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Review of environmental metrics used across multiple sectors and geographies to evaluate the effects of hydropower development[☆]

Esther S. Parish[*], Brenda M. Pracheil, Ryan A. McManamay, Shelaine L. Curd, Christopher R. DeRolph, Brennan T. Smith

Environmental Sciences Division, Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, TN 37831, United States

HIGHLIGHTS

- Hydropower literature review produced database of over 3000 environmental metrics.
- Metrics varied by project location, life cycle stage, size and literature type.
- Emergent properties of the metrics can help stakeholders evaluate sustainability.
- Measurable, repeatable & understandable metrics will improve licensing efficiency.

1. Introduction

The United States of America (U.S.) has a need for renewable and sustainable energy resources that can keep pace with increasing energy demands while minimizing adverse impacts to the environment and preserving quality of life for future generations [1,2]. Hydropower is a traditional U.S. renewable energy resource with the potential to expand [3]. However, hydropower development licensing can be a laborious, time consuming, confusing and expensive process. The opportunity exists to improve the existing hydropower license and permit approval process by enacting changes designed to increase efficiency, affordability and transparency. Increasing hydropower production in a sustainable manner will require consideration of potential benefits and tradeoffs throughout the hydropower supply chain and life cycle. In addition to technological developments, it will be necessary to achieve greater understanding of when, where, and how to measure the environmental effects of hydropower in order to effectively and transparently handle competing demands for energy, water, and land resources [4].

Licensing of hydropower facilities by the Federal Energy Regulatory Commission (FERC) in the U.S. is largely stakeholder-driven and can be challenging because this process relies on building consensus among various stakeholders of different expertise, technical lexicons, and values. Licenses are issued for 30–50 years [5] and require negotiations between the license applicant and stakeholders such as federal, state, tribal, and municipal governments, non-governmental organizations, and more to decide how to study project impacts, what the project impacts are, and how to mitigate them through protection, mitigation, and enhancement measures that will become part of the license [6]. Decisions about how a hydropower project impacts the environment are based on a broad suite of quantitative and qualitative environmental information including information about resident biota, water quality, and timing and magnitude of river flows.

Some metrics used to assess the environmental effects of hydropower may be preferred by a particular stakeholder group, and this can add complexity to achieving consensus during FERC licensing negotiations. A single source containing a diversity of metrics from across different literature sources with different perspectives and objectives

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[*] Corresponding author at: Renewable Energy Systems Group, Environmental Sciences Division, Oak Ridge National Laboratory, P.O. Box 2008 (MS-6036), Oak Ridge, TN 37831-6036, United States.

E-mail addresses: parishes@ornl.gov (E.S. Parish), pracheilbm@ornl.gov (B.M. Pracheil), mcmanamayra@ornl.gov (R.A. McManamay), curdsl@ornl.gov (S.L. Curd), derolphcr@ornl.gov (C.R. DeRolph), smithbt@ornl.gov (B.T. Smith).

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Table 1
Categories of environmental metrics related to hydropower projects.

Category name (abbreviation)	Definition	Importance for understanding hydropower impacts
Biota & Biodiversity (BB)	BB metrics characterize the types of plant and animal species found in the watershed, as well as their absolute abundance and relative abundance to each other.	Accurate assessments of species' population and community changes reflect the overall health of the ecosystem. Shifts in aquatic, riparian and terrestrial populations and communities have been linked to several aspects of hydropower construction and operation, including decreased longitudinal connectivity and changes in flow velocities in rivers, inundation of uplands upstream of dams, changes in ground water depth both up and downstream of dams, and changes in sediment and flow regimes.
Connectivity & Fragmentation (CF)	CF metrics assess the degree to which a land cover type or ecosystem maintains continuity (connectivity) or the degree to which an ecosystem or land cover type is disconnected through fragmentation.	Quantifying connectivity changes is important for a full accounting of the environmental effects of hydropower. Dams and their associated infrastructure can disrupt aquatic, riparian, and terrestrial connectivity, as well as groundwater connectivity, all of which can directly affect the habitat quantity and quality for organisms in an ecosystem.
Geomorphology (GM)	GM metrics characterize the dynamic evolution of topographic and bathymetric features created within an ecosystem.	Hydropower development can disrupt a river system's geomorphologic equilibrium through altered sediment and flow regimes. These changes have the potential to impact the availability and quality of habitat for plants and animals within the system.
Infrastructure & Design (ID)	ID metrics relate to the selection of hydropower equipment, associated infrastructure, and management practices.	Hydropower production involves the construction of structures in-stream (for impounding water and generating power) as well as in adjacent riparian and terrestrial lands (for transmitting power and accessing the site). The choice of hydropower equipment, associated infrastructure and management practices can bear directly and indirectly on a variety of environmental attributes through land cover fragmentation for running transmission lines, exposure of animals and humans to electromagnetic fields, changes in the volume and timing of water releases, the use of industrial lubricants needed to keep hydropower turbines properly working, etc.
Land Cover (LC)	LC metrics characterize the physical material at earth's surface pre- and post-hydropower development.	Land cover type is an important measure of ecosystem health because it influences many other environmental properties ranging from river and floodplain sedimentation rates to fragmentation of habitats and wildlife populations at scales ranging from site to landscape. Land cover changes can be used to more-fully describe ecosystem changes associated with hydropower development, such as increases in wetted surface from reservoir formation, and fragmentation of the surrounding landscape through installation of supporting infrastructure (e.g., transmission lines, roads).
Water Quantity (W1)	W1 metrics characterize the amount of water found within streams, reservoirs and/or groundwater aquifers as well as the flows between them.	The hydrologic cycle can be altered by hydropower development through the impoundment of previously free-flowing water, increased evaporation rates, and/or altered groundwater recharge patterns. Because hydropower systems may be operated to fill a variety of purposes, changes to water quantity may occur at a variety of temporal scales. Changes to hydrologic regimes can ultimately affect human and wildlife populations through altered water availability and habitats.
Water Quality (W2)	W2 metrics relate to water quality characteristics, including water temperature, dissolved oxygen levels, and nutrient and pollutant concentrations.	Changes in water quality can adversely affect the health of humans and wildlife. Water quality characteristics can be directly or indirectly affected by hydropower development and operation.

Table 2
Three types of environmental metrics.

Metric type	Definition	Examples
Measure	A direct measurement of environmental phenomenon	temperature reading, species counts
Statistic	A mathematical summarization of collected environmental measures	average water temperature, flood return interval
Indicator	A measure or statistic whose values have been used to indicate positive or negative movement toward or away from a goal established by stakeholders	reforestation, habitat loss

may help hydropower stakeholders to identify more mutually agreeable metrics for assessing the environmental impacts of hydropower. For example, the International Hydropower Association (IHA) has created a Hydropower Sustainability Assessment Protocol (HSAP) intended to promote and certify more sustainable hydropower projects [7]. HSAP offers a way to assess the performance of a hydropower project across more than 20 sustainability topics that include environmental, social, technical and economic aspects, and the protocol also includes several 'cross-cutting issues' (e.g., climate change, human rights) which feature in multiple topics. While U.S. and Canadian hydropower industries participated in the IHA HSAP development, the protocol was not meant to overlay existing hydropower processes in the U.S. and Canada, but instead to focus on countries without established environmental statutes and robust regulatory programs. Another approach to hydropower sustainability assessment is the Low Impact Hydropower Institute (LIHI): a non-profit U.S. organization whose mission is to create a defined standard for "low impact" and incentivize river ecosystem improvements through the creation of a certification program [8,9]. LIHI certification involves addressing a series of goal statements associated with eight cultural and environmental impact criteria. Peer-reviewed scientific literature frequently contains studies assessing environmental impacts of hydropower, but because studies in peer-reviewed scientific journals are typically narrowly focused, the metrics used in these studies may be more discipline-specific and may not be represented in

Table 3
Hydropower project life cycle stages associated with environmental metrics.

Stage name	Definition of life cycle stage	Examples of actions taken curing this stage
Initial project determination	Hydropower project planning phase	Identify potential project site location; Develop project objectives
Permitting and regulatory approval	Dam licensing phase	Conduct environmental sampling to assess initial conditions (e.g., flora, fauna, water quality); Obtain federal, state, and local approvals for the proposed project
Pre-commissioning activities	Interim between receipt of license and initiation of construction activities	Obtain financing and final ownership approvals; Finish engineering plans, contracts and materials procurement; Establish power purchase agreements
Construction	Construction phase of the hydropower project	Prepare site; Impound water; Construct powerhouse and transmission infrastructure; Implement environmental mitigation activities; Develop recreation infrastructure
Operations & maintenance	Implementation phase of the hydropower project	Release water; Generate and transmit power; Conduct periodic sampling activities; Maintain equipment
Decommissioning	Dismantling phase of the hydropower project at the end of its useful life	Remove and dispose of project structures
Multiple	Activities that may occur throughout two or more life cycle stages	Water sampling; Population surveys

Table 4
Spatial scales of environmental metrics related to hydropower.

Spatial scale	Definition	Examples
Within_dam	Metrics associated with internal dam components	Turbine type
Dam	Metrics associated with the dam itself	Fish passage; Seismic stability
Reservoir	Metrics associated with the impoundment located immediately upstream of the dam	Shoreline erosion; Algal blooms; Siltation rates; Offgassing
River_downstream	Metrics associated with the river downstream of the dam, including the tailwater	Flow rate; Dissolved oxygen levels; Water temperature; Fish counts
River_upstream	Metrics associated with the upstream mainstem and tributaries	Flow rate; Dissolved oxygen levels; Water temperature; Fish counts
Basin	Metrics associated with the watershed in which the hydropower project is located	Water consumption rates; Number of stream tributaries
Landscape	Metrics associated with the terrestrial landscape surrounding the hydropower project	Percent forest cover; Number of road crossings; Miles of transmission lines
Project	Metrics associated with the entire hydropower project (e.g., multiple dams)	Water temperature; Fish condition; Genetic diversity

sustainability protocols. Some of these studies may be associated with FERC or other hydropower licensing investigations, so the metrics used in the peer-review literature may also be represented in license documentation. However, because studies in peer-review literature may be motivated by intellectual novelty, this source of literature might also provide a very different suite of environmental metrics.

In this paper, we describe a new database of hydropower-related environmental measurements recorded by researchers across multiple scientific disciplines, locations, sustainability certification processes, and licensing efforts. We present this aggregated information about previous efforts to increase transparency and enable the development of robust indicators of environmental sustainability for this renewable energy resource [10]. Specifically, we describe (1) the body of environmental metrics uncovered during a hydropower literature review conducted across several sectors, (2) the life cycle status and physical characteristics of the hydropower facilities from which the metrics originated, and (3) the worldwide geographic distribution of the hydropower facilities from which the metrics originated. Due to the large volume of literature related to hydropower sustainability, this study focuses on the physical and ecological aspects of the potential environmental effects of hydropower.

2. Materials and methods

Before starting our literature review, we established a data collection framework to capture important attributes about the environmental metrics (Section 2.1). We then collected environmental metrics from licensing documents, low-impact and sustainable certification documents, and recent peer-reviewed literature (as detailed in Section 2.2) and recorded attributes for each identified metric within a relational Microsoft Access database for further analysis. We used this process to gain a better understanding of the types of environmental metrics used to describe the environmental effects of hydropower projects across a wide variety of aquatic and terrestrial ecosystems.

2.1. Data collection framework

Environmental metrics are the most fundamental levels of environmental information upon which assessment of hydropower effects and procedural stipulations are based. We first defined seven Categories of environmental metrics (Table 1) intended to capture the general environmental concepts that govern river ecology, enable thematic analysis, and allow for consistent visualization of findings. We defined these seven broad categories—Biota & biodiversity, Connectivity & fragmentation, Geomorphology, Infrastructure design & development, Land cover, Water quality, and Water quantity—based on potential effects (positive or negative) of hydropower project on watersheds, landscapes, and aquatic ecosystems (Table 1).

We chose to classify environmental metrics as measures, statistics, or indicators (see definitions in Table 2) to describe the level of analysis and interpretation associated with the metric [11]; we refer to this attribute as the metric's Type. We also defined attributes for capturing the dam life cycle Stages (Table 3) and Spatial scales (Table 4) that would be assigned to each captured metric.

In order to be included in our Environmental Metrics for Hydropower (EMH) database, the observed metric had to be measurable, repeatable, and broadly understandable as determined by the document reviewers (authors: BMP, RAM, CRD, ESP), who had good collective knowledge on this topic. Once an environmental metric was identified in a document, we created an entry for the metric in our database that included information such as the facility name, the river, and geographic location along with the metric Type, Category, Life Cycle Stage and Spatial Scale (Tables 1–4). Later we used three databases to obtain ancillary information such as generating capacity, generation, dam characteristics, and reservoir properties: the National Hydropower Asset Assessment Program (NHAAP) database [12] and National Inventory of Dams (NID) [13] for hydropower facilities in the United States and the Global Reservoir and Dam (GRanD) database [14] for non-U.S. hydropower projects. Online searches were then used to supplement information about hydropower projects that were not listed

Table 5
U.S. FERC/LIHI hydropower projects included in database. We reviewed 8 FERC documents pertaining to 4 projects and 8 LIHI documents pertaining 5 projects. License numbers, owners, capacities and generation rates were all obtained from LIHI [9].

Hydropower project	FERC No.	LIHI No.	U.S. State	River	Owner	Capacity (MW)	Average annual generation (MWh)	Metrics
Bowersock Project	13526	15	KS	Kansas River	Bowersock Mills and Power Company	7	32,726	71 FERC, 46 LIHI
Holtwood Hydroelectric Project	1881	116	PA	Susque-hanna River	PPL Holtwood, LLC	252	590,044	132 FERC, 32 LIHI
Milford Hydroelectric Project (includes Milford Dam & Gilmans Falls Dam)	2534	113	ME	Penobscot River; Stillwater Branch	Black Bear Hydro Partners, LLC	7.8	55,186	39 FERC, 16 LIHI
Nisqually Project (includes La Grande and Alder dams)	1862	8	WA	Nisqually River	City of Tacoma	114	573,000	41 LIHI
Smoky Mountain Project (includes Chilhowee, Calderwood, Cheoah, and Santeetlah dams)	2169	18	NC, TN	Little Tennessee River	Brookfield Smoky Mountain Hydropower LLC	376.6	1,361,821	461 FERC, 30 LIHI

in any of these three databases.

2.2. Literature selection

To capture a broad swath of measurements from multiple sectors concerned with potential effects of hydropower development, we based our literature review of environmental metrics on a combination of FERC regulatory documents, LIHI and IHA HSAP certification documents, and peer-reviewed scientific journal articles.

FERC's responsibilities include licensing and inspecting private, municipal, and state hydroelectric projects, and there are currently about 1030 active, non-federal hydropower projects licensed by the agency [5]. FERC orders issuing new licenses and notices of environmental assessments—plus the environmental impact assessments themselves—for all of these projects can be obtained from the FERC e-library at https://www.ferc.gov/docs-filing/elibrary.asp. Typically, FERC orders are structured to provide a description of project facilities, a discussion of major environmental elements and stakeholder concerns, and then subsequent articles specifying the approved facilities and operations and explaining how environmental impacts will be addressed. Because FERC specifies facility dimensions and capacities (e.g., dam storage) during licensing, these elements are interpreted as metrics describing environmental impact along with traditional metrics (e.g., water temperature). For instance, if the licensee increases the capacity of a project, this will likely require re-opening a license, as potential subsequent environmental impacts from the action must be reassessed.

At least 130 US hydropower projects have been certified using the LIHI protocol [9], and LIHI documentation is openly available through the institute's webpage at https://lowimpacthydro.org. The structure of the LIHI Certification process is defined by eight cultural and environmental goal statements that define the purpose or objective that must be satisfied, and a series of alternative standards are provided by which each criteria's goal can be met. In consultation with LIHI staff, applicants prepare a description of project facilities and complete a LIHI application. The application is structured to document how the applicant has addressed each of the eight criteria, and additional supporting documents, such as fish passage plans, monitoring plans, and maps of facilities are provided.

For this analysis, we selected five U.S. non-federal hydropower projects (Table 5) that have recently undergone both FERC relicensing and LIHI certification to represent a wide range of generation capacities and infrastructures as well as a broad geographic distribution across the U.S. (Fig. 1). We reviewed eight FERC documents [15–22] pertaining to four of the five selected hydropower projects. The Nisqually Project was not included in the FERC document review due to the length of time involved with extracting information from these dense documents. It took us an average of eight hours to extract metrics from a FERC document (as compared to an average of 20–30 min to extract metrics from a journal article). We also reviewed eight LIHI documents [23–30] pertaining to the five U.S. hydropower projects and ten dams listed in Table 5.

After examining the thirteen international hydropower projects that had been reviewed and published from 2012 to 2015 using the IHA HSAP [7], we selected four of them to include because they represented four different continents and three different HSAP protocol stages (Table 6). The four protocol documents [31–34] were freely available from the IHA website at http://www.hydrosustainability.org/Protocol-Assessments.aspx.

We used systematic review guidelines established by the Center for Environmental Evidence [CCE; 35] to identify a large set of peer-reviewed journal articles pertaining to the environmental effects of hydropower projects and then to select a subset of the identified articles for detailed review and environmental metrics extraction (Fig. 2). Using the CEE methodology, we set rigorous and repeatable study inclusion criteria and documented environmental and hydropower search terms, search dates, and studies included. We created a list of search strings

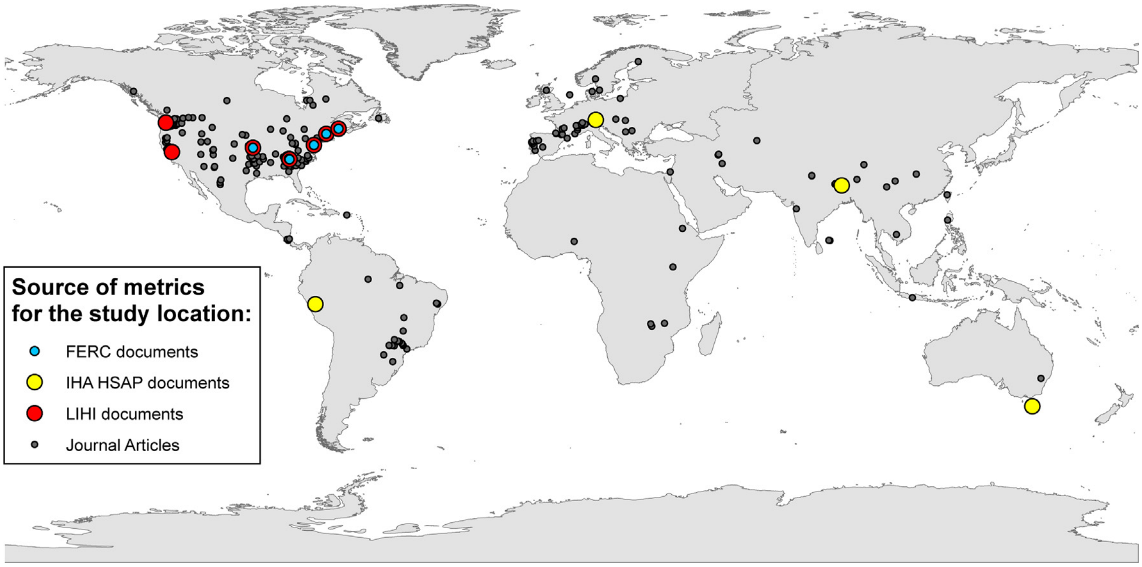

Fig. 1. Map showing the 231 study locations used to collect environmental metrics discovered by this literature review.

Table 6
List of IHA hydropower projects reviewed for environmental metrics [7].

Hydropower project	Country	River	Owner	Capacity (MW)	IHA HSAP protocol stage	Metrics
Chaglla	Peru	Huallaga	Empresa de Generación Huallaga S.A.	456	Implementation	43
Kabeli A	Nepal	Kabeli	Kabeli Energy Limited	37.6	Preparation	40
Walchensee-kraftverk	Germany	Isar	E.ON Hydro Fleet	124	Operation	8
Trevallyn	Australia	Esk	Hydro Tasmania	96	Operation	16

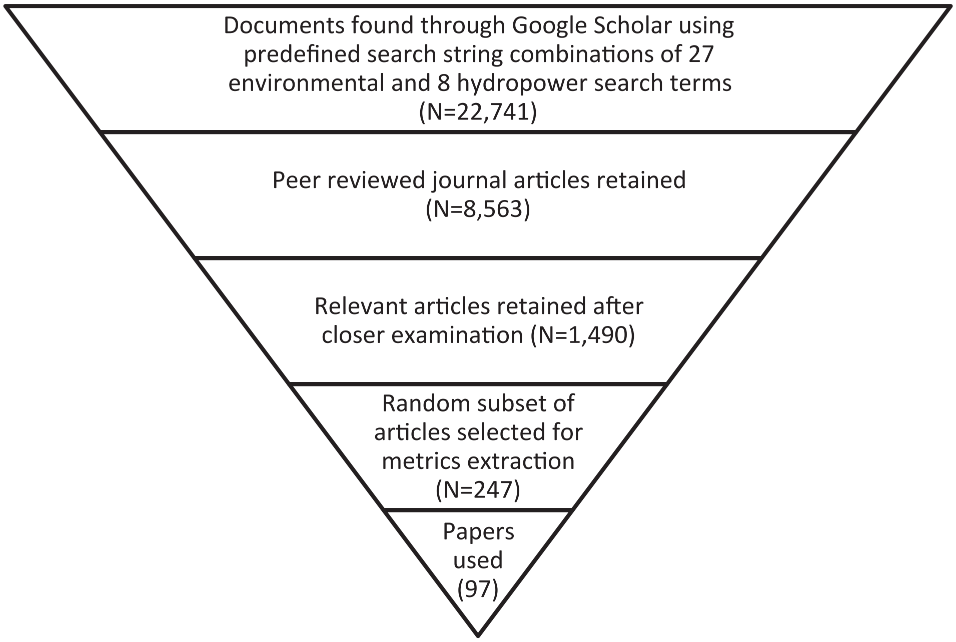

Fig. 2. Steps taken to select peer-reviewed journal articles used for environmental metrics extraction.

that would represent multiple stakeholder viewpoints and generate comprehensive results that were representative but not overly duplicative. Based on our collective knowledge and expertise, we developed over 216 unique search strings (Table 7) by combining one of 27 environmental terms (e.g., “Land cover”, “biodiversity”) with 1/8 hydropower terms (e.g., “dam”, “powerhouse”). Quotations around compound terms such as “flow regime” or “stilling basin” were used to help restrict search results to those relevant to this review. Wild card searches were used to include multiple forms of words. For example, “alter*” would search for “altered”, “alteration”, “alters”, etc. The predefined search strings were used in Google Scholar from September 9–22, 2016, yielding 22,741 documents. Peer-reviewed papers that contained mention of environmental characteristics at hydropower facilities in the paper title, abstract, or executive summary were retained for further review. Papers that contained terms signaling potential relevance to this project were also retained for further review even if

Table 7
Search terms used to create pre-defined search strings for a systematic review of peer-reviewed literature. Each search string was comprised of one environmental term and one hydropower term.

Environmental Term	Hydropower Term
Alter*	Conveyance
Assess*	“Dam* OR Barrage*”
Biodiversity	“Hydropower OR Hydroelectric”
Biot*	Infrastructure
“Communit* OR Community”	Powerhouse
“Connect* OR Connectivity”	“Reservoir* OR Impound*”
Effect*	“Tailrace* OR Tailwater*”
Environment*	Turbine
Fish*	
Flow*	
“Flow regime*”	
“Fragment* OR Fragmentation”	
Geomorph*	
Impact*	
“Land cover”	
Limnolog*	
Macroinvert*	
Macrophyte*	
Measur*	
Metric*	
Mussel*	
Population	
Quantif*	
Sediment*	
Sustain*	
“Water quality”	
“Water quantity”	

hydropower was not specifically mentioned (e.g., papers that discussed watershed land use change over time because of hydropower development and reservoir inundation, or papers that discussed organism response river flow or regulation). In this way, we narrowed down the large literature selection to 1490 relevant articles. Due to time constraints, a subset of 247 of these articles was randomly selected for analysis and the rest were set aside for possible future use. Only 97 of these 247 peer-review journal articles ended up containing environmental metrics, meaning quantitative or qualitative information characterizing the environment at, near, or associated with a hydropower plant. Table 8 summarizes the countries, rivers, hydropower projects, number of metrics, and metric categories associated with each of the 97 selected peer review journal articles [36–132].

3. Results

During our review of 117 documents, we discovered 3183 unique environmental metrics recorded during a variety of studies related to dams and hydropower projects. These metrics were related to 231 dams and study locations worldwide (Fig. 1) and were unique combinations of category, measurement type, lifecycle stage, and spatial scale. Several of the studies (i.e., points in Fig. 1) considered multiple small dams. Most of the study sites were in North America (121) and Europe (53), followed by South America (29), Asia (20), Africa (6) and Australia (2). The dams ranged in size from small earthen dams and one inflatable dam built solely for irrigation, flood control, and/or recreational purposes to powered dams with capacities ranging from micro size (i.e., less than 0.1 MW) to as much as 22,500 MW. The geographic distribution, size and ownership of the U.S. dams captured by this literature review relative to the entire U.S. hydropower fleet is shown in Fig. 3. ‘Non-powered dams’ (see black dots on Fig. 3A) were described in some of the peer-review journal articles. This category of hydropower projects includes dams currently managed for flood control, irrigation and/or recreational purposes (with no electric power generation) as well as a few older dams that have been decommissioned and are therefore no longer mapped as part of the U.S. hydropower fleet.

The literature review produced environmental metrics across all hydropower project life cycle stages (Fig. 4), but most of the metrics in all 7 environmental categories had been collected during the Operations & maintenance stage (86% total). Few of the metrics had been collected during the Pre-commissioning (3%) and Initial project determination (2%) stages, and even fewer had been collected during project Decommissioning (1%). An additional 7% of the environmental metrics were recorded as having been collected during Multiple (two or more) life cycle stages of the hydropower project under investigation. Fig. 4 shows that a substantial number of Connectivity & fragmentation metrics (21% of the category total) were collected during Pre-commissioning activities.

The relative abundance of metrics collected in each of the seven environmental categories is summarized by source document type in Fig. 5. Overall, the largest proportion of the collected 3183 metrics related to Water Quantity (32%) and Water Quality (30%). All source documents produced the greatest number of metrics for Water Quantity except for the IHA HSAP documents, which yielded 38% Water Quality and only 12% Water Quantity metrics. The third largest category overall was Biota & Biodiversity (15%), and it was relatively evenly represented by each source, comprising 15–22% of the total metrics gathered from each document type. There were relatively few metrics gathered from the other four categories of Connectivity & Fragmentation (7%), Geomorphology (6%), Infrastructure & Design (5%), and Land Cover (4%). The IHA documents produced the most Geomorphology metrics (13%). Infrastructure & Design metrics were much more prevalent in the LIHI (22%) and FERC documents (12%) than in the journal articles (1%) and IHA documents (6%).

The relative abundance of metrics in each environmental category was also examined by hydropower project size, with size defined by total megawatt generation capacity (Table 9). Note that many of the source documents described multiple hydropower projects, so the total number of metrics reflected in this table (i.e., 5160) is larger than the number of unique metrics collected by the literature review. A total of 22 metrics was collected from the only micro project captured by this effort, and these metrics were nearly evenly divided between Water Quantity (10 metrics) and Biota & Biodiversity (12 metrics). The 26 small projects yielded 629 metrics that mostly pertained to Water Quantity (35%) and Biota & Biodiversity (24%). The 62 medium-sized projects yielded 1659 metrics pertaining primarily to Water Quantity (59%), Geomorphology (15%) and Biota & Biodiversity (11%). The 48 large projects yielded 1474 metrics which also primarily pertained to Water Quantity (47%), Geomorphology (18%) and Biota & Biodiversity (14%). The 46 very large projects captured by this effort yielded 1,376 metrics, and in this case the majority were related to Water Quality (58%). Metrics pertaining to all 7 environmental categories were collected from hydropower projects of all sizes (except in the case of the single micro project).

The geographic distribution of the collected environmental metrics by category across the continents (Fig. 6A) shows a predominance of Water Quantity and Water Quality metrics across all continents with a more even mix of the two categories across Europe, South America, Africa and Asia. Given that the pie sizes indicate the relative number of metrics collected across each continent, one can see that the environmental metrics captured by the database were largely from North America and Europe with very few from Oceania.

4. Discussion

Examination of the 3183 environmental metrics discovered by our literature review showed that they coalesced around 45 subcategories of environmental metrics and that most of these subcategories were represented by a variety of metric types, including simple measurements, statistics, and indicators (Table 10). We view this resulting list of environmental metrics subcategories (Table 10) as a potential envelope of environmental measurements that might be used to improve

Table 8
List of journal articles reviewed for environmental metrics.

Journal article	Continent	Country (or countries)	Dam(s) or study location	River(s)	Metrics	Categories
Agostinho_etal_2008 [36]	S. America	Brazil, Paraguay	Tres Irmaos, Corumba, Itaipu, and Porto Primavera Dams	Corumba, Parana, Tiete, Parana Yacyreta, Parana	4	BB
AlonsoGonzalez_etal_2008 [37]	Europe	Spain	Proposed dam	Tormes	26	BB, W1
Anderson_etal_2008 [38]	S. America	Costa Rica	Suerkata, Toro I, Toro II, Volcan, Segundo, El Angel, Dona Julia, Cariblanco, and Don Pedro Dams	Sarapiqui, Toro, Volcan, Agnel, Tuolumne	9	W1
Andriolo_etal_2013 [39]	S. America	Brazil	Porto Primovera Dam	Paraná	4	BB
Arias_etal_2011 [40]	Asia	Cambodia	Proposed dam	Mekong	6	GM, LC
Armanini_etal_2014 [41]	N. America	Canada	Steephill Falls Generating Station	Magpie, Batchawana	3	BB
Arnekleiv_etal_2007 [42]	Europe	Norway	Mjosa Dam	Gudbrandsdalslågen	5	BB, W1, W2
Bacheler_etal_2004 [43]	N. America	United States	Carite Dam	La Plata	4	BB
Bain_etal_1988 [44]	N. America	United States	Stream reach flow modified by four dams (no names provided)	Connecticut	12	BB, GM
Bambace_etal_2007 [45]	S. America	Brazil	Serra da Mesa and Tucurui Dams	Toncatins	3	W1
Bárdossy_etal_2004 [46]	Europe	Slovakia	Gabicikovo Dam	Danube	18	W1
Bartholow_etal_2004 [47]	N. America	United States	Iron Gate, John C. Boyle, Keno, and Copco Dams	Klamath	20	W1
Bastien_etal_2011 [48]	N. America	Canada	Sarcelle Dam	Eastmain	4	W2
Bates_1962 [49]	N. America	United States	Kentucky Dam	Tennessee	2	BB
Beamesderfer_etal_1990 [50]	N. America	United States	John Day Dam	Columbia	22	W1
Beghelli_etal_2012 [51]	S. America	Brazil	Itupararanga Dam	Sorocaba	9	BB, W2
Beilfuss_etal_1994 [52]	Oceania	Australia	Windamere Dam	Cudgegong	12	W1
Bell_1985 [53]	N. America	Canada	Seton Dam	Seton	2	W1
Benchimol_etal_2014 [54]	S. America	Brazil	Balbina Dam	Uatuma	6	W1
Benejam_etal_2016 [55]	Europe	Spain	Sixteen small hydropower plants: Brutau 1, Brutau 2, Pardines, El Molí Rialp, Feitús, Cruanyes, Molí de Sart, Matabosch, Montagut, Molí Gran Pont Vell, Cal Gat, Surribes, L'Escala, La Cubia, Fàbrica Tomàs, Crous	Upper Ter	9	BB, GM
Benjankar_etal_2012 [56]	N. America	United States	Libby Dam	Kootenai	3	BB, W1
Benn_etal_1994 [57]	Africa	Zambia, Zimbabwe, Mozambique	Kariba, Kafue George, and Cahora Bassa Dams	Zambezi, Kafue	9	W1
Bennett_etal_2010 [58]	N. America	Canada	Trent-Severn Waterway locks and dams	Trent-Severn Waterway	1	BB
Bergman_etal_2014 [59]	Asia	Israel	Nahal Oz Dam	Nahal Yare'akh River	9	W1
Berkes_1982 [60]	N. America	Canada	La Grande 1 Dam	La Grande	5	BB
Bhatt_and_Khanal_2010 [61]	Asia	Nepal	Indrawati III Dam	Indrawati	15	W1, W2
Bhatt_and_Khanal_2011 [62]	Asia	Nepal	Upper Bhotekoshi Hydropower Project	Bhotekoshi	19	W1
Bhatt_etal_2012 [63]	Asia	Nepal	Upper Bhotekoshi Hydropower Project	Bhotekoshi	18	W1, W2
Bhutiani_etal_2014 [64]	Asia	India	Tehri Dam	Bhagirathi	20	W2
Bini_etal_1999 [65]	S. America	Paraguay	Itaipu Dam	Parana Yacyreta	13	BB, W1
Black_etal_2005 [66]	Europe	Scotland	Megget Dam	Allt a' Chireachain, Megget	333	BB, CF, GM, ID, LC, W1, W2
Bond_etal_1978 [67]	Africa	Mozambique	Cahora Bassa Dam	Zambezi	53	BB, GM, ID, LC, W1, W2
Branco_etal_2012 [68]	Europe	Portugal	A total of 196 stream sampling sites in three river basins.	Tagus, Mondego, Vouga	27	BB, CF, GM, ID, W1, W2
Bravard_etal_1999 [69]	Europe	France	River reaches (no named dams)	Rhone, Drôme, Drac, Ain	6	CF, GM, W1
Budhu_etal_1994 [70]	N. America	United States	Glen Canyon Dam	Colorado	5	GM, W1
Calles_etal_2013 [71]	Europe	Sweden	Ätrafors HEP	Atran	6	BB, W1
Callisto_etal_2005 [72]	S. America	Brazil	Paulo Afonso, Xingo, and Moxoto Dams	Sao Francisco	22	BB, W1, W2
Carley_etal_2012 [73]	N. America	United States	Daguerre Point and Harry L. Englebright Dams	Yuba	12	GM, W1
Chicharo_etal_2006 [74]	Europe	Portugal	Alqueva Dam	Guadiana	23	BB, W1, W2
Chiu_etal_2013 [75]	Asia	Taiwan	Unnamed dam	Dajia	7	BB, GM
Churchill_2013 [76]	N. America	United States	Denison Dam	Red	21	BB, W1, W2
Craven_etal_2010 [77]	N. America	United States	Flint River and R L Harris Dams	Flint, Tallapoosa	44	BB, W1
Dai_etal_2011 [78]	Asia	China	Three Gorges Dam	Yangtze	12	W1, W2
Dauble_1986 [79]	N. America	United States	Priest Rapids Dam	Columbia	7	BB, CF, W2

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Table 8 (*continued*)

Journal article	Continent	Country (or countries)	Dam(s) or study location	River(s)	Metrics	Categories
de_Almeida_etal_2005 [80]	Europe	Portugal	Fourteen hydropower plants: Ribeiradio, Sr.a do Monforte, Alvito, Pêro Martins, Atalaia, Asse-Dasse, Castelo de Paiva, Castro Daire, Póvoa, Midões, Alvarenga, Pinhosão, Portela, and Girabolhos	Vouga, Côa, Ocreza, Mondego, Paiva	2	W1
deAlmeida_etal_2003 [81]	S. America	Brazil	Barra Bonita, Ibitinga, Mario Lopes Leao, Tres Irmaos, Taquarucu, Nova Avanhadava, Rosana, Capivara, and Bairi Dams	Tiete, Paranapema	3	BB
Dean_and_Schmidt_2013 [82]	N. America	United States	Caballo, Elephant Butte, Luis L. Leon, La Boquilla, and Francisco I. Madera Dams	Rio Grande, Rio Conchos	10	GM, W1
Duchemin_etal_1995 [83]	N. America	Canada	Laforge 1 and La Grande 2 Dams	LaForge, La Grande	20	W1, W2
Ebel_1969 [84]	N. America	United States	Priest Rapids, McNary, Ice Harbor, Grand Coulee, Bonneville, Chief Joseph, The Dalles, Wanupum, Rocky Reach, and Rock Island Dams	Columbia, Snake,	18	BB, CF, W1, W2
Effler_etal_1988 [85]	N. America	United States	Cannonsville Dam	Delaware	25	W2
Englund_etal_2008 [86]	Europe	Sweden	Mallengan	Lillian	16	BB, LC, W2
Foster_and_Rahs_1985 [87]	N. America	Canada	Proposed dam	Stikine	9	BB
Froebrich_etal_2007 [88]	Asia	Turkemenistan	Kaparas Dam	Amu Darya	10	W1, W2
Gain_etal_2013 [89]	Asia	Tibet	Zangmu Dam	Brahmaputra	28	W1
Galbraith_etal_2015 [90]	N. America	United States	Parr Shoals, Upper Androscoggin, William O'Huske Lock and Dam, New Savannah Bluff Lock and Dam, Adam T. Bower Memorial (inflatable) Dam, Amoskeag, Falls Village, Holts Pond Dam, Holyoke, Sinclair, Lloyd Shoals, Tillery, Oxford, Santee, Tar River Reservoir Dam, John H. Kerr	Broad, Androscoggin, Cape Fear, Savannah, Susquehanna, Merrimack, Housatonic, Neuse, Connecticut, Oconee, Ocmulgee, Pee Dee, Catawba, Santee, Tar, Roanoke	9	BB, W1
Galbraith_and_Vaughn_2009 [91]	N. America	United States	Pine Creek and Broken Bow Dams	Little, Mountain Fork	13	BB, W1
Gelwick_and_Matthews_1990 [92]	N. America	United States	Denison Dam	Red River	15	BB, W1, W2
Gobo_etal_2014 [93]	Africa	Nigeria	Kainji Dam	Kainji	5	BB, GM, W1
Graf_2006 [94]	N. America	United States	Albeni Falls, Beaver, Blakely Mountain, Buford, Center Hill, Coolidge, Dnison, Douglas, Eufaula, Flaming Gorge, Folsom, Fontana, Grand Coulee, Greers Ferry, Hartwell, Hungry Horse, John H. Kerr, Keystone, Kinzua, Monticello, Navajo, Norfork, Norris, Oologah Lake, Owyhee, Palisades, Pine Flat, Sam Rayburn, Sanford, Sardis, Shasta, Tenkiller Ferry, Tiber, Tuttle Creek, Whitney, and Wright Patman Dams	Allegheny, American, Angelina, Arkansas, Big Blue, Brazos, Canadian, Caney Fork, Chattahoochee, Clinch, Columbia, Flathead, French Broad, Gila, Green, Illinois, Kings, Little Red, Little Tallahatchie, Little Tennessee, Marias, North Fork of the White, Ouachita, Owyhee, Pend Oreille, Putah Creek, Red River, Roanoke, Sacramento, San Juan, Savannah, Snake, Sulphur, Verdigris, White	52	GM, W1
Grill_etal_2014 [95]	Asia	China	Multiple existing and proposed dams	Mekong	132	CF, W1
Guo_etal_2000 [96]	Asia	Indonesia	Wadaslintang Dam	Lunto	8	GM, ID, LC, W1
Hay_etal_2008 [97]	N. America	United States	Gavins Point and Fort Randall Dams	Missouri	33	BB, W1, W2
Heidari_etal_2013 [98]	Asia	Iran	Tarik Dam	Sefid-Rud	4	BB
Hughes_etal_2011 [99]	N. America	United States	Bonneville Dam	Columbia	8	ID, W1
Humborg_etal_2006 [100]	Europe	Sweden	Baltic Sea catchment	Vistula, Daugava, Oder	21	CF, GM, LC, W1, W2
Huo_etal_2015 [101]	Asia	China	Xiangjiaba Dam	Jinsha	18	W2
Huraut_etal_2002 [102]	Asia	Philippines	Ambuklao Dam	Agno	5	GM
Istávanovics_etal_2010 [103]	Europe	Hungary	Tisza Dam	Tisza	17	BB, W1, W2
Jepsen_etal_1998 [104]	Europe	Denmark	Tange Dam	Gudenå	2	BB
Jones_etal_2014 [105]	N. America	United States	Norris Dam	Clinch	7	BB, GM
Kaster_and_Jacobi_1978 [106]	N. America	United States	Eau Pleine Dam	Big Eau Pleine	2	BB, W1
Kemenes_etal_2007 [107]	S. America	Brazil	Balbina Dam	Uatuma	3	W2
Klaver_etal_2007 [108]	Europe	Romania, Serbia, Slovakia	Iron Gate II and Gabicikovo Dams	Danube	516	GM, W1, W2
Kotut_etal_1998 [109]	Africa	Kenya	Turkwel Dam	Turkwel	4	BB
Kumar_and_Sharma_2016 [110]	Asia	India	Koteshwar Dam	Bhagirathi	7	GM, LC, W1, W2
Laine_etal_1998 [111]	Europe	Finland	Isohaara Dam	Kemijoki	8	BB, GM, ID, W1, W2
Larinier_2008 [112]	Europe	France	77 small-scale hydro dams in clusters along 7 rivers	Gave d'Oloron, Corrèze, Vézère, Salat, Gave de Pau, Neste, Saison	6	BB
Lehman_2011 [113]	N. America	United States	Ford Lake Dam	Huron	34	W1, W2

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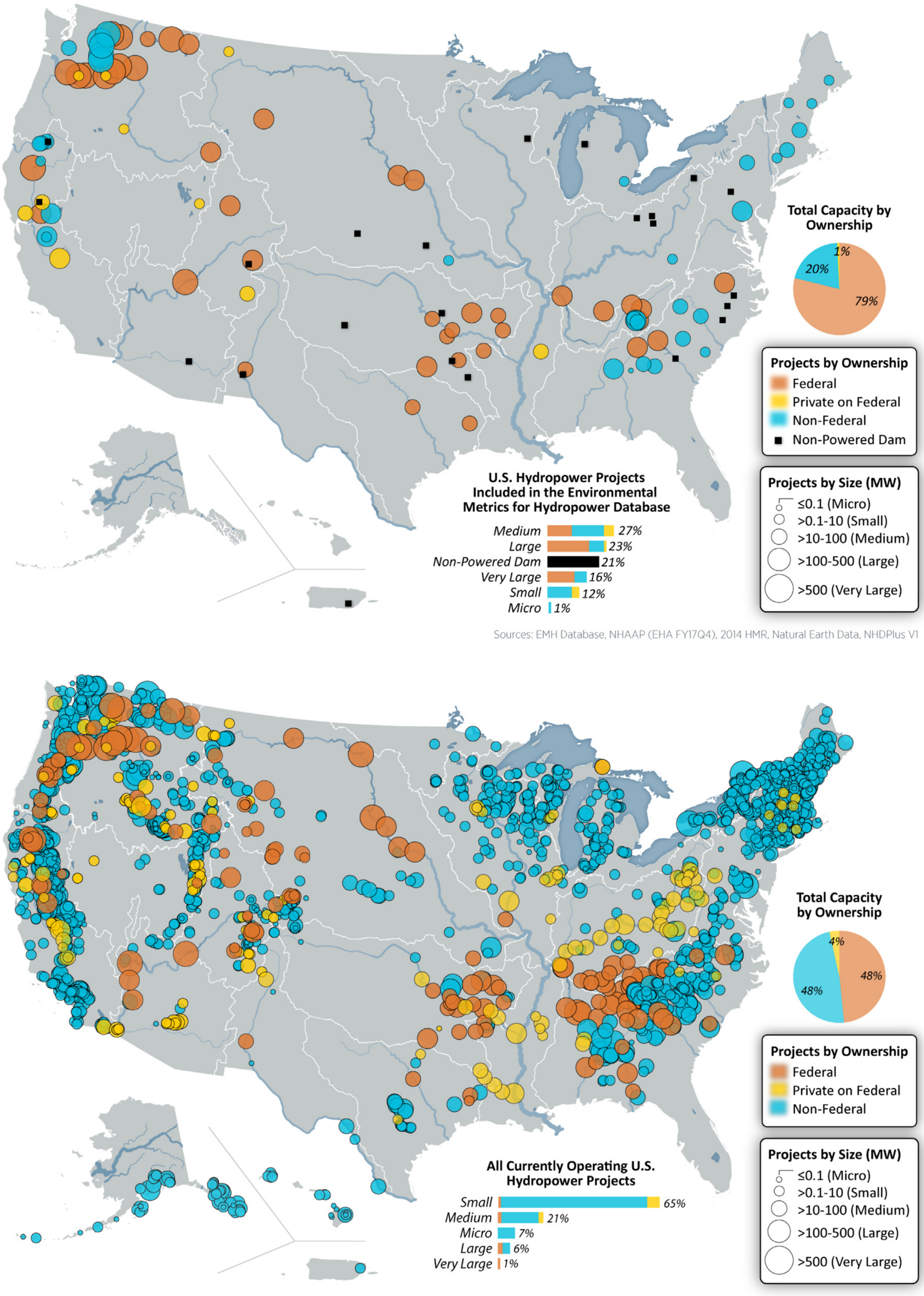
Table 8 (*continued*)

Journal article	Continent	Country (or countries)	Dam(s) or study location	River(s)	Metrics	Categories
Ma_etal_2016 [114]	Asia	China	Ertan Dam	Yalong Jiang	2	W1, W2
Malini_and_Rao_2014 [115]	Asia	India	Gangapur Dam	Godavari	6	GM
Meile_etal_2011 [116]	Europe	Switzerland	Chippis, Vouvray, Steg, Stalden, Salanfe, Barberine, Ackersand, Bitsch, Mauvoisin, and Grand Dixence Dams	Navisence, Rhone, Vispa, Salanfe, Barbarine	6	W1
Milošković_etal_2013 [117]	Europe	Serbia	Gruza Dam	Gruza	28	BB, W2
Mims_etal_2013 [118]	N. America	United States	McCloud, Glen Ferris, Dillon, Mohawk, Morrow Point, Ridgeway, Trenton, Wanship, Yellowtail, and Delaware Dams	McCloud, Kanawha, Licking, Wlhonding, Gunnison, Uncompahgre, Republican, Weber, Bighorn, Olentangy	31	BB, CF, ID, W1
Mistak_etal_2003 [119]	N. America	United States	Stronach Dam	Pine	57	BB, GM, W2
Muir_etal_2001 [120]	N. America	United States	Lower Granite, Lower Monumental, and McNary Dams	Snake, Columbia	7	BB, W1
Politano_etal_2012 [121]	N. America	United States	Wells Dam	Columbia	2	W2
Ribi_etal_2014 [122]	Europe	Switzerland	Maigrauge Dam	Sarine	4	BB, ID, W2
Ribolli_etal_2012 [123]	S. America	Brazil	Machadinho Dam	Pelotas	7	BB
Scruton_etal_2005 [124]	N. America	Canada	West Salmon Dam	West Salmon	8	BB, GM, W1, W2
Smith_etal_2016 [125]	N. America	Canada	E.B. Campbell Dam	Saskatchewan	6	GM
Soltani_etal_2010 [126]	Asia	Iran	15-Khordad Dam	Ghomrud	11	ID, LC, W1, W2
Song_etal_2015 [127]	Asia	China	Three Gorges Dam	Yangtze	8	GM, W1
Stevens_etal_1995 [128]	N. America	United States	Glen Canyon Dam	Colorado	7	BB, GM, LC
Tamene_etal_2006 [129]	Africa	Ethiopia	Group of micro dams for supplemental household irrigation.	Tekeze River Basin	18	GM, ID, LC, W1
Thomaz_etal_2009 [130]	S. America	Paraguay	Itaipu Dam	Parana Yacyreta	7	BB, W2
Thompson_etal_2011 [131]	N. America	United States	Camino Dam	Silver Creek	13	BB, GM, W1, W2
Tufford_etal_1999 [132]	N. America	United States	Santee Dam	Santee	37	BB, W1, W2



Sources: EMH Database, NHAAP (EHA FY17Q4), 2014 HMR, Natural Earth Data, NHDPlus V1

Sources: NHAAP (EHA FY17Q4), 2014 HMR, Natural Earth Data, NHDPlus V1

Fig. 3. Size and ownership distribution of U.S. hydropower projects captured by this environmental metrics for hydropower literature review (A) relative to the entire U.S. hydropower fleet (B).

efficiency in evaluating the potential environmental effects of hydropower projects. We caution that cataloging and categorizing measurements that have been used to assess hydropower effects on environmental systems should not be confused with evaluating the outcomes of existing US regulatory processes. A variety of legislation stipulates what US agencies must do, must not do, and may choose to do

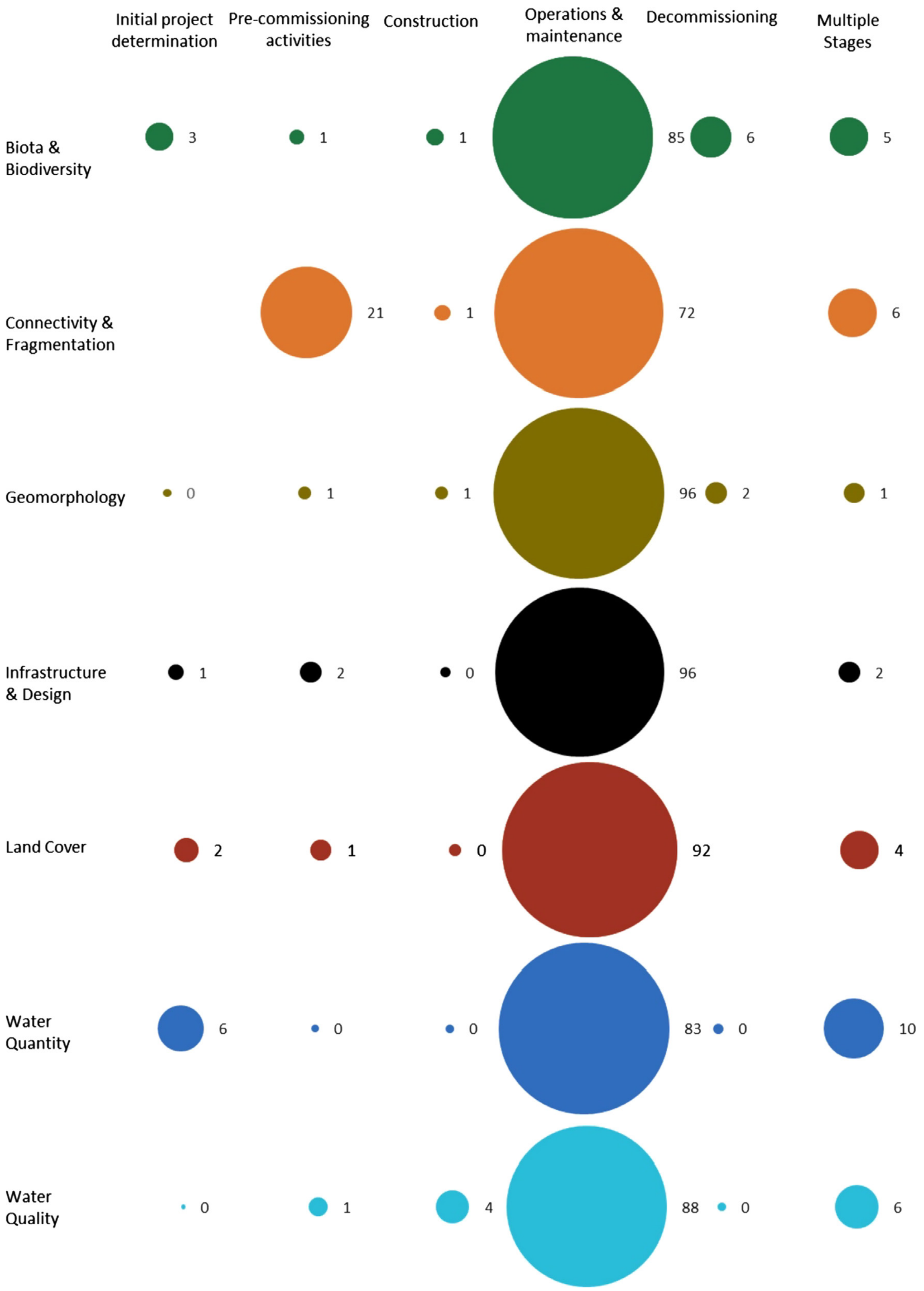


Fig. 4. Life Cycle Stages at which environmental metrics were recorded. The numbers represent the percent of each category's metrics recorded at that stage.

based upon a thorough assessment of a given project's potential impacts and developed protection, mitigation and enhancement measures.

The U.S. dams assessed through this literature review were widely distributed across the continental states. A comparison of the U.S. dams captured by this study compared a map of the entire U.S. hydropower fleet illustrates a trend toward capturing metrics related to larger, federally owned dams (Fig. 3). Small U.S. dams (0.1–10 MW) seem to be particularly underrepresented by this dataset of environmental metrics. We were unable to do a similar comparison for the non-U.S. dams due to insufficient hydropower fleet data at the global scale.

A map showing the distribution of collected environmental metrics by category across seven U.S. regions defined by U.S. Geological Survey

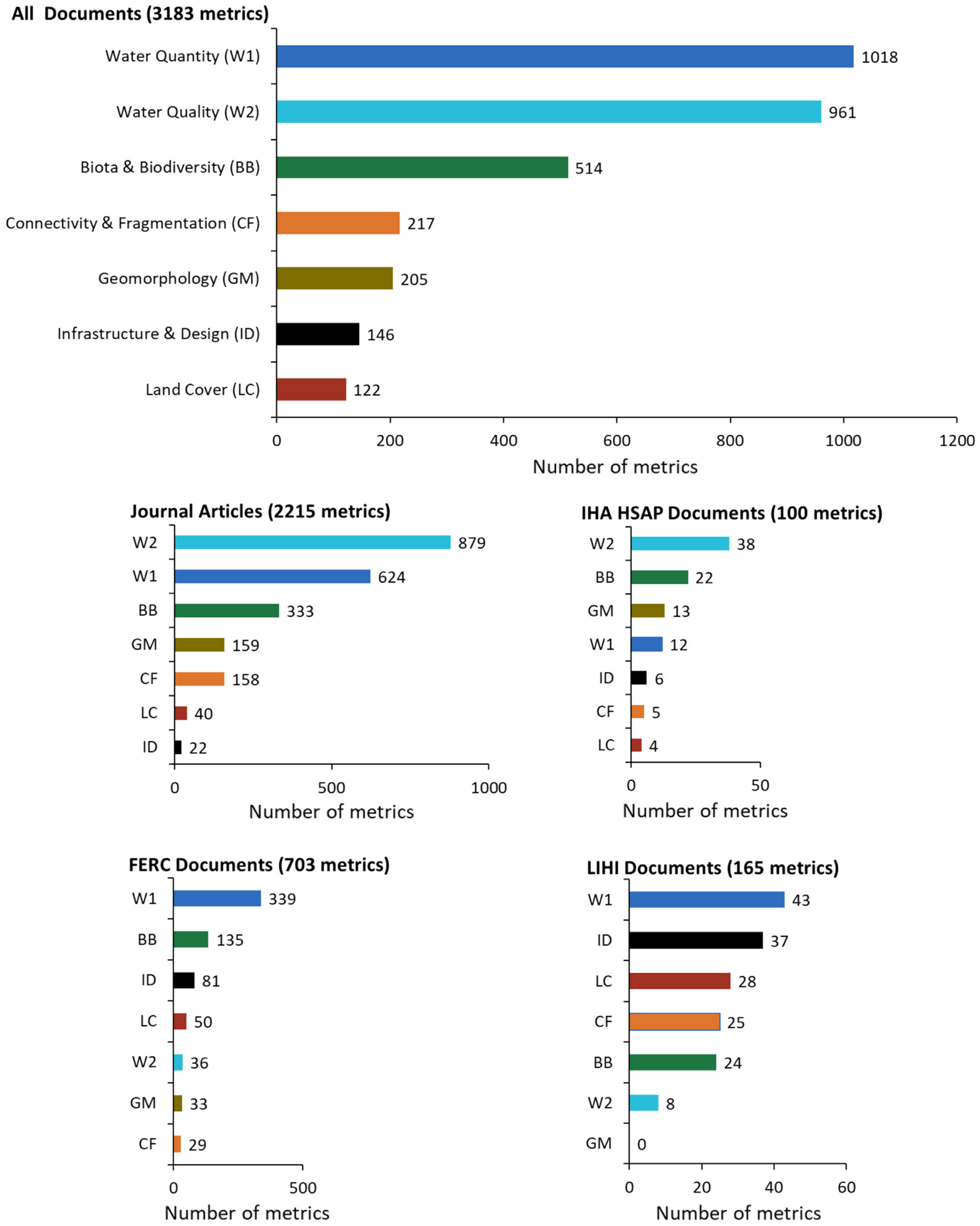


Fig. 5. Distribution of the environmental metrics by category and document type.

river basins (Fig. 6B) shows that a substantial number of the metrics were captured from documents pertaining to the Southeastern U.S. This highlights the fact that nearly 500 metrics were extracted for the Smoky Mountain Project located in the Tennessee Valley (Table 5) from documents pertaining to a settlement agreement process, which is typically more holistic than an integrated licensing process. The U.S. map (Fig. 6B) also shows that water quantity metrics predominated in all regions except for the Northeast. In contrast to the other regions, the Northeastern U.S. showed a more even distribution of metrics across the seven categories, with the largest number of metrics gathered in the category of Biota & Biodiversity. This makes sense given that the Northeastern U.S. contains many small hydroelectric plants that are run-of-river.

Most of the environmental metrics found during this literature

Table 9
Percentage of environmental metrics collected in each category by hydropower project size.

Hydropower project size	Metrics	W1 (%)	W2 (%)	BB (%)	CF (%)	GM (%)	ID (%)	LC (%)
Micro (≤ 0.1 MW)	22	45	0	55	0	0	0	0
Small (> 0.1–10 MW)	629	35	10	24	7	7	12	5
Medium (> 10–100 MW)	1659	59	7	11	1	15	4	4
Large (> 100–500 MW)	1474	47	7	14	4	18	6	4
Very Large (> 500 MW)	1376	20	58	6	10	4	1	1
All Projects	**5160**	**42**	**21**	**12**	**5**	**12**	**5**	**3**

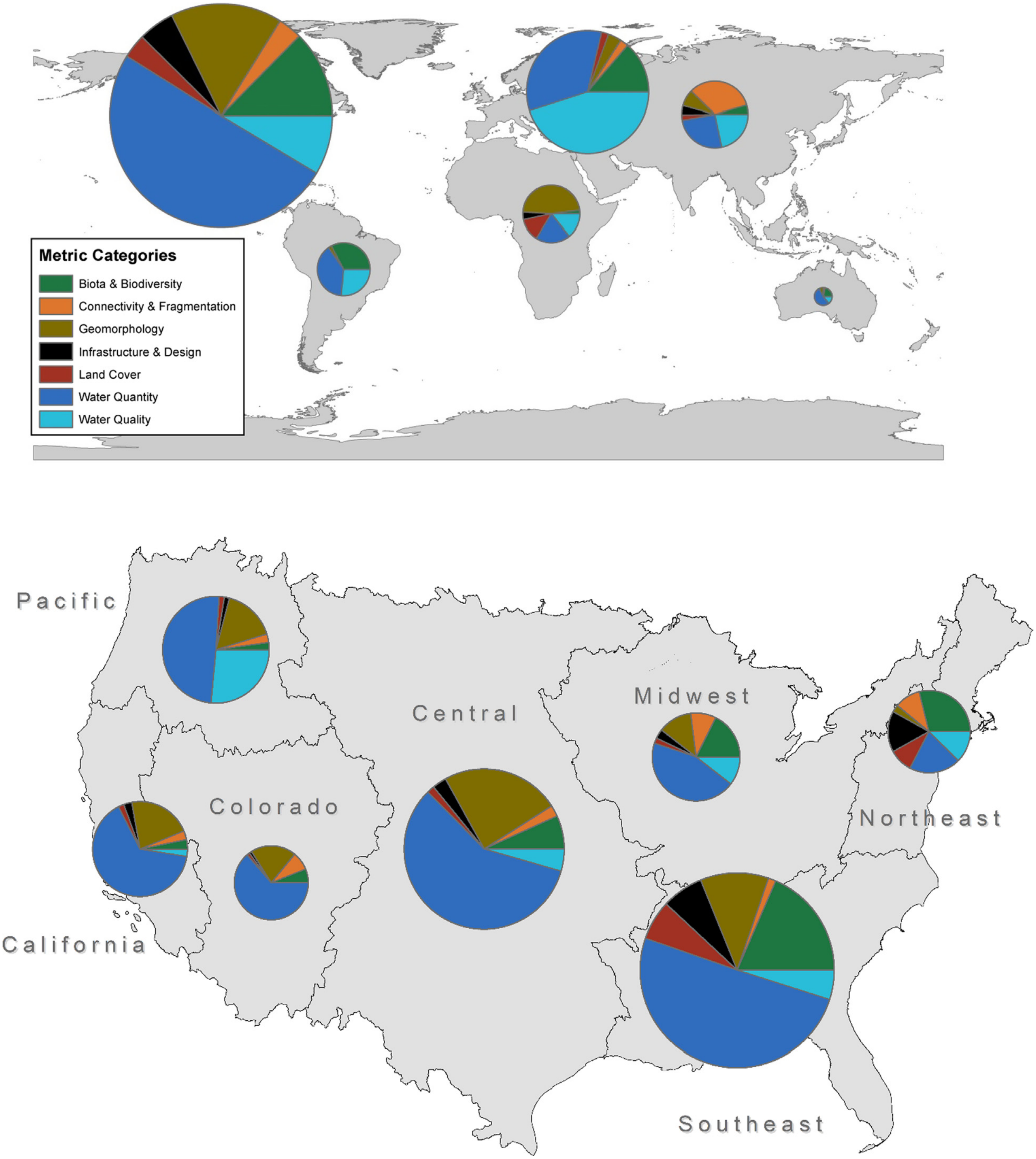


Fig. 6. Geographic distribution of the collected environmental metrics by continent (A) and by U.S. region (B).

Table 10
Emergent 45 subcategories of the environmental metrics discovered through this literature review of 117 documents. Metrics totals are also shown by type: M = Measures, S = Statistics, and I = Indicators.

Category	Parameter name	Parameter description	M	S	I	Metrics
Biota & Biodiversity	BB_Abundance, density	Count or other measures of organisms per area	42	52	6	100
	BB_Behavior, movement	Behavior of organisms including movement pattern, distance, duration, timing, and frequency	9	2	1	12
	BB_Colonization, extinction	Colonization or extinction of organisms in a study area	0	0	1	1
	BB_Demographics, age, sex, size	Population demographics, including age, sex, and size	27	8	0	35
	BB_Fitness, survival, growth, condition, reproduction, mortality	Fitness, survival, growth, condition, reproduction, or mortality of organisms	34	38	6	78
	BB_Functional group, or species or trait composition	Grouping of organisms by functional or trait status, percentage composition	34	12	20	66
	BB_Genetics, mixing, metapopulation	Genetics and population mixing, including metapopulation dynamics	0	7	5	12
	BB_Habitat, critical habitat, or surrogates of such	Indices of habitat, area, suitability, and so on, for organisms	25	4	28	57
	BB_Internal composition nutrient abnormalities	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	0	3	0	3
	BB_Life history trait characteristics	Life history trait characteristics and their values, such as duration of spawning, fecundity, reproductive mode (note this category deals only with characteristics themselves and not the composition of the community.)	8	14	1	23
	BB_Presence, absence, occupancy, or detection	Organism presence/absence in an area (including pseudo-absence), occupancy, and detection probability	51	2	13	66
	BB_Richness, diversity, evenness, or IBI types of measures	Species richness, diversity, evenness, or indices-of-biotic-integrity metrics used to characterize one or more components of the biotic community	33	4	19	56
Connectivity & Fragmentation	CF_Basin area	Some aspect of area of river basin	8	0	1	9
	CF_Dendritic network and riverscape	Fragment length, dendritic connectivity index, barrier index, river distance between dams and projects	96	5	73	174
	CF_Fish passage	Mitigated fish passage, including presence of upstream or downstream passage or length of bypass	16	14	4	34
Geomorphology	GM_Catchment and basin attributes	Upland soil characteristics, topography, and landscape erodibility metrics that could influence soil erosion and wasting related and subsequent sedimentation related to hydropower development	15	5	2	22
	GM_Channel	Channel properties such as bankfull width, wetted width, bankfull discharge, channel slope, braided channel, channelization	56	18	18	91
	GM_Flooplain valley	Metrics related to channel confinement, entrenchment, migration, etc.	10	2	6	18
	GM_Sediment and substrate	Sediment and substrate properties such as substrate particle size, bedload, sediment entrainment or deposition, bedrock composition	31	25	14	70
Infrastructure & Design	ID_Dam attributes	Head, dam height, spill gate type, bar rack, and so on	97	2	5	104
	ID_Fish passage	Characteristics of fish passage structures such as slope, velocity, and discharge	9	0	2	11
	ID_Turbine	Turbine characteristics including forces in the turbine environment such as pressure, shear, cavitation, turbine type, turbine speed, blade strike	15	5	1	21
Land Cover	LC_Area impacted, project area	Project boundary area, area impacted by the project as whole, not related to reservoir inundation or land cover	41	0	2	43
	LC_Floodplain or riparian vegetation	Properties of floodplain or riparian vegetation such as riparian encroachment or floodplain area	1	0	0	1
	LC_Land cover class	Type of land cover, changes in land cover	13	19	4	36
	LC_Protected land	Spatial properties of protected lands including losses or increases	14	3	3	20
	LC_Reservoir inundation	Reservoir area, upland or floodplain inundation, biomass inundated/lost	20	2	0	22
Water Quantity	W1_Basin attributes	Attributes related to factors that influence hydrology (or were used in the context of hydrology), such as climate and precipitation	2	1	3	7
	W1_Diversion	Quantitative properties of diversions such as volume or discharge of diversion or water for other uses	6	1	1	8
	W1_Downstream discharge and hydrology	Measures that describe the magnitude, frequency, duration, periodicity, and timing of flows downstream of a hydropower facility, including changes to these characteristics	89	514	272	875
	W1_Groundwater	Groundwater characteristics	3	19	0	22
	W1_Reservoir hydrology	Reservoir hydrological characteristics such as residence time, reservoir fluctuation, reservoir surface area, or degree of regulation	61	16	8	85
	W1_Upstream regulation and inflow	Measures describing the magnitude, frequency, duration, periodicity, and timing of flows upstream of a hydropower facility, including changes to these characteristics	25	11	1	37

(*continued on next page*)

Table 10 (*continued*)

Category	Parameter name	Parameter description	M	S	I	Metrics
Water Quality	W2_Algae, primary productivity	Algal concentration including measures of primary productivity such as chlorophyll *A* or cyanotoxin.	25	7	2	33
	W2_Buffering capacity	Characteristics including pH, alkalinity	26	9	0	35
	W2_Dissolved gasses	Concentration of non-greenhouse gases in water	9	0	0	9
	W2_Dissolved oxygen	Dissolved oxygen in water	9	9	2	20
	W2_Ecosystem function	Ecosystem vital rates and processes, including gross primary productivity, respiration, biochemical oxygen demand	5	7	1	13
	W2_Gas emissions	Concentration and ebullution of water-origin greenhouse gases	12	17	1	30
	W2_Nutrients	All non-rare elements essential to life: nitrogen, phosphorous, inorganic carbon, potassium, sulfur, and magnesium compounds (rare essential elements are included in “other elements”)	99	42	2	143
	W2_Organic material	Dissolved organic carbon and other organic non-pollutants	7	1	1	9
	W2_Other elements	Elements and compounds that are not listed on the EPA Toxic and Priority Pollutants list	461	9	0	470
	W2_Pollutants	Pollutants listed on the EPA Toxic and Priority Pollutants list that are not included in other EMH categories	69	0	7	71
	W2_Solid transport, turbidity, and conductivity	Descriptions of dissolved and suspended solids in water such as turbidity, suspended or dissolved solids, conductance	53	13	4	70
	W2_Temperature	Water temperature	33	18	4	60

review were obtained during the dam operations and maintenance life cycle stage (Fig. 4). This result could be related to the fact that many FERC requirements are related to the relicensing processes, i.e. after the construction phase has long been completed. We found that many of the scientific journal articles were narrowly focused on specific issues (e.g., impacts to a species of concern), making it difficult to use them to holistically assess the environmental effects of any particular hydropower project. Separating environmental metrics from socioeconomic metrics within the IHA HSAP documents was difficult due to IHA's integrated evaluation approach using complex indicators. The environmental metrics were most closely associated with six HSAP sustainability topic areas: biodiversity and invasive species; downstream flow regimes; erosion and sedimentation; reservoir planning; waste, noise and air quality; and, water quality. During the literature review, we discovered several environmental metrics did not fall into any of the seven categories that we had pre-defined (Table 1), including metrics related to noise pollution, electromagnetism, and solid waste disposal. We mention these in case future investigators would like to give these environmental aspects more consideration.

Many of the environmental metrics collected by this study were very closely related, and some of the different metrics were likely aimed at measuring compliance with the same requirements. Determining which of the many surveyed measurement units is most indicative of environmental change for each subcategory will be difficult. More research is needed to better understand the magnitude of metric change necessary to distinguish a true environmental signal from noise (e.g., changes due to natural environmental variability). Therefore, improving consistency and lowering the cost of environmental assessments undertaken by multiple agencies and researchers during hydropower project planning and development will require additional interdisciplinary research.

5. Conclusions

Stakeholders need transparent information about the patterns and commonalities among environmental metrics previously used to assess the environmental effects of hydropower development to inform their input into future regulatory decision-making processes that may involve trade-offs between conflicting development goals. More efficient and affordable consensus building may occur if hydropower stakeholders can have information about measurable, repeatable, and broadly understandable environmental metrics that can identify and quantify the benefits and costs during hydropower project development. We therefore undertook this examination of the raw environmental information underlying the existing hydropower licensing regulations, sustainability certifications, and scientific peer-reviewed literature to better understand the current state of practice. Our list of 45 emergent environmental subcategories (Table 10) establishes a preliminary envelope of measurements that are likely important for understanding the potential environmental effects of hydropower projects. The relative importance of these 45 subcategories of measurements will probably vary by project context [133], and their usefulness in quantifying a hydropower project's environmental sustainability will need to be tested through case study application.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.01.038.

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