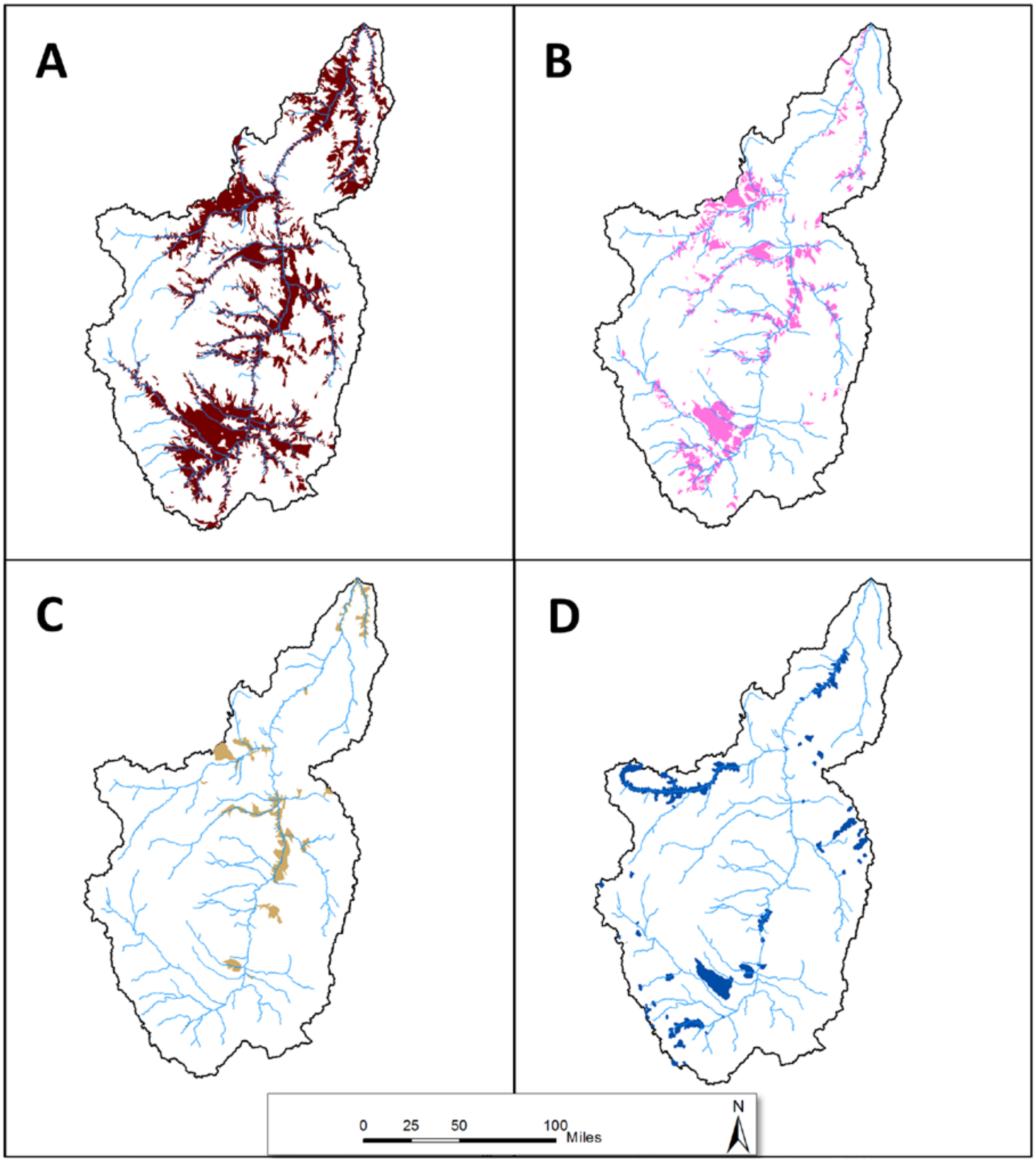

Figure 3.4. Distribution of select environmental issues by catchment, A) high hydrologic disturbance, B) irrigation diversions, C) EPA 303d-listed streams and D) Blue Ribbon trout streams

3.3 Direct Complementary Hydropower-Environmental Opportunities

We identified complementary hydropower-environmental opportunities for powering NPDs by evaluating spatially explicit, direct interactions between individual hydropower opportunities and environmental issues within the extent of NPD projects (Table 3.1). Specifically, we focused on four types of environmental opportunities associated with powering a non-powered dam:

- *Manage flow to mitigate impaired water quality* – Adding new turbine(s) could provide opportunities for improving flow to mitigate impaired water quality in downstream reaches.
- *Manage flow to mitigate hydrologic disturbance* – Adding new turbine(s) could provide opportunities for improving the timing and amount of flow to reduce hydrologic disturbance in downstream reaches.
- *Manage flow for existing whitewater/paddling* – Adding new turbine(s) could provide opportunities for improving the flow or public access to enhance whitewater or paddling recreation in downstream reaches.
- *Manage instream flow to maintain high-quality trout fisheries* – Adding new turbine(s) could provide opportunities to manage instream flow in downstream reaches containing high-quality trout fisheries.

Table 3.1. Number and capacity of NPD sites that may have complementary opportunities for environmental improvement in the Bighorn River basin.

Environmental Opportunity	Number	MW
Powering an NPD could provide better flow management in downstream reaches with water-quality impairment.	2	9.3
Powering an NPD could provide better flow management in downstream reaches with high hydrologic disturbance.	3	9.5
Powering an NPD could provide better flow management in whitewater/paddling reaches below the dam.	0	0
Powering an NPD could provide better flow management in downstream reaches with high-quality trout fisheries.	1	9.2
Total number and megawatts of sites that have at least one potential environmental opportunity[a]	3	9.5

(a) Note: The total number of sites and megawatts is not equal to the sum of the data in the rows above because some hydropower sites have more than one environmental opportunity

Of the 143 NPD sites evaluated, 4 met our criteria for a potential opportunity and of these 3 were associated with at least one of the complementary environmental opportunities above (Table 3.1; Figure 3.5). Complementary opportunities associated with the three NPD sites included opportunities to diminish hydrologic disturbance, and improve water quality and instream flow in high-quality trout fisheries. Potential generating capacities of these three opportunities ranged from 0.1 to 9.2 MW, representing a total capacity of 9.5 MW.

Most (94%) NPD sites were not considered practical opportunities because they had an estimated capacity of less than 0.1 MW. However, 34 sites (not mutually exclusive from those with capacities less than 0.1 MW) were also deemed impractical because they intersected catchments containing protected lands (GAP Status 1 or 2).

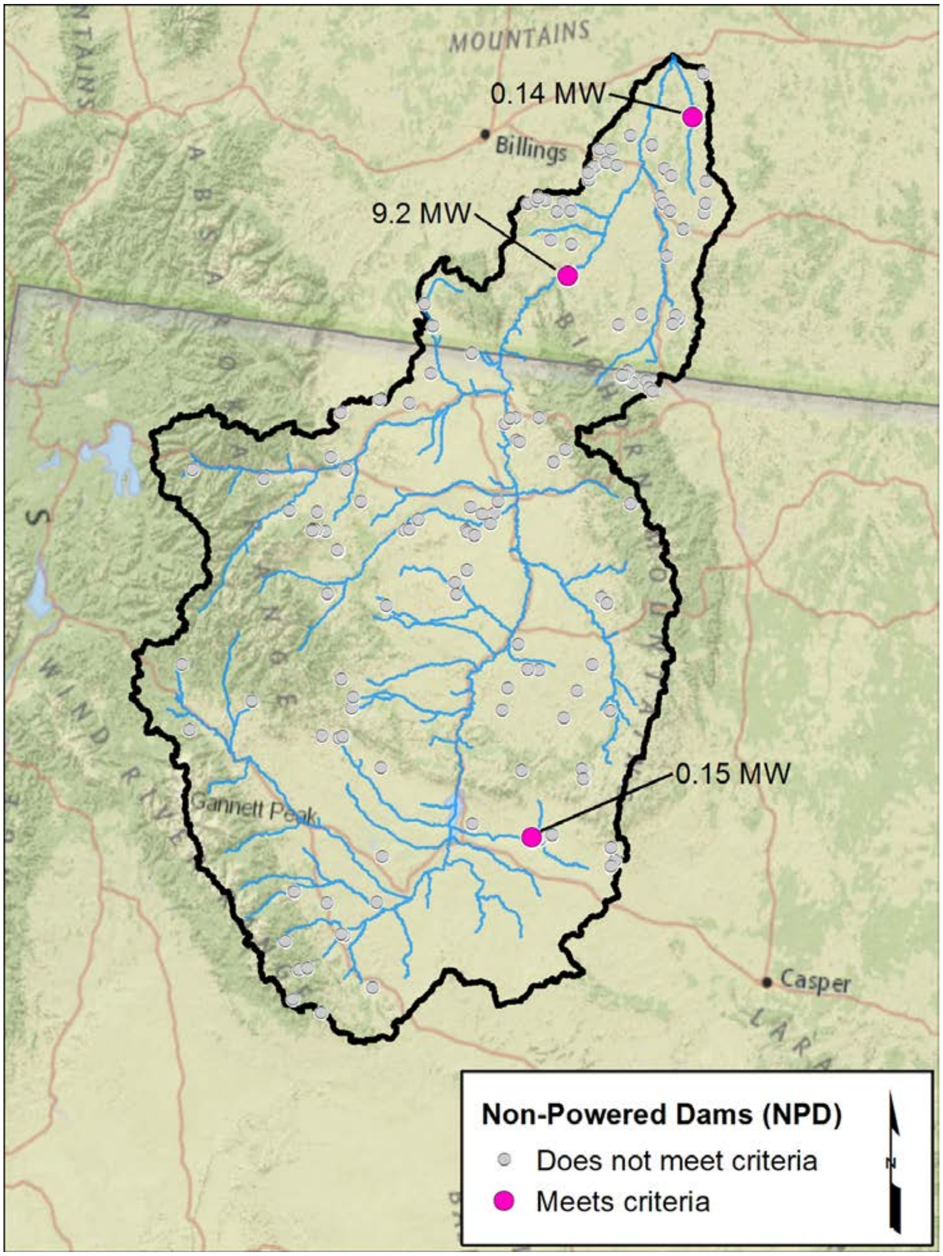

Figure 3.5. Non-powered dams in the Bighorn River basin having at least one complementary hydropower-environmental opportunity.

3.4 Indirect Complementary Hydropower-Environmental Opportunities

An *indirect* complementary hydropower-environmental opportunity is defined as an opportunity to improve an environmental condition that is not within the extent of or directly affected by the hydropower project of interest, but is within the same watershed as the potential hydropower site. In this sense, opportunities to improve an environmental condition are not linked to any one particular hydropower type, action, or location, and can be quantified as independent opportunities at multiple scales. Some environmental opportunities, however, may not be applicable to certain hydropower types due to lack of incentives or requirements. For example, there may not be sufficient financial, social, or regulatory incentives for low-impact projects such as in-canal hydropower to improve water quality, whitewater recreation, or reduce hydrologic disturbance elsewhere in the basin.

We aggregated indirect complementary opportunities at the sub-basin scale of eight-digit HUC drainages in the Bighorn River basin by summarizing the total number of each hydropower opportunity type (i.e., powering NPDs, NSDs, in-canal small hydropower, and efficiency improvements at existing powered dams,) and environmental opportunity type within the same drainage. We applied the same screening criteria used for analysis of direct complementary opportunities to the indirect opportunities; with the exception of existing powered dams because they are already permitted by FERC. Environmental issues that were considered as possible indirect complementary opportunities in this analysis included the following:

- *Impaired water quality* – Hydropower development could provide opportunities for improving water quality elsewhere in the drainage through actions such as dredging of contaminated sediment, flow restoration, or ecological restoration. (NOTE: This opportunity applies primarily to efficiency improvements at existing hydroelectric facilities, powering NPDs, and NSDs.)
- *Hydrologic disturbance* – Hydropower development could provide opportunities for reducing hydrologic disturbance elsewhere in the drainage through actions such as flow modification, dam removal, and watershed protection or enhancement. (NOTE: This opportunity applies primarily to efficiency improvements at existing hydroelectric facilities, powering NPDs, and NSDs.)
- *Whitewater recreation* – Hydropower development could provide opportunities for improving whitewater recreation elsewhere in the drainage through actions such as flow enhancements and improving or increasing recreational access. (NOTE: This opportunity applies primarily to efficiency improvements at existing hydroelectric facilities, powering NPDs, and NSDs.)
- *High-quality trout fisheries* – Hydropower development could provide opportunities to improve or maintain high-quality trout fisheries elsewhere in the drainage through actions such as increasing minimum instream flows, releasing cool water from the hypolimnion of deep reservoirs, restoring habitat, and improving recreational access. (NOTE: This opportunity applies primarily to efficiency improvements at existing hydroelectric facilities, powering NPDs, and NSDs.)
- *Instream flow filing* – Hydropower development could provide opportunities to secure instream flow filings elsewhere in the drainage through actions such as allocating or creating additional storage, and implementing water-conservation measures. (NOTE: This opportunity could apply to any of the hydropower opportunity types considered in this assessment.)

- *Potential canal entrainments* – Hydropower development could provide opportunities to reduce or prevent fish entrainment in irrigation canal systems by screening canal diversions or returns that connect to streams. (NOTE: This opportunity applies primarily to in-canal small hydropower opportunities and non-powered dams owned/operated by USBR that provide irrigation storage.)

Of the 143 NPD sites evaluated, 4 passed the initial screening criteria and represent a potential total of 9.6 MW added capacity in the basin (Table 3.2). The Lower Bighorn drainage exhibits the highest potential (9.4 MW) for powering NPDs, although most (9.2 MW) of this potential is attributed to Yellowtail Afterbay Dam, which the Crow Tribe has exclusive rights to develop (Public Law 111-291). Of the 204 NSD locations evaluated, 159 passed the screening criteria, representing a total capacity of 368.7 MW (Table 3.2). Drainages that exhibit the highest potential for NSD include the Lower Bighorn (116.2 MW), Upper Wind (83.9 MW), and Shoshone and Upper Bighorn (58.9 MW each). It is important to note the estimates of potential hydropower represent raw potential and do not reflect true potential for development based on technical or economic feasibility, social desire, environmental impact, or any other extrinsic factor. However, they provide a starting point for discussion of potential opportunities.

Increasing hydropower through efficiency improvements at existing hydroelectric facilities was also considered a potential opportunity in the Bighorn River basin. We applied a modest 1% increase in capacity for all four existing facilities in the basin to provide a benchmark for comparison to other hydropower opportunity types. A 1% increase in existing capacity would provide an additional 3 MW in capacity in the basin, most (83%) of which can be attributed to making efficiency improvements at Yellowtail Dam in the Big Horn Lake drainage (Table 3.2).

Of the 20,220 hydrologic catchments in the Bighorn River basin, 29% (5862) contained at least one of the environmental issues we included for potential indirect complementary opportunities (Table 3.3). The most prevalent issue in the basin, in terms of number of affected catchments, was areas indicated to have a high hydrologic disturbance index (Table 3.3). This issue is more common in Greybull and Upper and Lower Bighorn drainages. Areas with high hydrologic disturbance were included in the analysis of indirect complementary opportunities because they may represent locations where flow is altered and operations could be evaluated for prospects to improve environmental flows. Altering flow for environmental purposes may have benefits for numerous environmental issues, including impaired water quality, aquatic habitat, and recreation.

The presence of EPA 303d-listed stream reaches with impaired water quality was the second-most common environmental issue in the basin. Stream reaches with impaired water quality were most abundant in the Greybull and Upper and Lower Bighorn drainages (Table 3.3). The third-most common environmental issue in terms of number of affected catchments was the presence of canal diversions or returns that represent potential locations for fish entrainment (Table 3.3). The presence of potential canal entrainment locations was most common in the Shoshone, Greybull, and Upper Bighorn drainages.

By comparing raw hydropower potential and key environmental issues independently at the eight-digit HUC drainage scale, we can begin to identify where there may be greater potential for indirect complementary hydropower-environmental opportunities in the basin. For example, the Lower Bighorn drainage has the highest raw potential for hydropower in terms of additional capacity (125.7 MW; Table 3.2). However, most (92%) of this additional capacity may be attributed to NSDs, which likely have more environmental concerns than other hydropower opportunity types and would require greater compensatory mitigation. Analysis of existing environmental issues in the Lower Bighorn drainage indicates that hydrologic disturbance, impaired water quality, and maintaining high-quality trout fisheries are important environmental issues that should be considered in the context of any hydropower development. Improving water quality or recreational access where high-quality fisheries exist may be potential indirect complementary opportunities of a NSD in the Lower Bighorn drainage, although such development may exacerbate hydrologic disturbance in the drainage.

By contrast, the Shoshone drainage has a more balanced set of opportunities between in-canal and NSDs that could add considerable hydropower capacity if fully developed (72.4 MW). Analysis of existing environmental issues in the Shoshone drainage also shows a varied mix of potential mitigation needs. The related issues of hydrologic disturbance and canal entrainment are the most prevalent, but the drainage contains many of the issues considered in this assessment. The suite of hydropower opportunity types combined with the wide range of environmental issues in the drainage may provide a more tractable set of win-win scenarios than in drainages that have a more limited range of opportunities.

Table 3.2. Summary of hydropower opportunities by eight-digit HUC drainage.

	Existing Powered Dams		Non-Powered Dams		In-Canal Small Hydropower		New Stream-Reach Developments		All Opportunity Types	
8-Digit HUC Name	Number	MW	Number	MW	Number	MW	Number	MW	Total Number	Total MW
Badwater	0	0.0	1	0.1	0	0.0	0	0.0	1	0.1
Big Horn Lake	1	2.5	0	0.0	0	0.0	2	20.8	3	23.3
Dry	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Greybull	0	0.0	0	0.0	5	12.5	0	0.0	5	12.5
Little Bighorn	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Little Wind	0	0.0	0	0.0	0	0.0	1	1.0	1	1.0
Lower Bighorn	0	0.0	3	9.4	0	0.0	12	116.2	15	125.7
Lower Wind	2	0.2	0	0.0	10	6.9	2	22.6	14	46.0
Muskrat	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
North Fork Shoshone	1	0.3	0	0.0	0	0.0	3	4.2	4	4.5
Nowood	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Popo Agie	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Shoshone	0	0.0	0	0.0	33	13.5	5	58.9	38	72.4
South Fork Shoshone	0	0.0	0	0.0	0	0.0	2	6.0	2	6.0
Upper Bighorn	0	0.0	0	0.0	0	0.0	8	58.9	8	58.9
Upper Wind	0	0.0	0	0.0	0	0.0	9	83.9	9	83.9
Total Number/ Capacity	**4**	**3.0**	**4**	**9.6**	**48**	**32.9**	**44**	**372.6**	**100**	**418.0**

(a) Total added capacity for existing powered dams based on a 1% increase through efficiency improvements.
(b) Equal to the sum of the number of powered dams, non-powered dams, and new stream-reach development opportunities for a given drainage.
(c) Equal to the sum of the total added capacities for each hydropower opportunity type for a given drainage.

Table 3.3. Summary of affected catchments classified by environmental issues that represent potential indirect complementary hydropower-environmental opportunities.

Eight-Digit HUC Name	Water Quality	Hydrologic Disturbance	Whitewater Recreation	Blue Ribbon Trout Fishery	Instream Flow Filing	Potential Canal Entrainments	Total No. of Affected Catchments[(a)]
Badwater	0	112	0	0	0	4	113
Big Horn Lake	37	365	17	0	0	39	396
Dry	2	104	0	0	0	28	122
Greybull	638	1119	28	0	0	185	1227
Little Bighorn	0	216	0	0	15	48	244
Little Wind	0	165	0	0	0	45	177
Lower Bighorn	157	719	0	79	0	36	764
Lower Wind	6	278	27	0	0	25	283
Muskrat	0	56	0	0	0	0	56
North Fork Shoshone	0	47	97	148	8	8	177
Nowood	11	188	20	0	0	44	220
Popo Agie	2	100	6	15	0	53	135
Shoshone	68	574	7	52	25	187	637
South Fork Shoshone	0	52	35	0	3	30	102
Upper Bighorn	92	735	0	43	0	128	787
Upper Wind	0	286	41	0	90	70	422
Total No. of Affected Catchments	**1013**	**5116**	**278**	**337**	**141**	**930**	**5862**

(a) The total number of affected catchments for individual HUCs is not equal to the sum of the values in the rows because some catchments may have more than one environmental issue.

Examining potential indirect linkages between hydropower and environmental issues can also be performed using map-based data visualization. Figure 3.6 illustrates an example of how tabular information such as that in Table 3.2 and Table 3.3 can be displayed to visualize regional differences in raw hydropower potential and the number of hydrologic catchments affected by at least one environmental issue. Similar map schemas could be used to illustrate more specific comparisons of hydropower opportunities and environmental issues depending on a person’s given interest. For example, drainages could be colored by potential capacity increase for one hydropower opportunity type and labeled by number of affected catchments for one particular environmental issue.

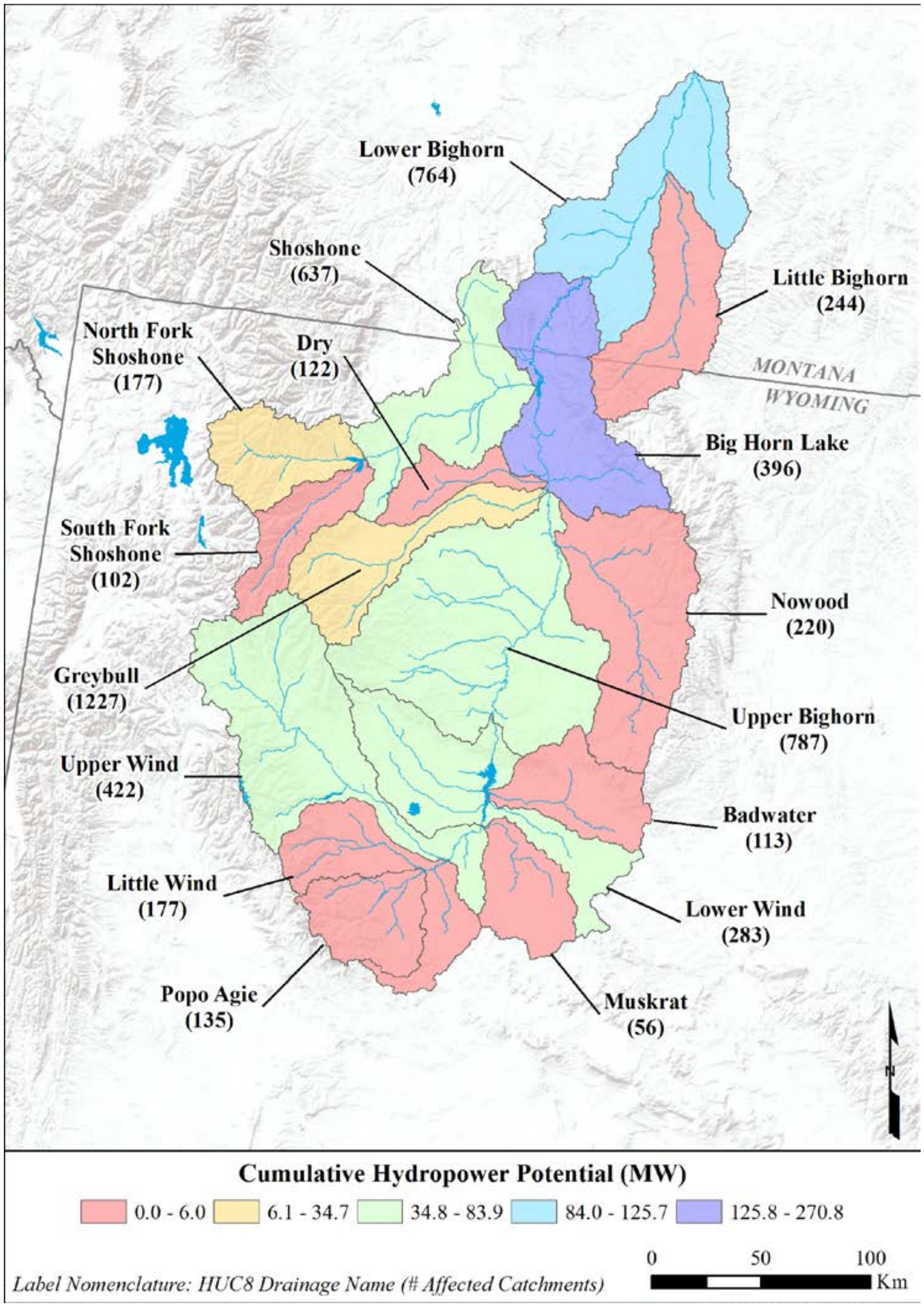

Figure 3.6. Cumulative hydropower potential and number of hydrologic catchments (in parentheses) affected by one or more environmental issues. (NOTE: Cumulative hydropower potential represents potential capacity increases for efficiency improvements at existing facilities, powering non-powered dams, new in-canal small hydropower, and new stream-reach developments.)

4.0 Discussion

The Phase 1 Scoping Assessment for the Bighorn River basin provides a general, high-level assessment of potential complementary hydropower-environmental opportunities. The assessment is intended to provide information about the number of potential opportunities for hydropower development and associated environmental improvements in the Bighorn River basin. The Phase 1 approach is designed to guide a rapid initial assessment of hydropower and associated environmental opportunities at a basin scale. Key strengths of the approach are that it is nationally deployable, relatively quick to implement (6 months or less), and useful for examining and visualizing opportunities under a variety of scenarios. The BSOA data model and geospatial database enable the approach to be implemented for any river basin. The data model and database can be used to standardize identification and visualization of opportunities across basins, but are also flexible enough to allow for customized assessments of opportunities. The database schema and GIS tools can be used to quickly build a BSOA geospatial database for a given basin.

4.1 Assumptions of Phase 1 Approach

Several key assumptions were made during the Phase 1 development. One assumption is that the hydrologic units used in our analyses (eight-digit HUC drainages and catchments) are appropriate spatial units for examining relationships (positive or negative) between hydropower opportunities and environmental issues. The purpose of using hydrologic units (or some other spatial polygon) is twofold. First, hydrologic units were chosen for our analyses because they are hydrologically derived and hierarchically arranged, which is appropriate for relating environmental issues that are tied to hydrology and affected by hydropower. Second, using hydrologic drainages resolves an analytical challenge of relating hydropower opportunities and environmental issues that may be spatially disparate but functionally linked. In doing so, it also helps to satisfy a goal of the BSOA Initiative to expand the scale of analysis to identify commonality among the sometimes disparate goals of regional stakeholders. It should be noted that hydrologic units of a particular scale are not uniform in size and shape; thus, there may be some spatial ambiguity when relating hydropower opportunities and environmental issues and use of hydrologic units may appear to exaggerate or minimize the relative footprint of an opportunity or issue.

It is important to note that complementary hydropower-environmental opportunities were treated equally; i.e., we did not prioritize or weight opportunities. The reason one opportunity was not considered more important than another at the same location was that we wanted to present the full realm of opportunities in an unbiased manner to facilitate discussion among stakeholders to assist with identifying the opportunities that are most valuable to regional interests. Moreover, the total number of opportunities at one location did not make that location more or less important than another in the scoping assessment process. The Phase 1 methodology is intentionally agnostic to the relative importance of any given opportunity because it is intended to provide a high-level assessment to facilitate stakeholder engagement and inform in-depth technical analysis.

4.2 Key Findings

Several key findings were apparent in our assessment of hydropower and environmental opportunities in the Bighorn River basin. They are as follows:

- Most of the NPD locations provided very little potential (<0.1 MW) and were removed from further consideration early in our screening process. Only four NPDs remained after screening, representing a total capacity of 9.6 MW, and a single dam provided nearly all of the power potential for NPD in the basin. Yellowtail Afterbay Dam accounted for 9.2 MW of the total, although this site is not considered a general opportunity because the Crow Tribe has exclusive rights to development (Public Law 111-291).
- In-canal and in-conduit opportunities represent significant power potential with relatively low impacts. The 48 sites that met the screening criteria represent a combined capacity of 32.9 MW. Though several of the canal assessment documents concluded the economics of developing the resources were not compelling, policy and local markets may have shifted sufficiently to warrant a further look. Though in-canal opportunities are of low impact, if environmental improvement can be associated with development (reduced water loss via canal lining or piping) creative collaboration may be possible.
- This assessment considered possible locations for the development of new dams (NSDs) identified by NHAAP that have purely a hydropower focus. However, increasing water storage to improve water security for agriculture is driving the development of new dams in the basin. Currently, five new storage projects are being pursued in the basin; if developed they would add over 20,000 acre feet. It is unknown whether these new reservoirs and reservoir expansions are being investigated for potential hydropower. If they are, they could provide hydropower while mitigating low flow conditions during the late summer when withdrawal demands are high. Considering hydropower in conjunction with new storage may create an additional revenue stream for other storage projects, infrastructure improvement, and water conservation. If the location of NSDs can be considered in the planning for additional storage sites, the additional revenue from power at these sites may allow for more advanced mitigations strategies and reduce the resistance to development.

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