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A Checklist of River Function Indicators for hydropower ecological assessment☆

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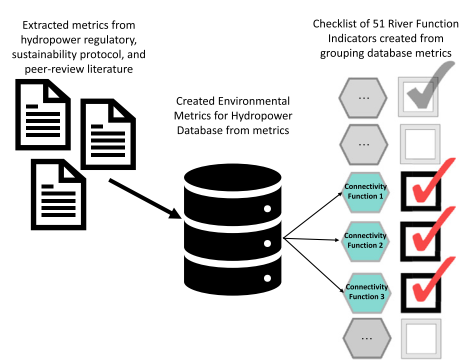
HIGHLIGHTS

- Stakeholders often drive hydropower ecological impact studies.
- Unbiased, science-based indicators may improve ecological outcomes.
- Checklist of River Function Indicators names functions rivers support or maintain
- Indicators based on metrics used by stakeholders so their priorities are emergent

GRAPHICAL ABSTRACT



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ABSTRACT

Hydropower generation has advantages for societies that seek low-carbon, renewable energy alternatives, but sustainable hydropower production will require an explicit consideration of potential tradeoffs between socio-economic and environmental priorities. These tradeoffs are often explored during a formal environmental impact assessment process that can be complex and controversial. The steps taken to address stakeholder concerns through impact hypotheses and field studies are not always transparent. We have created a Checklist of River Function Indicators to facilitate stakeholder discussions during hydropower licensing and to support more transparent, holistic, and scientifically informed hydropower environmental analyses. Based on a database of environmental metrics collected from hydropower project studies documented by the Federal Energy Regulatory Commission (FERC), the International Hydropower Association, the Low Impact Hydropower Institute, and peer-reviewed scientific literature, our proposed Checklist of River Function Indicators contains 51 indicators

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in six categories. We have tested the usefulness of the Indicators by applying them to seven hydropower projects documented by FERC. Among the case study projects, 44 of the 51 Indicators were assessed according to the FERC documentation. Even though each hydropower project presents unique natural resource issues and stakeholder priorities, the proposed Indicators can provide a transparent starting point for stakeholder discussions about which ecological impacts should be considered in hydropower planning and relicensing assessments.

1. Introduction

Exchanging fossil fuel power generation for hydropower generation can result in a lower carbon footprint (Raadal et al., 2011) and given the need to meet increasing global energy demands while achieving reductions in carbon-based energy systems, there is renewed interest in hydropower potential (Zarfl et al., 2014; Gernaat et al., 2017; Couto and Olden, 2018). A hydropower facility continuously and dynamically interacts with upstream and downstream aquatic and terrestrial environments, impacting river ecosystems. As a result, hydropower development has been linked with such environmental impacts as alteration of flow regimes, blocked fish migrations, and aquatic habitat degradation (Poff et al., 1997; Nilsson et al., 2005; Cooper et al., 2017).

Science-based frameworks and protocols are needed to minimize environmental impacts that may accompany the socioeconomic benefits of increased hydropower development. Environmental measurements can help explain and predict hydropower-induced changes to riverine ecosystems and their functions such as regulation of water quality, maintenance of the river channel, and maintenance of biodiversity. While it is not our intent to provide an extensive review of the literature of existing paradigms that inform hydropower sustainability sciencethat includes those describing natural river ecosystem function, such as the River Continuum Concept (Vannote et al., 1980), the Natural Flow Regime (Poff et al., 1997), and the Stream Functions Pyramid Framework (Harman et al., 2012), and impounded river ecosystem function such as the Serial Discontinuity Concept (Ward and Stanford, 1995) and many others (e.g., Flood-pulse Concept—Junk et al., 1989; Riverscape Concept—Fausch et al., 2002; Riverine Ecosystem Synthesis —Thorp et al., 2006). Generalized river responses to dam regulation are described by the Indicators of Hydrologic Alteration (Richter et al., 1996), and frameworks for evaluating holistic riverine ecosystem impacts (e.g., Petts, 1984; Poff et al., 2010). However, any one of these concepts and frameworks alone is not enough to guide holistic hydropower ecological impacts assessment that explicitly and simultaneously incorporates biological, geomorphological, and hydrological impacts in an actionable way. For example, while the Ecological Limits of Hydropower Alteration (ELOHA; Poff et al., 2010) provides a robust framework for proposing and testing hypotheses about the cascading ecosystem effects of river flow alteration, ELOHA does not provide a mechanism for examining the impacts of dam fragmentation and associated fish and sediment blockages that can be detrimental to riverine ecosystems. Moreover, none of these frameworks provide indicators that can enable assessment of a full-suite of ecological impacts of hydropower to ecosystems.

In this paper, we propose a Checklist of River Function Indicators that embeds these existing hydropower sustainability foundational concepts in a simple and practical way for use with diverse stakeholders during applied hydropower licensing or certification processes. These Indicators are intended to support more efficient, transparent, holistic, and scientifically informed selection of environmental analyses to address potential impacts of concern. Specifically, our objectives in this paper are to 1) describe the creation of the Checklist of River Function Indicators and 2) evaluate the potential usefulness of the Indicators for future hydropower licensing discussions.

2. Materials and methods

2.1. Database description

The creation of the Environmental Metrics for Hydropower (EMH) Database, Version 1 that served as a foundation for our proposed Checklist of River Function Indicators (a.k.a., Checklist) has been described in Parish et al. (2019).The EMH database can be accessed through ORNL's website at https://hydropower.ornl.gov/research/projects/envirometrics. The database includes >3000 environmental metrics collected from hydropower project studies documented by the U.S. Federal Energy Regulatory Commission (FERC), the International Hydropower Association (IHA), the Low Impact Hydropower Institute (LIHI), and peer-reviewed scientific literature (Fig. S1). Because these 121 documents were authored or influenced by diverse hydropower stakeholders from across the globe, the environmental priorities of the scientists and stakeholders involved in creating these documents emerged as Indicators in the Checklist of River Function Indicators. In this way, the EMH Database provides an integrated platform for identifying the possible environmental impacts of a hydropower project. For the purposes of the EMH Database, metrics were defined as direct measurements of environmental phenomena, statistics, or indicators whose values have been used to indicate positive or negative movement toward or away from a goal established by stakeholders.

Each environmental metric in the EMH Database was assigned to one of six categories described in Table 1: Biota and Biodiversity (BB), Water Quality (WQual), Geomorphology (GM), Connectivity and Fragmentation (CF), Water Quantity (WQuant), and Landscape and Land Cover (LC). Although recreation and cultural issues are also important factors in hydropower environmental impact assessments, we explicitly focused on ecological issues at this time. However, some of our BB metrics may be useful to assessments of recreational and cultural impacts such as metrics of sport fish that are targeted in recreational angling, wildlife and plants that are essential to hunting, wildlife viewing, or aesthetic values, or culturally important species of fish and wildlife. Similarly, WQuant metrics that describe flow conditions needed to support recreationally and culturally important species may also support these assessments.

2.2. Creation of Checklist of River Function Indicators

The Checklist of River Function Indicators describes the major ecological components of a hydropower-altered river ecosystem including both the Indicators a river needs to maintain the ecosystem (e.g., downstream discharge, reservoir inflow) and the functions a river maintains in the ecosystem (e.g., animal habitat and movement; population structure). We created this checklist by binning the environmental metrics from the EMH Database, Version 1 (Parish et al., 2019) into River Function Indicators within the six categories (Tables 1, S2–S3). Functions were named based on groups of metrics that were measuring a common characteristic of an ecosystem. Functions were only named after completion of the literature review database and were emergent properties of the whole of metrics included. In this way, River Function Indicators named integrate the points of view of multiple hydropower stakeholders and the environmental scientific community.

Table 1
Descriptions of the 6 River Function Categories and 51 River Function Indicators. The 'Indicator ID' column refers to the EMH Database Indicator identification number. River Function Indicators were derived from grouping metrics found in the EMH Database that was created through pulling metrics from a literature review of US Federal Energy Regulatory Commission hydropower licensing Environmental Impact Statements and licenses, International Hydropower Association Sustainability Protocol documentation, Low Impact Hydropower Institute certification documents, and published, peer-reviewed, scientific literature (Parish et al., 2019).

River function category (abbreviation)	Indicator ID	Description
Biota and Biodiversity (BB)		Types and numbers of plant and animal species associated with the river ecosystem, both in absolute abundance and relative abundance to each other.
Abundance, density	I1	Count or other measures of organisms per area
Life history trait characteristics	I2	Life history trait characteristics and their values, such as duration of spawning, fecundity, reproductive mode (characteristics themselves and not the composition of the community)
Presence, absence, occupancy, or detection	I3	Organism presence/absence in an area (including pseudo-absence), occupancy, and detection probability
Species diversity	I4	Species richness, diversity, evenness, or indices-of-biotic-integrity metrics used to characterize one or more components of the biotic community
Behavior, movement, colonization, extinction	I5	Behavior of organisms in study area, including colonization, movement patterns, distance, duration, timing, frequency and/or extinction
Demographics, age, sex, size	I6	Population demographics, including age, sex, and size
Survival, reproduction, growth	I7	Fitness, survival, growth, condition, reproduction, or mortality of organisms
Functional group, species or trait composition	I8	Grouping of organisms by functional or trait status, percentage composition
Genetics, mixing, metapopulation	I9	Genetics and population mixing, including metapopulation dynamics
Habitat or critical habitat	I10	Indices of organism habitat, including habitat area, suitability, etc.
Internal composition nutrient abnormalities	I11	Nutritional composition and makeup of organisms, including elemental stoichiometry; includes levels of internal homeostasis, as well as morphological, genetic, or hormonal abnormalities caused by contaminants
Algae/primary productivity	I51	Measures for algal populations and communities forming basal food web resources
Connectivity and Fragmentation (CF)		The degree to which an ecosystem maintains continuity (connectivity) or disconnection (fragmentation).
Basin area	I12	Some aspect of area of river basin
Dendritic network and riverscape	I13	Fragment length, dendritic connectivity index, barrier index, river distance between dams and projects
Fish passage	I14	Mitigated fish passage, including presence of upstream or downstream passage or length of bypass
Geomorphology (GM)		The dynamic evolution of topographic and bathymetric features created and maintained within a riverine ecosystem including the floodplain and other hydrologically connected areas.
Catchment and basin attributes	I15	Upland soil characteristics, topography, and landscape erodibility metrics that could influence soil erosion and wasting related and subsequent sedimentation related to hydropower development
Channel	I16	Channel properties such as bankfull width, wetted width, bankfull discharge, channel slope, braided channel, channelization
Floodplain valley	I17	Metrics related to channel confinement, entrenchment, migration, etc.
Sediment and substrate	I18	Sediment and substrate properties such as substrate particle size, bedrock composition
Landscape and Land Cover (LC)		Land cover type can influence many river ecosystem properties including sedimentation rates, terrestrial and wetland habitat fragmentation, and the speed at which water moves from upland areas into the river and its hydrologically connected areas.
Area impacted, project area	I19	Project boundary area, area impacted by the project as whole, not related to reservoir inundation or land cover
Floodplain or riparian vegetation	I20	Properties of floodplain or riparian vegetation such as riparian encroachment or floodplain area
Land cover class	I21	Type of land cover, changes in land cover
Protected land	I22	Spatial properties of protected lands including losses or increases
Reservoir inundation	I23	Reservoir area, upland or floodplain inundation, biomass inundated/lost
Water Quantity (WQuant)		The amount of water found within streams, reservoirs and/or groundwater including the duration, frequency, magnitude, periodicity, timing, and rate-of-change of these flows.
Basin attributes	I24	Attributes related to factors that influence hydrology (or were used in the context of hydrology), such as climate and precipitation; catchment size and geology
Diversion	I25	Quantitative properties of diversions such as volume or discharge of diversion or water for other uses
Downstream discharge duration	I26	Downstream discharge duration, where duration is the period associated with a specific flow condition (Poff et al., 1997)
Downstream discharge frequency	I27	Downstream discharge frequency, where frequency refers to how often a flow above a given magnitude recurs over some specified time interval (Poff et al., 1997)
Downstream discharge magnitude	I28	Downstream discharge magnitude, where magnitude is equivalent to the amount of water moving past a fixed location per unit time (Poff et al., 1997)
Downstream discharge periodicity	I29	Downstream discharge periodicity, meaning the order of occurrence of events of a certain magnitude (e.g., did the ten largest floods over a 100-year period all take place in the first 10 years?); flow periodicity affects sediment erosion and deposition as well as the life history completeness of aquatic species; periodicity results from complex interactions of local climate, basin topography, land use patterns, riverbed morphology, and other factors (Yang et al., 2014)
Downstream discharge rate-of-change	I30	Downstream discharge rate-of-change, i.e., flashiness, refers to how quickly flow changes (Poff et al., 1997)
Downstream discharge timing	I31	Downstream discharge timing, where timing refers to the regularity (i.e., predictability) with which flow of a defined magnitude occurs (Poff et al., 1997)
Groundwater	I32	Groundwater characteristics
Reservoir hydrology	I33	Reservoir hydrological characteristics such as residence time, reservoir fluctuation, reservoir surface area, or degree of regulation
Upstream inflow duration	I34	Upstream inflow duration, where duration is the period of time associated with a specific flow condition (Poff et al., 1997)
Upstream inflow frequency	I35	Upstream inflow frequency, where frequency refers to how often a flow above a given magnitude recurs over some specified time interval (Poff et al., 1997)
Upstream inflow magnitude	I36	Upstream inflow magnitude, where magnitude is equivalent to the amount of

Table 1 (*continued*)

River function category (abbreviation)	Indicator ID	Description
		water moving past a fixed location per unit time (Poff et al., 1997)
Upstream inflow periodicity	I37	Upstream inflow periodicity, meaning the order of occurrence of events of a certain magnitude (e.g., did the ten largest floods over a 100-year period all take place in the first 10 years?); flow periodicity affects sediment erosion and deposition as well as the life history completeness of aquatic species; periodicity results from complex interactions of local climate, basin topography, land use patterns, riverbed morphology, and other factors (Yang et al., 2014)
Upstream inflow rate-of-change	I38	Upstream inflow rate-of-change, i.e., flashiness, refers to how quickly flow changes (Poff et al., 1997)
Upstream inflow timing	I39	Upstream inflow timing, where timing refers to the regularity (i.e., predictability) with which flow of a defined magnitude occurs (Poff et al., 1997)
Water Quality (WQual)		The properties and composition of flowing water including water temperature, dissolved gas levels, and nutrient and contaminant concentrations.
Algae/primary productivity	I40	Algal concentration including measures of primary productivity such as chlorophyll A or cyanotoxin
Buffering capacity	I41	Characteristics including pH, alkalinity
Dissolved gases	I42	Concentration of non-greenhouse gases in water
Dissolved oxygen	I43	Dissolved oxygen in water
Ecosystem function	I44	Ecosystem vital rates and processes, including gross primary productivity, respiration, biochemical oxygen demand
Gas emissions	I45	Concentration and ebullition of water-origin greenhouse gases
Key elements	I47	Elements and compounds that are not listed on the EPA Toxic and Priority Pollutants list
Macromolecular pollutants	I48	Pollutants listed on the EPA Toxic and Priority Pollutants list that are not included in other EMH categories
Nutrients and organic material (C, N, P)	I46	Dissolved organic carbon and other organic non-pollutants essential to life, including nitrogen, phosphorous, and inorganic carbon
Solid transport, turbidity, and conductivity	I49	Descriptions of dissolved and suspended solids in water such as turbidity, suspended or dissolved solids, conductance
Water temperature	I50	Water temperature

To provide insight into where the Indicators may be useful for supporting regulatory and sustainability assessment protocols, we created relationships between the categories that structure the Checklist and FERC resources evaluated for impact in licensing, IHASP Best Practices Guidelines for Hydropower Sustainability, and LIHI criteria for certifying facilities as low-impact. Relationships between categories and evaluation criteria were determined from definitions provided in FERC (FERC, 2017), IHASP (IHA, 2018), and LIHI (Sale et al., 2016) documentation.

2.3. Stakeholder Advisory Board input

Our Checklist of River Function Indicators was developed from our EMH Database (Parish et al., 2019) through consultation with a 23-member hydropower stakeholder advisory board composed of members from regulatory and resource agency staff, tribes, NGOs, developers, utilities, other hydropower industry representatives and government and academic scientists with expertise in topics relevant to hydropower. The advisory board met with the project team approximately two to three times per year from 2016 to 2018 and advised on the potential applicability of data products and synthesis to U.S. Federal Energy Regulatory Commission (FERC) licensing and hydropower sustainability. The Advisory Board played a key role in construction of the Checklist and selecting the seven case studies presented in this paper.

2.4. Case study selection and analysis

To evaluate the potential usefulness of the proposed Checklist of River Function Indicators for future hydropower licensing discussions, we used a case study approach to crosscheck it against the environmental metrics recorded during seven past FERC hydropower project relicensing processes. These seven projects were selected from across the U.S.A. through consultation with the Advisory Boards. Seven case study projects were chosen as opposed to a larger or smaller number of case studies due to project budgetary constraints. The complexities stemming from a wide range of interests and natural resource issues from one FERC project to another lent itself well to a case study approach for understanding how our Checklist might be useful in hydropower regulation. This approach also allowed us to identify initial caveats in the Checklist and to understand how relevant the Checklist is given current regulations.

For this case study exercise, we chose projects with diverse project characteristics in terms of installed capacity, geography (Fig. 2), number of dams in the project, mode-of-operation (e.g., run-of-river, peaking, storage, store and release; McManamay et al., 2016), dam ownership, and low-impact certification (Table 2). A hydropower project is defined as one or more hydropower plants or associated non-powered dams operated and licensed as a group, and the seven case study projects addressed in this paper included a total of 13 individual facilities.

At the recommendation of our Stakeholder Advisory Board, we added environmental metrics from two additional projects to conduct the case studies. We included information from FERC licenses, Environmental Impact Statements, and Additional Information Requests (FERC, 1996; FERC, 1997; FERC, 2007; FERC, 2008; FERC, 2010; FERC, 2011) to the EMH Database, Version 2 using the methodology described in Parish et al. (2019). Each new metric was assigned to the one Indicator that best described that metric. We then assessed the potential usefulness of our Indicators for stakeholder discussions during hydropower development by tallying the number of metrics, tallying the frequency of occurrence of the six categories, and finally tallying the individual Indicators for each case study facility and project.

2.5. Case study site descriptions

The following subsections provide brief introductions to each of the seven FERC projects used to validate our Checklist of River Function Indicators. Key information about the seven projects is summarized in Table 2, and maps of the project locations are provided as Fig. 1. Note that four of the projects include multiple dams/facilities.

2.5.1. Nisqually

The Nisqually River Project is a 114 MW capacity project approximately 65 km south of Tacoma, Washington that is comprised of two hydropower facilities: 50 MW Alder Dam operated in peaking mode and 64 MW La Grande Dam (upstream of La Grande Dam) operated in run-of-the-river mode. This project is located in the Marine West Coast Forest Ecoregion which is characterized by high precipitation, extended growing season and moderate mean annual temperatures (Perakis et al., 2011). These facilities are owned by Tacoma Public Utilities and located on the Nisqually River in Washington State. Both dams were licensed under the same Federal Energy Regulatory Commission (FERC) license in 1997. This project has been certified as low-impact by the Low-Impact Hydropower Institute (LIHI). There are 29 fish species in the project watershed (Table S3) and threatened and endangered species and species of special concern located within the project boundary include birds (Bald Eagle (*Haliaeetus leucocephalus*), Northern

Table 2
Project/dam characteristics for case study sites including project and dam name, year of FERC license issuance, river where facility is located, installed project and facility capacity, mode-of-operation of each facility, reservoir residence time, reservoir maximum storage volume (million m^3), mean annual discharge, number of species of concern listed on the IERC license, and number of fish species in the project watershed based on analysis of NatureServe data (NatureServe, 2010) and detailed in Table S3.

Project/dam	Year	River	Dam height (m)	Installed capacity (MW)	Mode-of-operation	Residence time (d)	Storage volume (mcm)	Mean annual flow (cm)	# Species of concern	# Fish species
Bowersock*	2011			7					1	72
Bowersock		Kansas	4	7	Run-of-river	<1	2	197		
Dorena	2010			8					1	26
Dorena		Row	47	8	Run-of river	89	162	21		
Holtwood*	2009			107					10	56
Holtwood		Susquehanna	17	107	Run-of-river	<1	23	1062		
Jackson*	2011			112					5	21
Culmback		Sultan	6	112	Store and release	59	239	15		
Sultan Diversion			80	NPD	Diversion	<1	0	15		
Millord*	1998			8					7	34
Gilman Falls		Stillwater Branch	2	NPD	Run-of river	0	3	113		
Millord		Penobscot	10	8	Run-of river	<1	3	393		
Nisqually*	1997			114					4	29
Alder		Nisqually	101	50	Peaking	43	298	40		
La Grande			66	64	Run-of-river	2	9	<1		
Smoky Mountain*	2005			377					36	103
Calderwood		L. Tennessee	70	157	Run-of river	5	54	135		
Cheoah			72	140	Run-of river	<1	1	126		
Chilhowee			27	50	Run-of river	5	61	136		
Santeetlah		Cheoah	66	45	Storage	110	255	14		

* Low-Impact Hydropower Institute certified projects.

Spotted Owl (*Strix occidentalis caurina*), Marbled Murrelet (*Brachyramphus marmoratus*)) and fish (Chinook Salmon (*Oncorhynchus tshawytscha*)).

2.5.2. Jackson

The Henry M. Jackson Hydroelectric Project is a 112 MW capacity project approximately 80-km northeast of Seattle, Washington comprised of two dams: 112 MW Culmback Dam operated in run-of-river mode and the non-powered Sultan Diversion Dam that is only used for diversion. This project is located in the Marine West Coast Forest Ecoregion near the ecoregion boundary with the Northwestern Forested Mountains Ecoregion. The depths of turbine intakes at Culmback Dam can be adjusted to help regulate water temperature of releases into the Sultan River. These facilities are owned by Snohomish County Public Utility District Number 1 and located on the Sultan River in Washington State. Both dams were licensed under the same FERC license in 2011. This project has been certified as low-impact by the LIHI. There are 21 fish species in the project watershed and threatened and endangered species and species of special concern located within the project boundary include a federally threatened bird (Marbled Murrelet), and federally threatened fish (Pink Salmon (*Oncorhynchus gorbuscha*), Chum Salmon (*Oncorhynchus keta*), Puget Sound Chinook Salmon, Puget Sound Steelhead (*Oncorhynchus mykiss*)).

2.5.3. Smoky Mountain

The Smoky Mountain Hydropower Project is the largest of the case study projects located approximately 110-km southeast of Knoxville, Tennessee with a total listed project capacity of 377 MW from four dams: 140 MW Calderwood Dam, 118 MW Cheoah Dam, 52 MW Chilhowee Dam, and 40 MW Santeetlah Dam. This project is located within the Eastern Temperate Forests Ecosystem which is characterized by temperate, humid climate, dense and diverse forest cover, and dense human population (Gilliam et al., 2011). This project is owned by Brookfield Renewable and located in North Carolina with all dams on the Little Tennessee River and operated in run-of-river mode except for Santeetlah Dam which is located on the Cheoah River and operated in storage mode. All four facilities were licensed on the same FERC license in 2005. This project has been certified as low-impact by the LIHI. There are 103 fish species in the project watershed and threatened and endangered species and species of special concern located within the project boundary include birds (Peregrine Falcon (*Falco peregrinus*), Bald Eagle, Osprey (*Pandion haliaetus*)), amphibians (Hellbender (*Cryptobranchus alleganiensis*), Blackbelly Salamander (*Desmognathus quadramaculatus*), Junaluska Salamander (*Eurycea junaluska*)), mammals (River Otter (*Lontra canadensis*), Southern Appalachian Woodrat (*Neotoma floridana haematoreia*), Meadow Jumping Mouse (*Zapus hudsonius*), Indiana Bat (*Myotis sodalist*)), reptiles (Green Anole (*Anolis carolinensis*)), fish (Smoky Dace (*Clinostomus* sp. cf. *funduloides*), Tuckasegee Darter (*Etheostoma gutselli*), American Eel (*Anguilla rostrata*), Lake Stugeon (*Acipenser fulvescens*), Black Buffalo (*Ictiobus niger*), Smallmouth Buffalo (*Ictiobus bubalus*), Sauger (*Sander canadensis*), River Redhorse (*Moxostoma carinatum*), Spotfin Chub (*Cyprinella monacha*), Yellowfin Madtom (*Noturus flavipinnis*), Smoky Madtom (*Noturus baileyi*), Duskytail Darter (*Etheostoma percnurum*)), freshwater mussels (Appalachian Elktoe (*Alasmidonta raveneliana*)), and plants (Climbing Fumitory (*Adlumia fungosa*), White-leaved Leatherflower (*Clematis glaucophylla*), Branching Whitlow Grass (*Draba incana*), Buffalo Clover (*Alysicarpus vaginalis*), Eastern Turkey Beard (*Xerophyllum asphodeloides*), Carolina-star Moss (*Plagiomnium carolinianum*), Chalk Maple (*Acer leucoderme*), Butternut (*Juglans cinereal*), American Pillwort (*Pilularia Americana*), Dwarf Bristle Fern (*Trichomanes petersii*), an unnamed liverwort (*Megaceros aenigmaticus*), Virginia Spiraea (*Spiraea virginiana*)).

2.5.4. Milford

The Milford Hydroelectric Project located approximately 30-km northeast of Bangor, Maine is an 8 MW project comprised of two dams: the non-powered Gilman Falls Dam and 8 MW Milford Dam operated in run-of-river mode. These facilities are owned by Black Bear Hydro Partners, LLC with Gilman Falls Dam located on Stillwater Branch and Milford Dam located on the Penobscot River in Maine. This project is also located in the Eastern Temperate Forests Ecosystem. Both facilities were licensed on the same FERC license in 1998 to Bangor Hydro-Electric Company. A license amendment was granted in 2005 that allowed the installation of additional turbine capacity and delay of installation of upstream and downstream fish passage infrastructure

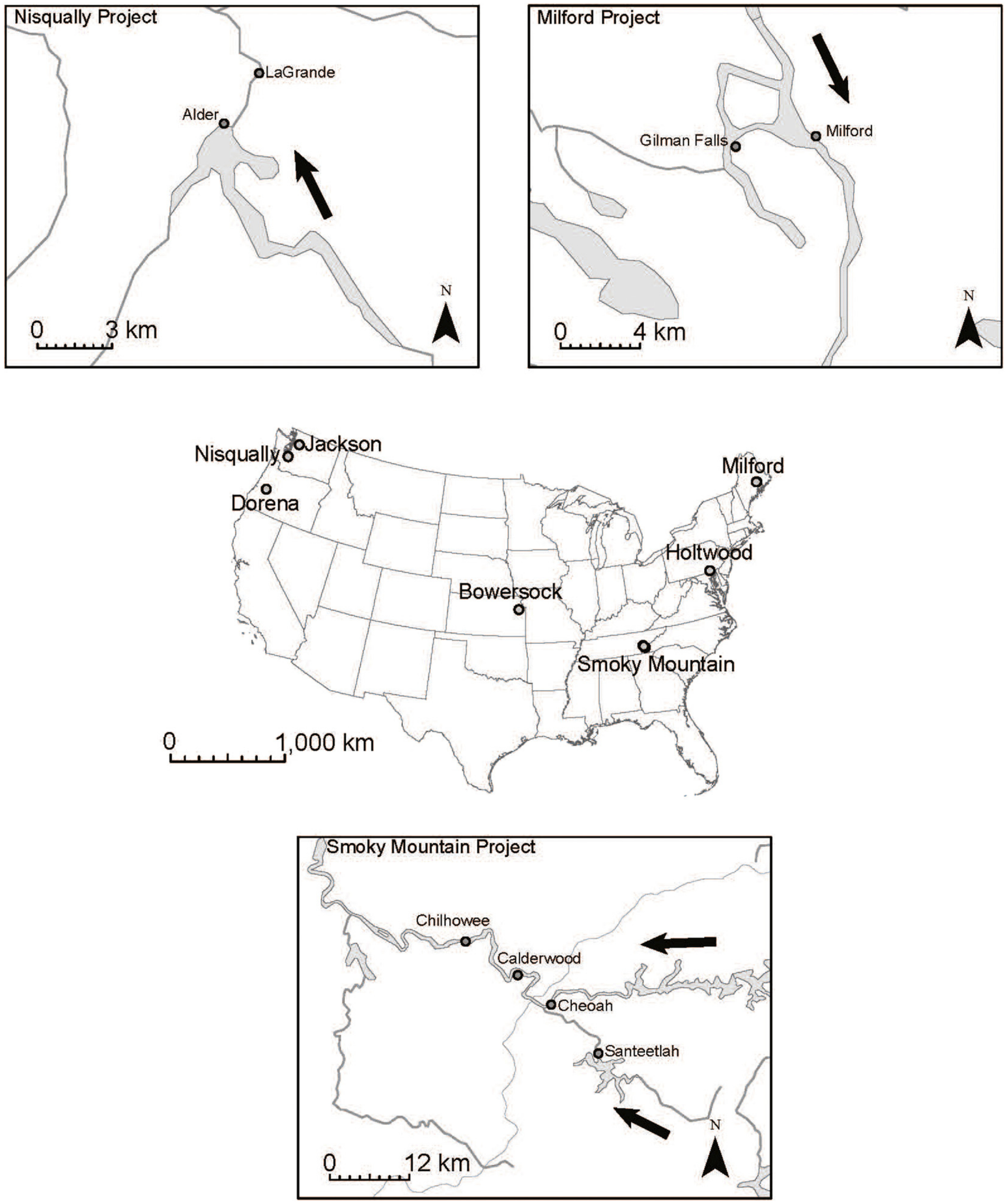

Fig. 1. Map of the USA showing locations of case study projects. Inset maps show detail for those hydropower project that included multiple dams/facilities. Arrows indicate direction of water flow.

until a later date. The license was transferred to Black Bear Hydro Partners, LLC in 2009 with all existing provisions in place. This project has been certified as low-impact by the LIHI. There are 34 fish species in the project watershed and threatened and endangered species and species of special concern located within the project boundary include Alewife (*Alosa pseudoharengus*), American Eel, American Shad (*Alosa sapidissima*), Atlantic Salmon (*Salmo salar*), Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*), Blueback Herring (*Alosa aestivalis*), and Shortnose Sturgeon (*Acipenser brevirostrum*).

2.5.5. Bowersock

The Bowersock Hydropower Plant is a 7 MW facility operated in run-of-river mode and is comprised of the Bowersock Dam on the Kansas River in the city of Lawrence, Kansas. This project is located in the Great Plains Ecosystem which is characterized by a relatively arid climate and grassland cover (Clark, 2011). This facility is owned by the Bowersock Mills and Power Company and was issued an original license in 2011 to accommodate installation of a new turbine that increased generation capacity. Prior to installation of this turbine, this facility was exempt from FERC license requirements because it produced <5 MW of power. Expansion of power production capacity led to the need for a FERC license. This project has been certified as low-impact by the LIHI. The state threatened fish, the Shoal Chub (*Macrhybopsis hyostoma*), is listed as located within the project boundary.

2.5.6. Dorena

The Dorena Hydroelectric Facility is located approximately 200-km south of Portland, Oregon and is an 8 MW facility operated in run-of-river mode on the Row River in Oregon. This project is also located within the Marine West Coast Forest Ecoregion. The hydropower facility is owned by Fiera Infrastructure and operates at the Dorena Lake Dam, which is owned and operated by the United States Army Corps of

Engineers. The Dorena Project was issued an original FERC license in 2010, granted for adding power to a non-powered dam. There are 26 fish species in the two project watersheds (the Dorena project is on the boundary of two watersheds) and the federally threatened fish (Upper Willamette River Chinook salmon) is located within the project boundary.

2.5.7. Holtwood

The Holtwood plant is located approximately 100-km east of Philadelphia, Pennsylvania and is a 107 MW facility operated mostly in run-of-river mode at the Holtwood Dam on the Susquehanna River in Pennsylvania. This project is also located in the Eastern Temperate Forests Ecoregion and is currently owned by Brookfield Renewable, although the license amendment was granted in 2009 to PPL Holtwood LLC when they replaced turbines to expand generation capacity and add upstream fish passage for anadromous fish species. The license amendment extended the license until 2030 so that the license would expire simultaneously with the Safe Harbor Project located upstream of the Holtwood plant. The amended license was issued in 1980 and would have expired in 2014. This project has been certified as low-impact by the LIHI. There are 56 fish species in the project watershed and threatened and endangered species and species of special concern located within the project boundary include birds (Bald Eagle, Osprey, Great Blue Heron (*Ardea herodias*)), fish (American Shad, Alewife, Blueback Herring (*Alosa aestivalis*)), and plants (American Holly (*Ilex opaca*), Sticky Goldenrold (*Solidago simplex*), White Doll's Daisy (*Boltonia asteroids*)). American Eel were not present in significant quantities in the project area when the license amendment was granted, but provisions were made in the Pennsylvania state 401 water quality certification to provide upstream and downstream eel passage.

3. Results

3.1. Using the Checklist of River Function Indicators to support existing protocols

The categories in our Checklist of River Function Indicators were relevant to 75% of the criteria used for LIHI certification and resource types for FERC (Fig. 2a). The Checklist categories were relevant to 35% of the best-practices listed in the IHA Hydropower Sustainability Assessment Protocol (HSAP) (Fig. 2b). Most of the FERC, LIHI and IHA HSAP categories that were not included in the Checklist of River Function Indicators addressed human dimensions of hydropower impacts that were specifically excluded from this research effort, including: Cultural and Socioeconomic Resource categories for FERC assessments; Project-Affected Communities, Resettlement, Indigenous Peoples, Labor and Working Conditions, Public Health, Communications and Consultation, Governance, Demonstrated Need and Strategic Fit, Integrated Project Management, Asset Reliability and Efficiency, Financial Viability, Project Benefits, Economic Viability, and Procurement categories for HASP assessments; and Historic Protection and Free Recreational Access categories for LIHI assessments. The HSAP category of Waste, Noise, and Air Quality indicators was a notable exception previously mentioned in our discussion of the EMH database creation (Parish et al., 2019).

3.2. Case studies

Our review of FERC documents for the seven case study projects yielded a total of 1122 environmental metrics. Across these seven projects, 43 of the 51 River Function Indicators and all 6 Categories were assessed (Fig. 3). Nearly half of the recorded environmental metrics ($n = 480$) were used to characterize the WQuant category (Fig. 4). In descending order, the BB category was addressed by 260 metrics, LC by 146 metrics, WQual by 126 metrics, CF by 62 metrics, and GM by 48 metrics.

Facilities within a project had similar proportions of Indicators assessed (Fig. 5). We have shown the proportion of each functional Category addressed to account for the fact that there are different numbers of Indicators within each Checklist category, ranging from 16 Indicators in the WQuant category to 3 Indicators in the CF category. Overall, the most commonly studied Indicators in each category from the case study projects were I10/Habitat, critical habitat, and surrogates (BB), I50/Water temperature (WQual), I18/Sediment and substrate (GM), I13/Dendritic network and riverscape (CF), I27/Downstream discharge frequency (WQuant), and I19/Area impacted, project area (LC). Only three Indicators were measured at every project: I10/Habitat or critical habitat (BB), I27/Downstream discharge frequency (WQuant), and I49/Solid transport, turbidity, and conductivity (WQual). Eight Indicators were not measured at any of the projects: I11/Internal composition, nutrient abnormalities (BB), I51/Algae/primary productivity (BB), I32/Groundwater (WQuant), I34/Upstream inflow duration (WQuant), I37/Upstream inflow periodicity (WQuant), I38/Upstream inflow rate-of-change (WQuant), I45/Gas emissions (WQual), and I47/Key elements (WQual; Table 3; Figs. 3–5).

3.2.1. Nisqually

A total of 48 environmental measurements were recorded for the Nisqually Project, including 20 at Alder Dam and 28 at La Grande Dam. These metrics supported 14 of the 51 Indicators in 5 of the 6 categories: three in the BB category (25%), four in the WQual category (36%), two in the GM category (50%), one in the CF category (33%), and four in the WQuant category (25%). No Indicators were assessed in the LC category. A few of the Indicators were only assessed at one of the two dams. Indicators that were assessed at Alder Dam but not at La Grande Dam included I31/Downstream discharge timing (WQuant), I33/Reservoir hydrology (WQuant), and I46/Nutrients and organic material (WQual) while Indicators assessed at La Grande Dam but not at Alder Dam included I7/Survival, reproduction, growth (BB), I16/Channel (GM), and I30/Downstream discharge rate-of-change (WQuant). The Indicators that were assessed at both facilities at the Nisqually project included I8/Functional group, species or trait composition (BB), I10/Habitat or critical habitat (BB), I14/Fish passage (CF), I27/Downstream discharge frequency (WQuant), I48/Macromolecular pollutants (WQual), I49/Solid transport, turbidity, and conductivity (WQual), and I50/Water temperature (WQual).

3.2.2. Jackson

Fourteen of the 51 Indicators and 5 of the 6 categories were assessed at the Henry M. Jackson Hydroelectric Project based on a total of 57 environmental measurements: three in the BB category (25%), four in the WQual category (36%), one in the GM category (33%), five in the WQuant category (31%), and one in the LC category (20%). No CF functions were assessed by the Jackson Project. Functions that were assessed by the 32 Culmback facility measurements but not by the 25 Sultan Diversion measurements included I33/Reservoir hydrology (WQuant), I36/Upstream inflow magnitude (WQuant), and I50/Water temperature (WQual). Only one Indicator—I25/Diversion (WQuant)—was assessed at the Sultan Diversion but not at the Culmback facility.

3.2.3. Smoky Mountain

A total of 718 environmental metrics were recorded for the Smoky Mountain Project, including 413 at Santeetlah, 117 at Calderwood, 97 at Chilhowee, and 91 at Cheoh. These metrics were related to 36 of the 51 Indicators and all 6 of the Function categories. Each of the dams addressed two or more Indicators in each of the 6 categories. Of the 36 Indicators measured, eight were from the BB category (67%), six were from the WQual category (55%), four were from the GM category (100%), three were from the CF category (100%), 10 were from the WQuant category (63%), and five were from the LC category (100%). All but one of the Indicators that were measured in this project were measured at the Santeetlah facility. Several Indicators that were

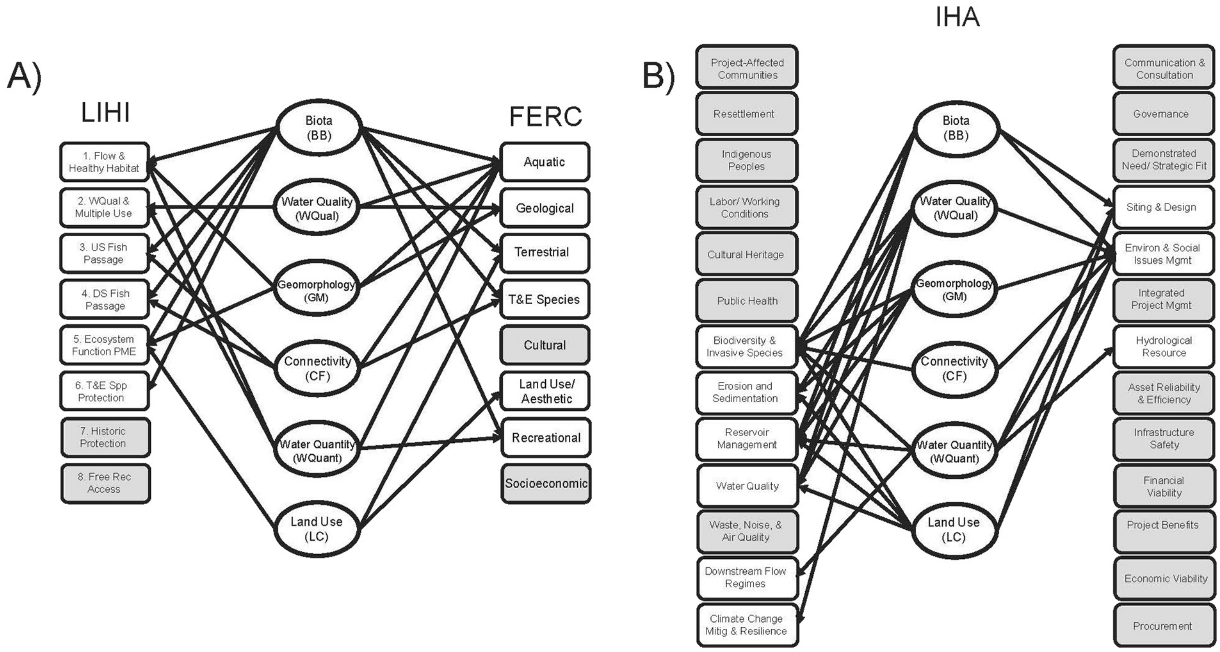

Fig. 2. Categories in the Checklist of River Function Indicators (middle column) and how they may support A) evaluation of Low Impact Hydropower Institute (LIHI) criteria (left column) during low-impact hydropower certification. The LIHI criteria are as follows: 1) Ecological flow regimes that support healthy habitats, 2) Water quality supportive of fish and wildlife resources and human uses, 3) Safe, timely, and effective upstream fish passage, 4) Safe, timely, and effective downstream fish passage, 5) Protection, Mitigation, and enhancement of the soils, vegetation, and ecosystem functions in the watershed, 6) Protection of threatened and endangered species, 7) Protection of impacts on cultural and historic resources, 8) Recreation access is provided without fee or charge, (right column) decisions about what environmental impact studies may be conducted during U.S. Federal Energy Regulatory Commission (FERC) resource categories and B) sustainability evaluations of hydropower facilities by the International Hydropower Association (IHA) Hydropower Sustainability Assessment Protocol (HSAP). Gray boxes indicate LIHI criteria, FERC resource categories, or IHA HSAP Best Practice Categories that are not included in our Checklist.

measured were not measured at all facilities in the project: I1/Abundance and density (BB; only measured at Chilhowee and Santeetlah), I5/Behavior, movement, colonization, extinction (BB; only measured at Santeetlah), I7/Survival, reproduction, and growth (BB; only measured at Cheoah and Santeetlah), I12/Basin area (CF; only measured at Cheoah), I16/Channel (GM; only measured at Calderwood and Santeetlah), I18/Sediment and substrate (GM; only measured at Santeetlah), I20/Floodplain or riparian vegetation (LC; only measured at Santeetlah), I26/Downstream discharge duration (WQuant; only measured at Calderwood and Santeetlah), I29/Downstream discharge periodicity (WQuant; only measured at Calderwood and Santeetlah), I30/Downstream discharge rate-of-change (WQuant; only measured at Santeetlah), I35/Upstream inflow frequency (WQuant; only measured at Cheoah and Santeetlah), I40/Algae/primary productivity (WQual, only measured at Calderwood and Santeetlah), I41/Buffering capacity (WQual; only measured at Santeetlah), and I46/Nutrients and organic material (WQual; only measured at Santeetlah).

3.2.4. Milford

Seventeen of 51 Indicators and 5 of the 6 Function categories were assessed for the Milford Hydroelectric Project based on a total of 58 environmental metrics recorded (38 at Milford and 20 at Gilman Falls): five BB (42%), two WQual (18%), two CF (66%), six WQuant (38%), and two LC (40%). No GM Indicators were recorded for the Milford Project. All Indicators that were assessed at Gilman Falls Dam were assessed at Milford Dam, but some Indicators assessed at Milford Dam were not assessed at Gilman Falls: I3/Presence, absence, occupancy, or detection (BB), I6/Demographics, age, sex, size (BB), I14/Fish passage (CF), Dissolved oxygen (WQual), and I23/Reservoir inundation (LC).

3.2.5. Bowersock

The 71 environmental measurements recorded for the Bowersock project related to 25 of the 51 Indicators in all 6 Functional categories including six BB (50%), five WQual (45%), one GM (25%), two CF (67%), seven WQuant (44%), and four LC (80%) indicators. All six categories of indicators were addressed by the Bowersock project, which recorded 71 environmental measurements.

3.2.6. Dorena

The 38 environmental metrics recorded at the Dorena project assessed 16 of the 51 Indicators and 5 of the 6 Functional Categories: Six BB indicators (50%), five WQual indicators (45%), two GM (50%), one CF (33%), and two WQuant (13%) indicators were addressed by the Dorena project. No LC indicators were recorded by the FERC documents related to this project.

3.2.7. Holtwood

The 132 environmental metrics recorded for the Holtwood project related to 30 of the 51 Indicators and all 6 Functional categories: eight BB (67%), four WQual (36%), four GM (100%), three CF (100%), eight WQuant (50%), and three LC (60%).

4. Discussion

4.1. River Function Indicator Checklist

The Checklist of River Function Indicators presented here provides unique insight into the impacts of hydropower development and operations because it draws from scientifically-based environmental metrics used in multiple types of sources of hydropower-focused environmental literature. This approach allowed for the key environmental priorities of stakeholders, industry, regulators, and the scientific community to emerge as Indicators in our Checklist. In this way, the Checklist can provide a scientifically rigorous backbone to support existing assessment processes useful to a diverse group of stakeholders, scientists, and industry personnel involved in hydropower regulation, licensing, and certification.

The Checklist of River Function Indicators is relevant to several criteria for FERC, IHA, and LIHI assessments and may represent places where this Checklist may support these assessments (Figs. 3–5). The Checklist is relevant to the greatest proportion of FERC and LIHI criteria

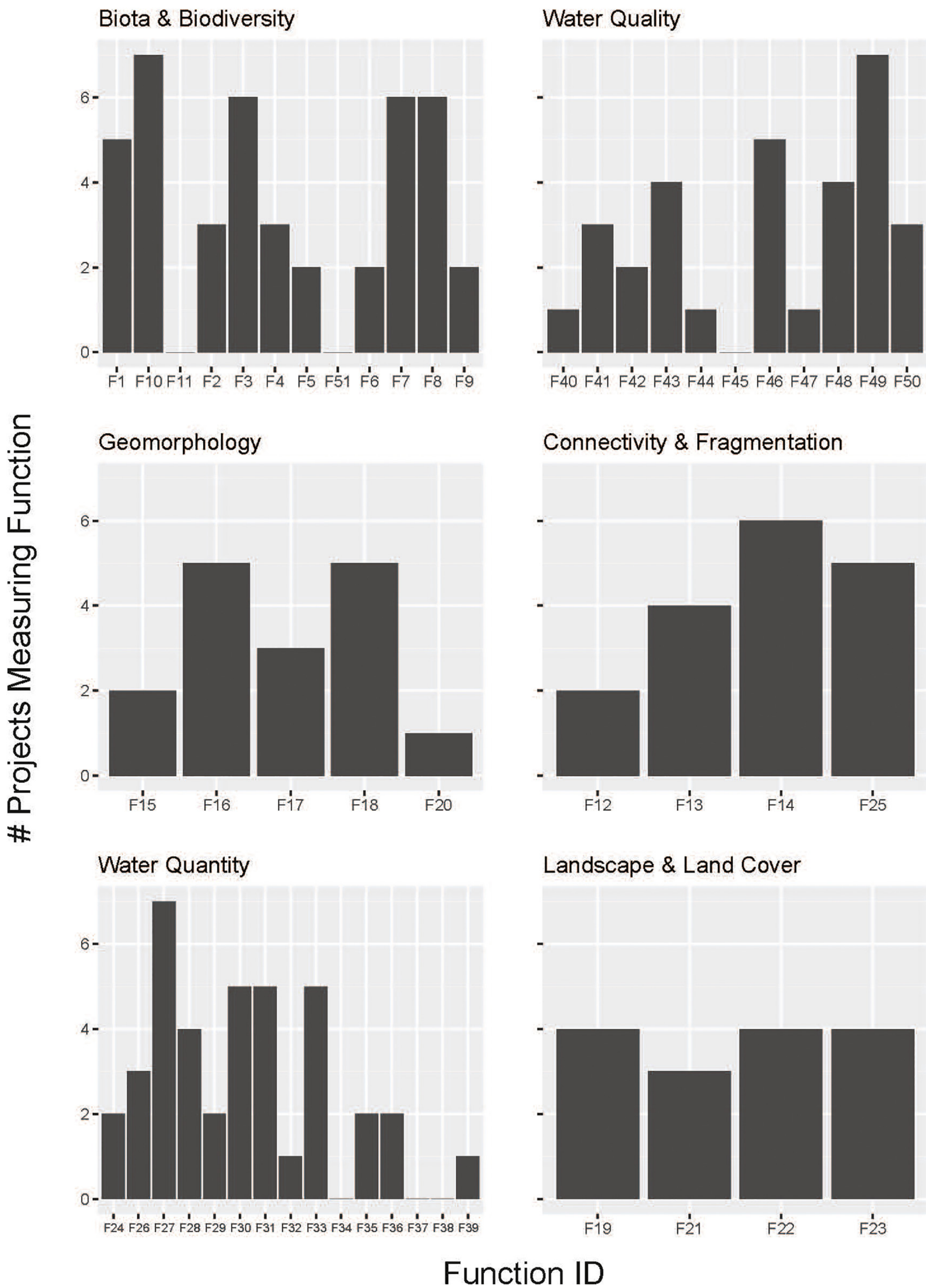

Fig. 3. Bar charts showing the number of projects that measured each of the river function indicators.

and is particularly relevant to assessments of existing facilities including those for adding power to non-powered dams. In FERC assessments, we envision that the Checklist may be most useful during the early phases of licensing or relicensing to facilitate stakeholder negotiations of determining what environmental studies to conduct. The LIHI certification process does not involve study negotiations, but this Checklist can be useful in providing an unbiased way in evaluating how or whether criteria were addressed at a project seeking low-impact certification. For IHA assessments, the checklist could be useful in evaluating nine of the 26 best practices. The Checklist is relevant to fewer IHA criteria than FERC or LIHI. The IHA has a prominent focus on the impact of hydropower to cultural, social and economic systems that were not evaluated by our Checklist. However, our goal in creating this Checklist was not to compete with existing protocols, but to support implementation of existing protocols where possible and there are places in all three types of assessments discussed in this paper (i.e., FERC, IHA, LIHI).

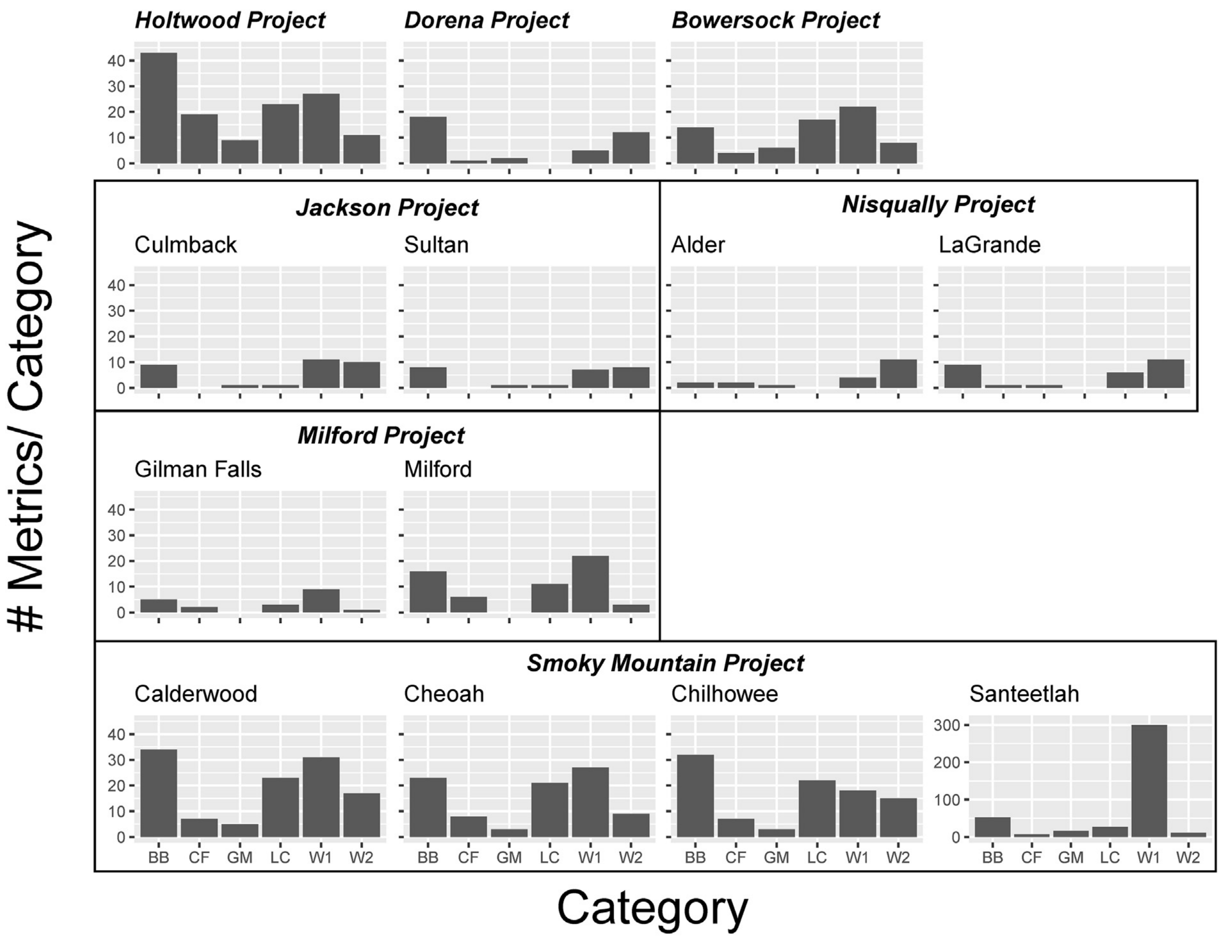

Fig. 4. Number of metrics used to assess each function by facility and project.

In any application of our Checklist of River Function Indicators, we stress the importance of incorporating existing information such as stream flow discharge data, geological surveys, and fisheries and wildlife population and habitat surveys for determining when and where Indicators would be useful for determining project impacts. We are not suggesting that all Indicators in our Checklist require a new study; at most hydropower projects, one or more Indicators may not have project nexus (i.e., impacts are caused by or related to the project under evaluation). For example, the I47/Key elements Indicator may only have project nexus if the project is on or near a contaminated site and there is risk of project activities introducing contaminants into the ecosystem. Similarly, this Indicator may have project nexus if existing geological information indicates high natural abundance of heavy metals such as sites rich in shales. Shales have high levels of selenium that could enter the aquatic environment due to reservoir inundation or downstream erosion (Pracheil et al., 2010). We have created a River Function Decision Support Tool (McManamay et al. in press) that helps to implement the Checklist of River Function Indicators when deciding on hydropower environmental impact studies. This tool can be used for determining when and where Indicators in our Checklist may have project nexus and can help licensees, stakeholders, or evaluators determine what environmental information already exists and where there are knowledge gaps should be addressed through additional study.

4.2. Case studies

Decisions about which environmental assessments to conduct during the FERC licensing process can be complex as diverse groups of stakeholders with different and sometimes competing interests negotiate which environmental studies to conduct. For example, in the USA, FERC license environmental assessments, such as the ones used in licensing the case study projects, are determined by project stakeholders which can include environmental, recreational, developer, Tribal, federal and state agencies and more. Each of these stakeholders may have different priorities and values that are reflected in the environmental assessments that are conducted. Moreover, when diversity of the parties involved in study negotiations is coupled with a unique suite of natural resource and economic issues at each project, distinct outcomes in environmental studies conducted can be expected.

The suite of factors that play into the environmental assessments conducted during FERC proceedings provide a sound rationale for the real-world applicability of the Checklist of River Function Indicators. If the Checklist contains Indicators that are seldom measured in real world scenarios, then it is possible that the Checklist does not capture the constraints of the FERC licensing process. These Indicators were created through an academically and scientifically rigorous process of literature review and incorporation of established understandings of ecosystem functions and processes in impounded river ecosystems. However, standing-up this Checklist to the challenges of real-world, complex assessments involving parties with varied interests are another challenge.

The case studies following summarize the topics addressed and/or discussed in the FERC environmental assessment documents we reviewed. The below discussion of case study results describes the rationale for why Indicators were or were not measured based on information from FERC and LIHI documents. In some cases, these case studies

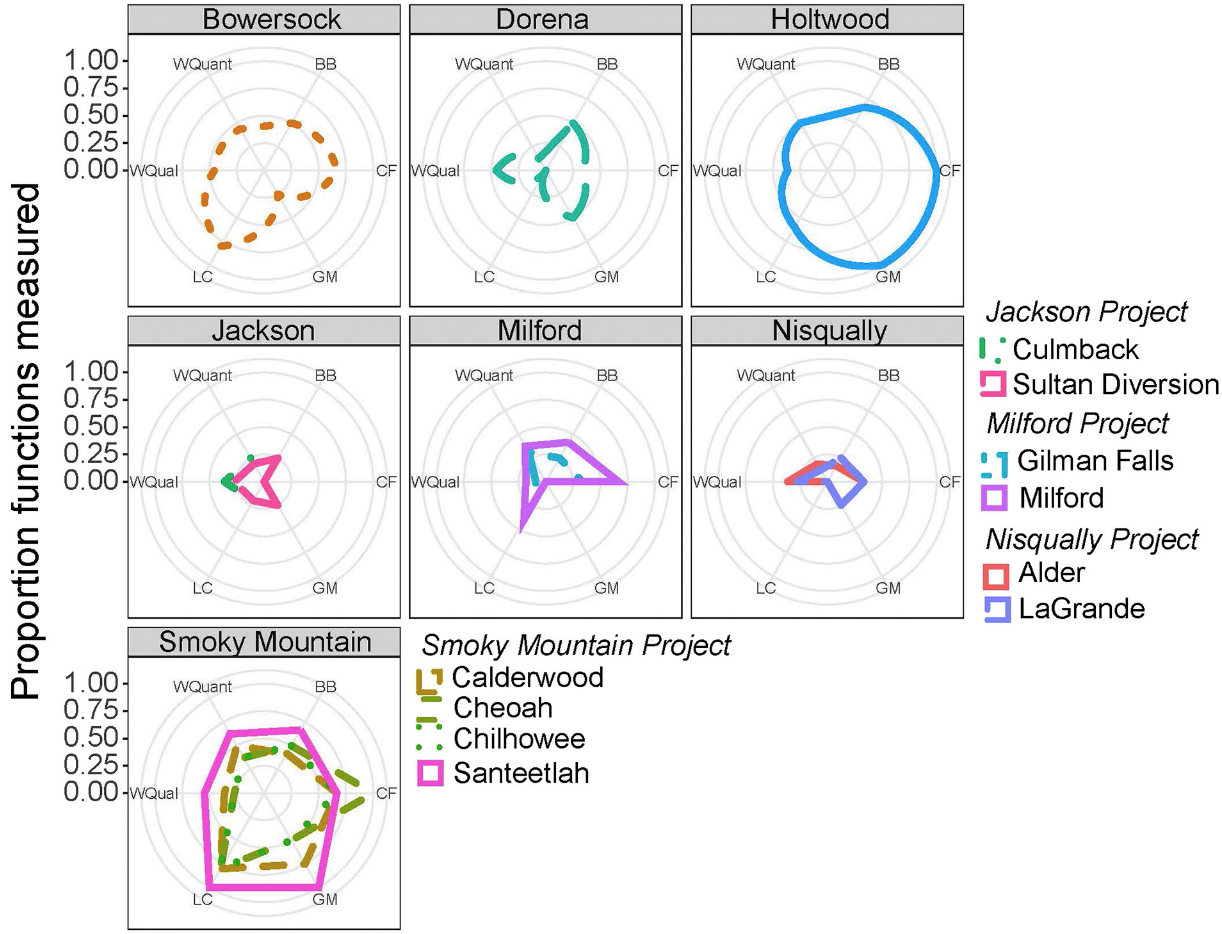

Fig. 5. Radar plots showing the proportion of river functions evaluated in each case study federal Energy Regulatory Commission license by category. For projects with more than one dam, functions evaluated at each dam are designated by different colored and textured lines. On the bar-labels, W1 refers to the Water Quantity (WQuant) category and W2 refers to the water quality (WQual) category.

may not reflect stakeholder discussions that occurred during the licensing proceeding where it was concluded that topics did not need to be addressed in the environmental review process. However, we attempted to capture the outcomes of stakeholder discussions that did not result in additional studies where possible in our descriptions.

4.2.1. Nisqually

Indicators assessed at La Grande Dam but not at Alder Dam were focused on riverine characteristics and fish survival due to the importance of anadromous salmon that inhabit the river downstream of La Grande Dam. Both fish survival studies and flow requirements are important for the persistence of salmonid fishes in rivers. Because the area inundated by La Grande reservoir contained a natural barrier to anadromous salmonid fishes, Indicators that assess these fish were deemed unnecessary for study. On the other hand, Indicators assessed at Alder Dam but not La Grande Dam were generally related to reservoir attributes such as I33/Reservoir hydrology (WQuant) and I46/Nutrients and organic matter because (WQual) Alder Dam forms a significant reservoir whereas La Grande Dam does not. There appear to be some commonalities to the Indicators that were not assessed at either facility. For example, several of the BB Indicators that were not assessed were closely related to animal population or community metrics, or to the I7/Survival, reproduction, growth Indicator that was assessed: I1/Abundance, density; I2/Life history trait characteristics; I3/Presence, absence, occupancy, or detection; I4/Species diversity; I5/Behavior, movement, colonization, extinction; and I6/Demographics, age, sex, size.

Only three WQuant Indicators were assessed and only downstream of Alder Dam which is a peaking facility—a facility that generates power/releases water in response hydroelectric generation demands, as opposed to La Grande Dam which is a run-of-river facility—a facility that has inflow and outflow that are approximately equal (McManamay et al., 2016). Relatively few fish species that might be affected by peaking flows are found in the project watershed and due to the presence of the natural fish barrier in the reservoir, the project was determined to have few impacts to fish. Additionally, the project watershed has few fish species suggesting that the food web is fairly simple and examining cascading effects of this project across trophic levels with measurements of many categories and types of Indicators would not be an obvious priority. The WQuant Indicators that were assessed at Alder Dam characterize the downstream discharge frequency and timing and reservoir hydrology and would capture some degree of flow alteration that would be important to understand for the salmonid fishes that are in the downstream reaches. No LC Indicators were assessed at this project, although few Indicators from this category were assessed across projects.

4.2.2. Jackson

The footprint of the Jackson project is relatively small potentially explaining why only one LC Indicator—I22/Protected lands—was assessed, although it was assessed at both facilities in the project. Several Indicators were assessed at Culmback Dam but not at Sultan Diversion. This may be because Sultan Diversion creates less impacts to the ecosystem than Culmback Dam. For example, Spada Lake, the reservoir created by Culmback Dam, is 722 ha compared to the few ha impoundment created by Sultan Diversion. Culmback Dam is a store and release facility meaning that it stores water for downstream hydroelectric

Table 3
Number of metrics used to assess each function at case study projects where CatID (Category ID) and IndID (Indicator ID) are the same as in Table 1. Projects with multiple hydropower facilities have individual facilities identified by numbers as follows: 1) Alder, 2) La Grande, 3) Culmback, 4) Sultan Diversion, 5) Calderwood, 6) Cheoah, 7) Chilhowee, 8) Santeetlah, 9) Gilman Falls, 10) Milford. Stot (subtotal) columns give the number of metrics used to assess each Indicator for each project and the Total column gives the total number of metrics used to describe each Indicator across all case study projects. Dark gray shaded rows indicate functions that were not assessed at any of the case study projects.

		Nisqually			Jackson			Smoky Mountain					Milford			Bowersock	Dorena	Holtwood	
CatID	IndID	1	2	Stot	3	4	Stot	5	6	7	8	Stot	9	10	Stot				Total
BB	I1									1	1	**2**	1	2	**3**	**1**	**1**	**6**	**13**
BB	I2													4	**4**			**3**	**7**
BB	I3				3	3	**6**	3	4	7	6	**20**	1	1	**2**	**4**	**5**	**5**	**42**
BB	I4							6	4	6	7	**23**				**3**		**8**	**34**
BB	I5										1	**1**					**1**		**2**
BB	I6													1	**1**			**1**	**2**
BB	I7		5	**5**					1		6	**7**				**1**	**1**	**1**	**15**
BB	I8	1	3	**4**	3	2	**5**	17	8	11	11	**47**				**2**	**3**	**9**	**70**
BB	I9							1	1	1	1	**4**							**4**
BB	I10	1	1	**2**	3	3	**6**	7	5	6	19	**37**	3	3	**6**	**3**	**7**	**10**	**71**
BB	I11																		
BB	I51																		
WQual	I40										1	**1**							**1**
WQual	I41							1			1	**2**				**1**			**3**
WQual	I42				1	1	**2**										**3**		**5**
WQual	I43							2	1	3	2	**8**		1	**1**	**1**		**6**	**16**
WQual	I44																	**1**	**1**
WQual	I45																		
WQual	I46	1		**1**							1	**1**				**1**	**1**	**1**	**5**
WQual	I47																		
WQual	I48	1	1	**2**	6	6	**12**									**3**	**2**		**19**
WQual	I49	3	3	**6**	1	1	**2**	4	1	1	2	**8**	1	1	**2**	**2**	**3**	**3**	**26**
WQual	I50	6	7	**13**	2		**2**	10	7	11	4	**32**					**3**		**50**
CI	I12								1			**1**						**1**	**2**
CI	I13							5	5	5	5	**20**	2	2	**4**	**3**		**6**	**33**
CI	I14	2	1	**3**				2	2	2	2	**8**		2	**2**	**1**	**1**	**12**	**27**
GM	I15							2	2	2	2	**8**						**2**	**10**
GM	I16		1	**1**				2			2	**4**				**6**	**1**	**3**	**15**
GM	I17							1	1	1	1	**4**						**1**	**5**
GM	I18	1		**1**	1	1	**2**				11	**11**					**1**	**3**	**18**
WQuant	I24															**5**		**3**	**8**
WQuant	I25					1	**1**	9	8	3	10	**30**	1	1	**2**	**1**		**3**	**37**
WQuant	I26							1			17	**18**	1	1	**2**				**20**

WQuant	I27	1	4	**5**	4	3	**7**	6	4	5	90	**105**	2	2	**4**	**6**	**4**	**4**	**135**
WQuant	I28							4		1	55	**60**	1	1	**2**	**2**		**4**	**68**
WQuant	I29							1			11	**12**							**12**
WQuant	I30		2	**2**	3	3	**6**				22	**22**					**1**	**1**	**32**
WQuant	I31	1		**1**				1	1	1	83	**86**		1	**1**	**1**		**1**	**90**
WQuant	I32																		
WQuant	I33	2		**2**	3		**3**	8	12	7	9	**36**	4	7	**11**	**6**		**9**	**67**
WQuant	I34																		
WQuant	I35								1		2	**3**							**3**
WQuant	I36				1		**1**									**1**		**2**	**4**
WQuant	I37																		
WQuant	I38																		
WQuant	I39							1	1	1	1	**4**							**4**
LC	I19							12	11	12	16	**51**	3	7	**10**	**12**		**18**	**91**
LC	I20										1	**1**							**1**
LC	I21							3	3	3	3	**12**				**2**			**14**
LC	I22				1	1	**2**	6	6	6	6	**24**				**1**		**2**	**29**
LC	I23							2	1	1	1	**5**		1	**1**	**2**		**3**	**11**
Total		20	28	48	32	25	57	117	91	97	413	718	20	38	58	71	38	132	1122

generation (McManamay et al., 2016) that can lead to tailwater dewatering. Studies tailored toward this mode-of-operation can be seen in the project documentation. The FERC license for this project specified many flow-related provisions including minimum instream flows, process flows, and ramping rates which correspond to the focus on WQuant Indicators in the assessment. The I14/Fish passage (CF) Indicators was not explicitly measured, but fish passage was considered and evaluated in several other ways in this license proceeding. For instance, the project license ordered construction of a fish passage structure at the Sultan Diversion Dam, construction of a fish berm that prevents injury at the Sultan Diversion Dam powerhouse, flow provisions that allow for fish passage at the Sultan Diversion Dam, and monitoring and evaluation of the fish population in the powerhouse tailrace to determine effectiveness of the fish berm.

4.2.3. Smoky Mountain

Smoky Mountain measured the highest number of Indicators and metrics used to quantify those Indicators and were particularly focused on the WQuant category. Smoky Mountain is located within a hotspot of North American freshwater fish diversity which may have played a role in the relatively high percentage of Indicators measured at this project. This is an area of high endemism with many species of fish with small range sizes (Januchowski-Hartley et al., 2016) thus creating the potential for the project to impact many sensitive species. As a point of comparison, the Smoky Mountain Project watershed has 36 fish species of concern compared to 10 fish species of concern in the case study project with the second highest number of fish species of concern (Table 2). Measuring a wide variety of Indicators in this case was deemed necessary to account for project impacts to a wide diversity of fishes and identify appropriate mitigation measures. Moreover, with such high biodiversity in the project watershed with complex food webs and diversity of habitats, assessing a large number of Indicators was necessary to understand cascading effects across trophic levels as well as impacts to species reproduction and sensitive life history stages.

The characteristics of the Santeetlah facility provides some added insight into why and when Indicators were studied during FERC licensing. One of the most important factors in determining what Indicators were assessed at this facility was the transfer of Cheoah River water used for power generation to the Little Tennessee River. Pipelines and tunnels transport Cheoah River water 8 km to the powerhouse on the Little Tennessee River and water used in power generation does not support biota in the Cheoah River. Many Indicators were studied on the Cheoah River to determine biological, water quality, and other needs to design flow requirements that would support the Cheoah River ecosystem (McManamay et al., 2010; McManamay et al., 2013a; McManamay et al., 2013b; Peoples et al., 2013). Other properties of the Santeetlah facility may also have been important in determining which Indicators to measure. Santeetlah has the largest footprint of any of the facilities in the project with 255 million m^3 of reservoir and 127 km of shoreline although it has the smallest installed capacity (MW) of the facilities in the project. This suggests that size of the reservoir impoundment may be an important factor in determining how many and which Indicators should be measured. Moreover, Santeetlah was also the only facility in the project that operates in the storage mode—a facility that controls the flow of water for downstream hydroelectric generation (McManamay et al., 2016) as opposed to the others that operate in run-of-river mode thus suggesting that flow modification is critically important in determining which Indicators are measured, particularly for BB and WQuant Indicators.

The Cheoah and Santeetlah facilities were the only ones that measured the I35/Upstream inflow frequency (WQuant) Indicator. Flows to the Smoky Mountain project are largely dictated by releases at the upstream Fontana Dam operated by the Tennessee Valley Authority and inflows into the Cheoah facility in particular are dictated by these releases. Inflows from the Santeetlah facility come from the upper Cheoah River, which drains predominately forested watersheds and are important for understanding water budgets in the Cheoah River especially because Santeetlah is a storage facility.

4.2.4. Milford

Like the Jackson Project, the differences in Indicators assessed at the two facilities making up the Milford project can be attributed to the way the two facilities at this project work together to generate power at the Milford Dam. The Gilman Falls Dam is non-powered, so Indicators related to fish turbine passage were not relevant and were not assessed. Gilman Falls Dam is located on a side-channel and serves to help create hydraulic head for power generation at the Milford Dam. Even though there were no I33/Reservoir hydrology (WQuant) Indicators specifically associated with the Gilman Falls Dam, these two facilities work in tandem to create a single reservoir and the Reservoir hydrology Indicator assessment measured at Milford Dam really applies to both facilities. The Gilman Falls Dam does impact downstream wetted area, and is therefore required to release a minimum flow, so some WQuant Indicators were still assessed at this facility. I14/Fish passage (CF) and more detailed BB Indicators related to fish populations (i.e., I3/Presence, absence, occupancy, detection and I6/Demographics, age, sex, size) were not assessed at Gilman Falls because of existing and newly ordered upstream and downstream fish passage facilities at Milford Dam due to presence of anadromous fish species. No Indicators from the GM category were assessed although the 2005 FERC license amendment requires plans for continuing streambank stabilization and an erosion monitoring downstream of the project in consultation with the Bureau of Indian Affairs and the Penobscot Indian Nation as a condition of license issuance.

4.2.5. Bowersock

This particular FERC license was unique among the case studies in that it was an original license for a facility that already had power. The dam owners were able to capitalize on federal economic stimulus dollars to upgrade their power generation capabilities through a powerhouse addition that made the facility no longer eligible for FERC license exemption. In this case, the project operated in run-of-river mode-of-operation both before and after the license and the additional environmental impact created by the expanded generation capacity was decided to be marginal. As well, construction activities only raised the head of the reservoir a few feet which was also determined to have marginal environmental impact. Conspicuously absent in the Indicators assessment was that of fish passage particularly given the historic and currently downstream presence of an endangered potamodromous fish species (Pallid sturgeon, *Scaphirhynchus albus*). Like the Jackson project, fish passage was considered in the assessment, although not explicitly by metrics that were rolled-up into the I14/Fish passage (CF) Indicators. Bowersock Dam provides a barrier to the spread of Asian carp species that can be dangerous to boaters and impact native fish (Fritts et al., 2018). The FERC license states that construction of a fish passage structure was considered at this facility (although not documented via metrics), but benefits from preventing the spread of Asian carp species were prioritized by stakeholders over expanding riverine connectivity for native fishes.

4.2.6. Dorena

This project was unique among case study projects in that the FERC license we examined was an original license that was granted for adding power to a previously non-powered U.S. Army Corps of Engineers dam. As a result, many of the environmental impacts of this hydropower facility were decided to be marginal compared to those created by the already existing dam. Fish passage did not already exist at the Dorena Dam, and while it was considered during the FERC licensing, it was not ordered for this facility. NOAA Fisheries determined that the Row River did not historically support an independent population of Chinook salmon (*Oncorhynchus tshawytscha*) protected by the Endangered Species Act. However, releases of juvenile Chinook salmon into a tributary near the tailwater of Dorena Dam suggest that fish may return to the base of Dorena Dam and tailrace monitoring was conducted. The FERC license also ordered installation of a tailrace barrier to prevent fish injury and mortality from hydropower generation as well as minimum flow requirements and flow monitoring. Only two WQuant Indicators were assessed in during the FERC licensing process: I35/Downstream discharge frequency and I38/Downstream discharge rate-of-change due to the control of dam releases and, hence, generation releases by the US Army Corps of Engineers and determined marginal additional impact on biota. Also, changes to the turbine and intake design of the installed turbine that led to higher fish entrainment and mortality than the originally proposed design still led to a decision of marginal impact on fisheries resources when compared to the preexisting condition when coupled with installation of an intake fish screen. The State of Oregon Water Quality Certification (included as a FERC License Appendix) stated that corrective measures needed to be implemented for project contributions to dissolved oxygen and total dissolved gas violations and a plan needed to be in place in case of a chemical spill. As a result, water quality Indicators were more heavily assessed for this project—I42/Dissolved gases, I46/Nutrients and organic material (C, N, P), I48/Macromolecular pollutants, I49/Solid transport, turbidity, and conductivity, and I50/Water temperature—leading to a license requirement of water quality monitoring.

4.2.7. Holtwood

Presence of several anadromous fish species of concern and installation of additional generation resources led to a large percentage of BB and CF Indicators measured. Compared to the other categories, the WQuant and WQual categories had a small number of Indicators measured at the Holtwood project. PPL Holtwood, LLC previously started licensing proceedings that were abandoned in 2008 due to unprofitable economic factors related in part due to the outcome of environmental studies and the need for expensive protection, mitigation and enhancement measures (Kleinschmidt, 2013). The LIHI application documentation for Holtwood clearly lays out that more WQuant and WQual Indicators were assessed during the earlier relicensing attempt. Since the studies for the abandoned licensing attempt were sufficiently up-to-date when the new license proceedings began in 2009, there was not a need to reevaluate what appear to be important Indicators (Table 2). Studies of WQual for the abandoned license proceedings indicated that the Holtwood tailrace may have issues with I43/Dissolved oxygen—an Indicator that was not assessed for the license reviewed for the present study and thus did not show up in the FERC documentation. Similarly, studies associated with the abandoned license attempt indicated that the water level in the Holtwood tailrace is governed by the downstream Conowingo hydropower project reservoir. These earlier studies also show that inflows into Holtwood Reservoir are almost entirely controlled by releases from the upstream Safe Harbor project, and that there can be infrequent channel dewatering downstream of the Holtwood Dam. The findings of those earlier studies provided evidence for a minimum flow requirement even though many relevant WQuant Indicators were not assessed.

4.2.8. Case study summary

The River Function Indicator Checklist is useful for understanding what key ecosystem Indicators were evaluated in environmental assessments, although reconstructing the underlying rationale for why particular Indicators were or were not assessed was not obvious in most cases without reading more detailed FERC or LIHI documentation. In some cases, reading FERC or LIHI documentation did not provide a clear path for why certain Indicators were not assessed. For example, no Indicators in the LC category appear to have been assessed at two projects and no Indicators in the GM category appear to have been assessed at one project. It is possible that these categories were assessed or at least discussed but this information did not make it into the documents we reviewed (although it could have been in a Settlement Agreement such as that for the Penobscot River where the Milford Project is located). It is also possible that these Indicators were assessed but the metrics were categorized as a related Indicator in another category. Aside from serving as a useful checklist for consideration in determining what hydropower environmental impact studies to conduct, the Checklist of River Function Indicators can serve as a useful list for determining what to document. Thoroughly documenting topics that are discussed in addition to the ones that are studied increases transparency by providing a record that a thorough job was done in determining what impacts are possible.

The Checklist appears to be useful to hydropower regulation, or at least in line with the current regulatory concerns. Major hydropower impacts appear to be well-addressed across the case study projects. For example, alteration to multiple time-scales of natural flow regimes is one of the key impacts of hydropower to aquatic resources (Richter et al., 1996; Poff et al., 1997; Poff et al., 2010; Bevelheimer et al., 2015) and the WQuant category had the greatest number of Indicators assessed. The BB category was also particularly well-addressed which reflects the common concern of impacts of hydropower to aquatic biota.

In general, the six of 51 Indicators that were not assessed at any of the projects (BB: I11/Internal composition, nutrient abnormalities, I51/Algae/primary productivity, WQuant: I32/Groundwater, I34/Upstream inflow duration, I37/Upstream inflow periodicity, I38/Upstream inflow rate-of-change, WQual: I45/Gas emissions, I47/Key elements; Table 3) may only have project nexus at a limited number of projects. For instance, the Indicators I11/Internal composition, nutrient abnormalities and I47/Key elements were not assessed in the case study FERC documents and may represent ecological Indicators that are only relevant in projects where there is a need to understand detailed information about the food web or specific predator-prey interactions (Vander Zanden and Rasmussen, 1999; Vander Zanden and Rasmussen, 2001; Pace et al., 2004). Likewise, the I47/Key elements Indicator may be important to assess when information about fish movement and environmental history is required (e.g., Pracheil et al., 2014) or when doing bioaccumulation or contamination studies (e.g., Palace et al., 2007; Halden and Friedrich, 2008; Pracheil et al., 2016). Furthermore, certain Indicators may represent emerging ecological concerns that are not of widespread regulatory concern. For example, I45/Gas emissions were not assessed at any project in our case study set, although greenhouse gas emissions are being regulated at some hydropower projects in the Pacific Northwest.

5. Conclusions

The Checklist of River Function Indicators presented in this study can provide a scientifically valid, simple and transparent starting point for guiding discussion when deciding what environmental impact studies to require during regulatory processes or sustainability certifications. We recognize that given unique conditions and issues at each project, it would not be practical or necessary for every hydropower project to conduct environmental impact studies for all 51 of the River Function Indicators to conduct a thorough assessment. In this way, our Checklist may be particularly useful when applied using the River Function Decision Support Tool that was designed to help licensees, regulators, and stakeholders determine project nexus and environmental knowledge gaps of the Indicators in our Checklist (McManamay et al., forthcoming). Our Checklist provides the scientific underpinnings to the River Function Decision Support Tool by providing a standardized list of ecological topics. Independently of the River Function Decision Support Tool, the Checklist can serve as a list of what to document (i.e., description of what environmental studies were conducted or why certain studies were not conducted) in licensing documents so that transparency of hydropower licensing can be increased and provide evidence that a thorough ecological assessment was conducted.

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Appendix A. Supplementary data

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