Advanced Review

Status and trends of dam removal research in the United States

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Aging infrastructure coupled with growing interest in river restoration has driven a dramatic increase in the practice of dam removal. With this increase, there has been a proliferation of studies that assess the physical and ecological responses of rivers to these removals. As more dams are considered for removal, scientific information from these dam-removal studies will increasingly be called upon to inform decisions about whether, and how best, to bring down dams. This raises a critical question: what is the current state of dam-removal science in the United States? To explore the status, trends, and characteristics of dam-removal research in the U.S., we searched the scientific literature and extracted basic information from studies on dam removal. Our literature review illustrates that although over 1200 dams have been removed in the U.S., fewer than 10% have been scientifically evaluated, and most of these studies were short in duration (<4 years) and had limited (1–2 years) or no pre-removal monitoring. The majority of studies focused on hydrologic and geomorphic responses to removal rather than biological and water-quality responses, and few studies were published on linkages between physical and ecological components. Our review illustrates the need for long-term, multidisciplinary case studies, with robust study designs, in order to anticipate the effects of dam removal and inform future decision making.

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INTRODUCTION

For millennia, humans have built dams on river systems for navigation, irrigation, flood control, and power generation. Although new dams are still being built to meet the needs of society, particularly in developing countries,[1] many dams are aging,[2] have become hazardous, or are no longer fully serving the functions for which they were designed. Although dam failures are rare, they can be costly in terms of property damage and loss of life.[3] Evolving safety and environmental standards in the U.S. are also making it more costly to maintain and repair aging dams. Fifty years ago, during the peak of government-sponsored dam construction in the U.S., a widespread movement calling for the removal of dams would have seemed far-fetched. Today, however, over 1200 dams have been removed, and the majority of these dams were removed within the last two decades[4,5] (Figure 1(a)). Dam removal is now considered as a viable option when the cost of keeping a dam in place exceeds the expense of its removal, particularly in locations where the possibilities for river restoration are high (e.g., Duda et al.[6]). Given the vast number (potentially >2,000,000)[7] and age structure of U.S. dams (up to 80% over 50 years old by 2020),[8] as well as shifting societal values, this upward trend in dam removal is likely to continue.

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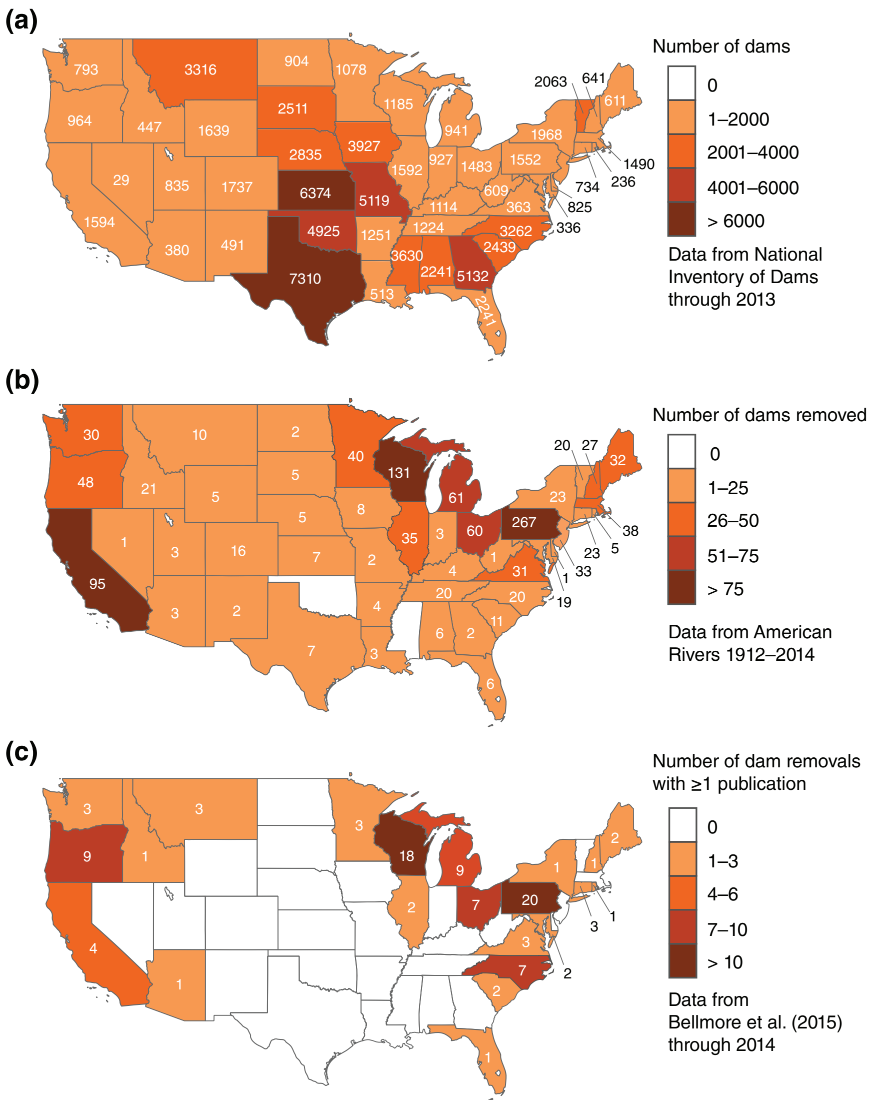

FIGURE 1 | Distribution of dams in the contiguous U.S. (a), the number of dams removed (b), and the number of published dam removal studies (c), by state. The number of dams from the National Inventory of Dams database does not accurately reflect all of the dams in the U.S. (see text).

Deciding whether to remove aging dams and how to do so with minimal adverse impacts, however, is complicated by uncertainties associated with potential environmental benefits and detriments.[9–12] On one hand, dam removal can re-establish more natural flows, water temperatures, and sediment regimes,[10,13–15] and allow native organisms to recolonize habitats that were formerly inaccessible.[16–18] On the other hand, removing dams can expose and mobilize large volumes of sediment and contaminants,[19–22] and facilitate the spread of invasive species.[23] From an environmental perspective, deciding whether and how to remove dams requires balancing these risks and benefits,[24,25] which in turn, necessitates relatively accurate predictions about how rivers will respond to dam removal and how long they may take to recover. Making these scientific predictions will require leveraging knowledge from expert opinion, conceptual and quantitative models, and, most importantly, from studies that empirically evaluate the physical and ecological responses to dam removal. Over the last two decades, as the practice of dam removal has accelerated, so too has the scientific evaluation of these projects. Understanding the extent to which this scientific research can inform dam-removal decision-making, however, will first require taking stock of the quantity, quality, and character of these studies. Although an earlier review of dam-removal science was conducted by the Heinz Center in 2002,[11,26] the practice and science of dam removal has proliferated since the time of these publications, and an updated review of the 'state of the science' is needed.

To address this need, we conducted an extensive literature search to identify published studies that contained empirical information associated with dam removal. One of the main goals of this literature search was to extract basic information from these studies[27] (http://doi.org/10.5066/F7K935KT), and to create an online visualization and analysis tool to make this information readily available to both practitioners and researchers (https://www.sciencebase.gov/drip/). It was not our aim to review study findings, but rather, to extract attributes that describe the design of the study, the type of response metrics monitored (physical, biological, water quality), and the characteristics of the removed dams (e.g., dam height, location, and removal date). In this article, we use the information from this database, as well as a database that contains information on the practice of dam removal in the U.S.,[4] to address the following questions:

1. What are the characteristics of dam removal studies (number, location, and size of dams) and how representative are these studies of all dams that have been removed in the U.S.?
2. What physical, biological, and water-quality responses are these studies measuring, over what duration, and what types of study designs are being employed?
3. Where are there gaps in the research that might limit the ability of dam-removal science to inform the practice of dam removal in the future?

DAM-REMOVAL DATABASES

USGS Dam-Removal Science Database

We identified dam-removal studies published through 31 December 2014 using ISI Web of Science, Google Scholar, and the U.S. Geological Survey (USGS) Publication Warehouse. The following keywords and phrases were queried (1): ISI Web of Science: (dam AND removal*) AND (stream OR river), (2) Google Scholar (Advanced Scholar Search; italics indicate the search term used by Google): *with the exact phrase* = 'dam removal'; *with at least one of the words* = ' stream OR river'; *where my words occur* = 'anywhere in the article,' and (3) the USGS Publication Warehouse: 'dam removal.' These searches identified 6068 documents. To identify relevant citations from this list, we first examined titles and abstracts. Citations that were not related to the science of dam removal (e.g., studies of beaver dams) were flagged as 'irrelevant'; all other documents were considered 'possibly relevant' (n = 586). Next, we examined the full text of each document, with documents containing empirical information on the biotic or abiotic responses to dam removal flagged as 'relevant.' In total, we identified 139 documents that contained empirical information on biotic and abiotic responses to dam removal in the U.S., and from these we extracted information on (1): characteristics of the dam and its removal (e.g., dam height, location, year of removal) (2); physical, water-quality, and biological response metrics that were measured; and (3) the type of experimental design employed, as well as the duration and frequency of sampling. A complete list of the different metrics extracted from each document is available in an online database[27] (http://doi.org/10.5066/F7K935KT). We recognize that dam-removal decision-making is based on social and economic factors as well as on potential physical and ecological responses[28–30]; however, an analysis of social and economic factors was outside of the scope of our literature review and this article.

American Rivers Dam-Removal Database

The American Rivers Dam Removal Database, maintained by the non-profit organization American Rivers (http://www.americanrivers.org/), lists dams that have been removed in the U.S. since 1912 (n = 1231).[4] American Rivers has collected these data annually since 1999 by surveying dam-removal practitioners, compiling information from state and federal agencies, and reviewing media references to dam removals (e.g., books, newspaper articles). Records in the database include dam name, waterbody name, state, year of removal, and dam height. The three primary criteria for inclusion in the database are (1): the dam removal was intentional (i.e., directly caused by humans) (2); the full vertical extent of the dam was removed over more than half of the dam's width; and (3) the dam was not later rebuilt in the same location. There was no minimum dam height for inclusion in the database. The database may under-represent the actual number of removals because of incomplete historical knowledge, inadequate formal tracking or limited information sharing by agencies, or disparities among states regarding what constitutes a dam, and thus a dam removal.

DATA ANALYSIS

We used information from the USGS Dam Removal Science Database and the American Rivers Dam

Removal Database to graphically analyze (1) the number of removed dams and studied dam removals by state (2); the cumulative number of removals and studied removals by year; and (3) the distribution of dam heights for removals and studied removals. We used the National Inventory of Dams (NID), a congressionally mandated database updated every 2 years by the U.S. Army Corps of Engineers (http://nid.usace.army.mil/), to compare the distribution of all dams (Figure 1(a)) to those that have been removed. Dam removal studies were categorized by publication outlet, experimental design, and the amount and duration of monitoring data available. Studies were grouped into four experimental designs, that were distinguished by the availability of spatial and temporal reference sites (1): before-after-control-impact (BACI), (2) before-after, (3) control-impact (space-for-time), and (4) impact only (i.e., only post-removal data collected). We recorded the types of variables that were monitored, which for the purposes of this manuscript were categorized into 15 different metric types (Web Table 1). These metrics were then grouped into three broad categories (1): physical metrics (e.g., channel morphology and hydraulics), (2) biological metrics (e.g., fish and invertebrates), and (3) water-quality metrics (e.g., water temperature, nutrients, and contaminants). To evaluate associations between metrics for dam-removal studies, we plotted pairwise co-occurrence among different metrics using the Circos Software package.[31]

NATIONWIDE PATTERNS OF DAM-REMOVAL RESEARCH

The distribution of existing dams is markedly different from the distribution of dam removals (Figures 1 (a) and (b)). Regions with relatively large numbers of dam removals include the upper Midwest and the Atlantic and Pacific coasts, such as Wisconsin, Pennsylvania, and California (Figure 1(b)). The difference between the distribution of existing dams and dam removals may be attributable to the removal of small dams (i.e., low-head and run-of-river dams, <2 m in height), which represent the majority of dam removals (Figure 2(a)) but do not meet NID inclusion requirements (i.e., ≥25 feet in height and >15 acre-feet in storage, or ≥50 acre-feet storage and >6 feet in height) unless they are considered hazardous.[7,32] Differences in socio-cultural history between states and regions may also partially explain the differences

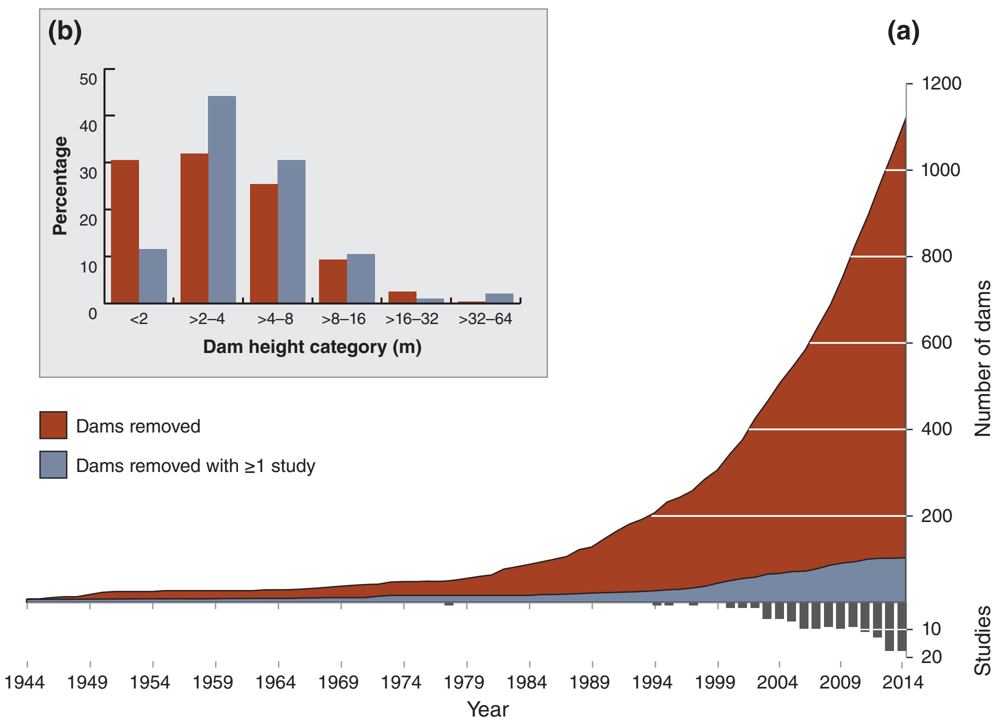

FIGURE 2 | Compilation of dams removed (orange) and dams with at least one published study (blue) by: (a) cumulative frequency distribution by year removed (exclusive of dams with no known date of removal), with a count of the number of dam removal studies published each year inserted below the x-axis, and (b) relative frequency (percentage) in each dam height category. Data from American Rivers[4] and Bellmore et al.[27]

between the spatial distribution of dams and dam removals. In New York, for example, the removal of Fort Edward Dam in 1973 released PCB-contaminated sediments downstream, causing substantial environmental impacts,[33] and may have led to heightened caution regarding dam removal. In contrast, a catastrophic dam failure in Pennsylvania caused the Johnstown Flood of 1889[34] that killed more than 2000 people and possibly improved public perception of dam removal as a means to assure human safety. These two adjacent states have similar numbers of dams in the NID (1969 and 1522 in New York and Pennsylvania, respectively) but have very different numbers of dam-removal projects (23 and 276, respectively). Although this particular comparison is speculative, historical events of this nature can influence public opinion, which may result in institutional and regulatory differences among states and associated differences in the motivation and capacity to remove dams.

The distribution of dam-removal studies is similar to patterns of dam removal (Figure 1(b) and (c)). The two states with the most dams removed, Pennsylvania and Wisconsin, also have the largest number of studied dam removals (20 and 18, respectively). Regions with the greatest numbers of studied dam removals include the upper Midwest and Atlantic and Pacific coasts, with few studied dam removals in the interior of the conterminous U.S.. These regional patterns of dam-removal research may be related to the timing of removals relative to the initiation of interest in studying the effects of removal. For instance, dam removals in the interior of the U.S. that are included in the American Rivers database largely occurred prior to the first dam-removal publication[35] that we identified from the literature. It is also notable that there are several states where a large number of removals have occurred, but our literature search yielded few (e.g., California, New Hampshire) or no (e.g., Maine, New Jersey) scientific studies that met our criteria. This finding may be attributed to our inclusion criteria, search methods, publication latency, or an actual absence of studies.

The number of dam-removal studies has not increased at the same rate as the number of dam removals, particularly during the past three decades (Figure 2(a)). Based on our literature review, by the end of 2014, only 9% of all dam removals had been scientifically evaluated. Interestingly, this percentage is similar to that reported for river restoration efforts in general.[36] This seemingly low percentage of studied dam removals may be explained, in part, by the relative scarcity of published studies associated with the removal of small dams. Dams less than 2 m in height represented 28% of all dam removals in the U.S., but they comprised only 12% of all studied dam removals (Figure 2(b)), a pattern which could be explained by the removal of large high-visibility dams that attract more research funding and public interest (or because scientific assessments are viewed as unnecessary for smaller dam removals). For instance, removal of the 12-m-high Marmot Dam in Oregon—one of the larger dam removals to date—is associated with 12 scientific studies. The slower overall rate of increase in dam-removal studies relative to dam-removal practice may also be related to delays between data collection and publication; for long-term studies, there may be lags of several years between removal and publication.

CHARACTERISTICS OF DAM-REMOVAL STUDIES

Of the documents that we identified in our literature search, more than 50% were peer-reviewed journal articles (Figure 3(a)), followed by theses (24%), and reports (16%; primarily by federal and state government agencies). Non-peer-reviewed reports ('grey literature') from private consultants and local agencies were generally not identified by the search engines we employed. Google Scholar, for instance, generally searches for documents with a clear list of authors, which is frequently not included by local agencies and consulting firms. Thus, although these documents may contain relevant information, their relative inaccessibility may reduce their utility for informing dam-removal science and practice.

The BACI experimental design was the most prevalent approach for studying the effects of dam removal (36% of studies; Figure 3(b)). Although the BACI design has limitations,[37] it is generally considered a robust approach for detecting responses to unreplicated treatments.[38] Overall, approximately 80% of studies had temporal (before-after) and/or spatial (control-impact) control sites. These control sites provide a baseline from which to calculate the direction and magnitude of dam-removal responses. The necessity of a control, however, depends on the type of question being addressed. Impact studies (those without a control) can provide important insights into rates of physical and ecological changes after dam removal.[39] However, these studies do not permit the interpretation of post-removal changes in the context of pre-removal or control site conditions (e.g., upstream conditions). Whether a study employs a temporal and/or spatial control depends on funding availability, sufficient advance notice of dam

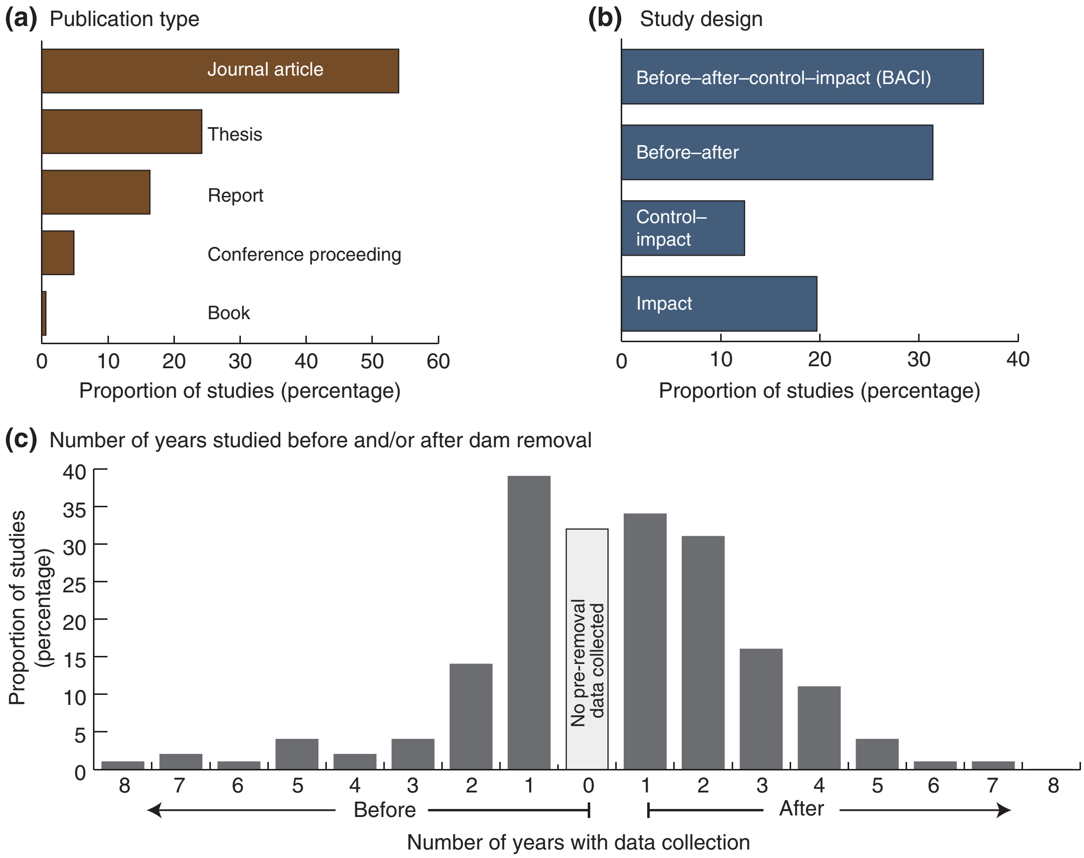

FIGURE 3 | Summary statistics of dam removal research showing proportion of studies by (a) type of publication, (b) type of study design, and (c) the number of years of before/after dam removal data collection. Note that for study designs with no pre-dam removal data (i.e. control/impact and impact categories) 'years before' data are included as a zero (light gray bar).

removal, the existence of an appropriate control site (e.g., McHenry and Pess[40]), and the types of research questions being addressed.

Although 65% of studies monitored conditions before the dam was removed, monitoring was generally short in duration (one or two years; Figure 3(c)). The collection of longer-term pre-removal data can be difficult because it is often hard to predict when dam removal will occur. For many small dam removals in particular, short planning phases prior to removal may limit opportunities for data collection. We also found that the duration of post-removal monitoring was limited. Only 35% of studies had post-removal monitoring for longer than 2 years, and only 5% for longer than 5 years (Figure 3(c)). The scarcity of longer-term monitoring (longer than 5 years) may be caused by limited funding for data collection or lack of interest by scientists.[41] In addition, many responses to dam removal can happen relatively quickly (e.g., sediment erosion and deposition[42,43]), after which there may no longer be motivation to continue monitoring. In contrast, ecological responses to dam removal may take decades to detect.[44,45]

Studies on the effects of dam removal generally measured physical responses more frequently than biological and water-quality responses (Figure 4). The top five monitored metrics were all physical, and all were measured in over 30% of studies (Figure 4(c)). Fish were the only biological metric that was measured in more than 30% of studies, followed by aquatic macroinvertebrates (19%) and riparian vegetation (13%; Figure 4(b)). No water-quality metrics were measured in more than 20% of studies (Figure 4(a)), and contaminants were only measured in 6% of dam removal studies, even though this information is regularly collected during the permitting process.[46] Given the potential negative consequences associated with contaminants (such as the New York case study listed above[33]), it is likely that reservoirs with elevated contaminant concentrations were not prioritized for removal. We hypothesize that physical metrics were measured more frequently

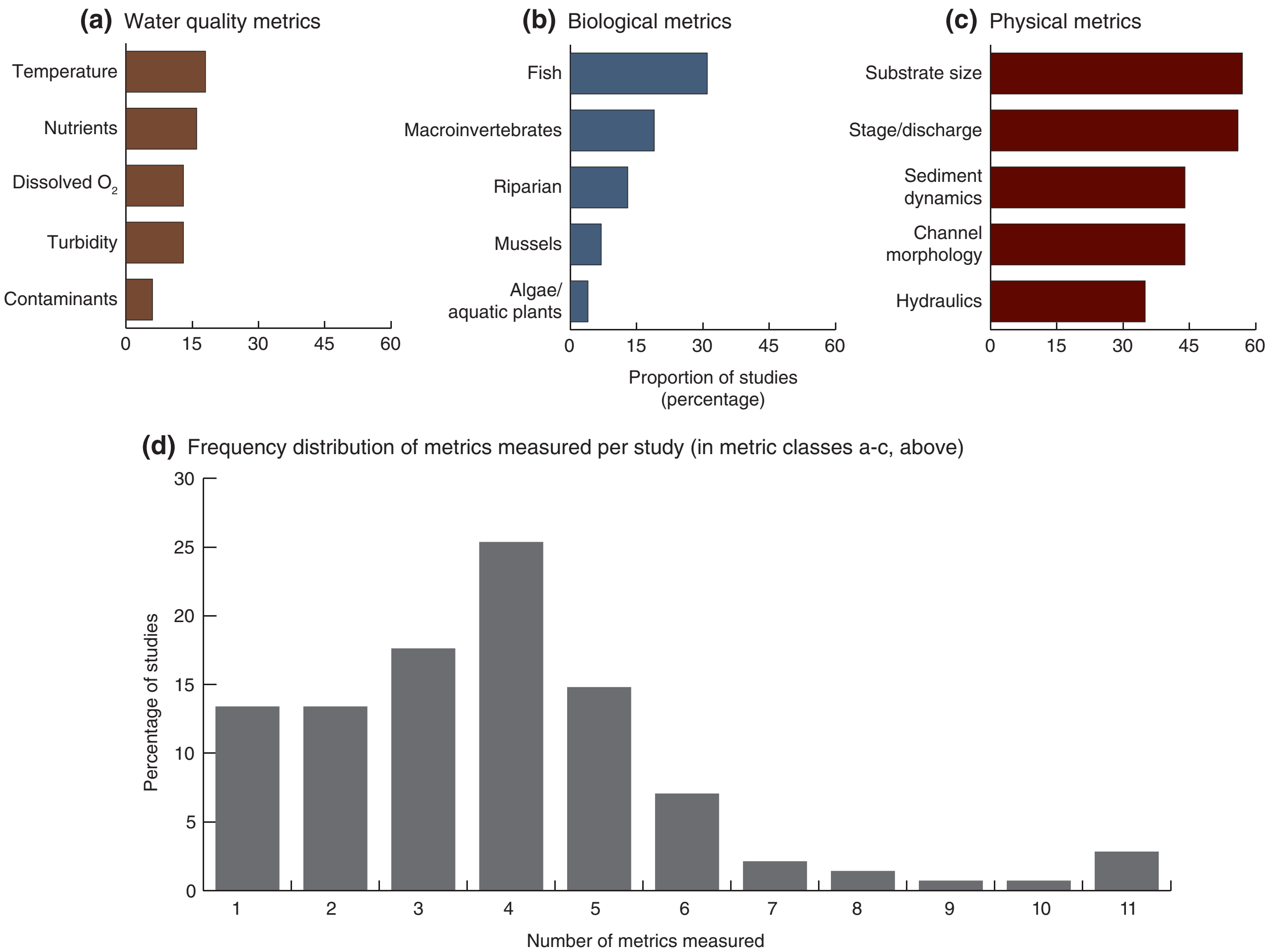

FIGURE 4 | Proportion of dam removal studies (n = 139) classified by type of response metrics measured (a–c) and the total number of metrics measured per study (d).

than biological and water-quality metrics because the focus in early dam-removal studies was on showing that dams can be removed safely, with low risks associated with flooding and sediment deposition. As dam removals continue, however, the prevalence of biological and water-quality monitoring are likely to increase as the focus turns to understanding the longer-term ecological recovery.

Most studies (85%) measured 5 or fewer of the 15 dam-removal monitoring metrics that we enumerated (Figure 4(d)). This finding suggests that most studies evaluate a specific aspect of dam removal (e.g., sediment dynamics or fish) rather than the broader ecosystem response (although there are notable exceptions, e.g.,[47,48]). Moreover, co-occurrence analysis among the dam-removal response metrics illustrated that physical responses were not frequently measured in conjunction with biological and water-quality responses (Figure 5). Studies that measured a given physical component of the system were much more likely to measure another physical component of the system than a biological or water-quality component. Channel morphology, for instance, is strongly linked to all other physical metrics in the circular plot (Figure 5), but it is only weakly linked to biological and water-quality metrics. Conversely, we found that many biological and water-quality metrics were measured more frequently with physical metrics than metrics of the same category. These patterns of co-occurrence may reflect assumptions about causation associated with dam removal. For example, biological and water-quality responses are assumed to be dependent on physical responses, and physical responses are frequently assumed to be independent of biological and water-quality influences (although this is frequently incorrect[49]). Holistic ecosystem studies may also be difficult to identify in the literature because physical, biological, and water-quality findings from the same dam removal get published in separate journal articles. For example, Doyle et al.[50] described the

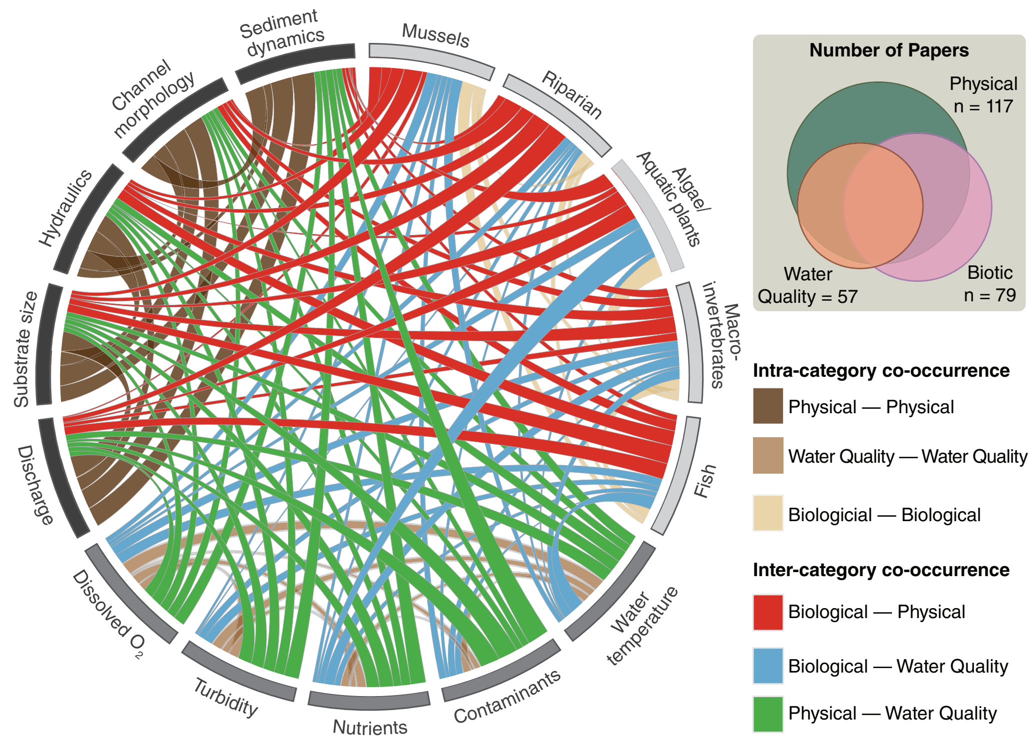

FIGURE 5 | Pairwise co-occurrence patterns of different response metrics monitored in dam removal studies, assigned to physical, biological, and water-quality categories (outer ring). Ribbons inside the circle connect metrics that were measured in the same papers. The base of each ribbon has a width proportional to the number of studies in which that metric was monitored in conjunction with the metric at the other end. To read the figure, start with a given metric of interest (e.g., fish), and compare the width of the different ribbons at base of the metric. Wider-based ribbons connect to metrics that were frequently measured in conjunction with the selected metric, whereas narrow ribbons connect to metrics that were less frequently measured in conjunction with the selected metric. Ribbon colors denote co-occurrence patterns both within and among categories (see legend). Inset Venn diagram shows the number of studies per category, with the amount of overlap proportional to co-occurrence.

geomorphic response of the Baraboo River to the La Valle Dam removal in Wisconsin, whereas Stanley et al.[51] described the macroinvertebrate response.

CHALLENGES AND OPPORTUNITIES

Our review illustrates that there is a growing body of scientific literature that reports on the outcomes of dam removal. These studies were undertaken in a research environment often driven by independent actors working across wide geographic areas, and frequently with limited funding for research and monitoring. Despite these conditions, scientists have mobilized data-collection efforts to evaluate project outcomes and to take advantage of novel research opportunities. These efforts have helped focus and define research questions and inform practice. For example, in the Elwha River, Washington, decades of experiments,[52] physical and numerical models,[53,54] and monitoring[43,55] have helped manage the removal of two large dams storing 21 million m^3 of sediment.[56] Nevertheless, our review identified several 'potential' gaps in the scientific study of dam removal in the U.S. (Table 1). We emphasize 'potential'

TABLE 1 | Gaps in the Science of Dam Removal

Only 9% of dam removals have been described in published scientific literature.
No dam removal studies exist in the central U.S., and many states have few studies relative to the number of removed dams.
There are few studies of the smallest dam removals (those less than 2 m in height) relative to the prevalence of their removal.
Monitoring is generally short-term (1–2 years) and often includes little or no data prior to dam removal.
Fewer studies report biological and water-quality responses to dam removal relative to physical responses (e.g., sediment and flow).
Few holistic ecosystem-level studies exist that attempt to measure linkages among physical, water-quality, and biological responses.

because more studies are needed to explore the extent to which these gaps may actually limit our ability to draw inferences, interpret findings, or make decisions. However, by explicitly highlighting these gaps, we provide clear directions for future study.

By comparing dam removals that have been studied to all dam removals, we found (1) that fewer than 10% of removals have been studied, (2) almost no studies have occurred across the central U.S., and (3) studies of small dam removals are underrepresented in the literature relative to the prevalence of their removal. The extent to which these discrepancies limit predictive capacity and decision-making will depend on the transferability of this scientific information to other locations. For example, the low proportion of studied removals only limits predictive capacity if those removals are not representative of the range of local and regional factors that control responses to removal, such as channel slope, land use, location of the dam in the watershed, proximity to other dams, and the type and age of the dam.[24] Monitoring all removals is not feasible, and given the upward trend in dam removal, the proportion of studied removals is likely to further decline in the future. In this context, limited resources for monitoring will need to be focused on those removals that provide the greatest power to inform decision making. Additional analyses are needed to gauge the 'representativeness' of dam-removal research by comparing the local and regional environmental context of studied removals to dam removals without studies, and dams (particularly older dams) that are likely to be removed in the future.

Along with the challenge of appropriately distributing research efforts, there is also a need for studies that are robust enough to evaluate both short- and long-term ecosystem responses to dam removal. Most of the studies identified in our review only measured short-term responses, and often with limited or no pre-removal data collection. This lack of monitoring information could compromise our ability to understand long-term ecological responses, and to separate those responses from background environmental variability. Although some responses can happen relatively quickly following removal (e.g., sediment transport[5,42]), river channels and adjacent riparian vegetation may continue to adjust for several decades,[24,57] which in turn can have long-term effects on the recovery of aquatic organisms such as fishes.[58]

The paucity of biological and water-quality studies (in comparison to physical studies), as well as holistic ecosystem studies, may also limit our understanding. Because river ecosystems are inherently complex and interconnected,[59] physical, water-quality and biological responses to removal may interact in complex ways. For instance, fish responses to dam removal may be directly linked to changes in dissolved oxygen and water turbidity, and indirectly influenced by sediment deposition on macroinvertebrate prey.[60] A mechanistic understanding of these complex linkages is critical for predicting how specific components of the systems will respond to dam removal. This understanding will require holistic ecosystem studies that integrate multiple scientific disciplines (sensu Bushaw-Newton et al.[47]) and employ a combination of experimental, observational, and modeling approaches. Moreover, because river restoration actions such as dam removal are ultimately a societal decision, holistic evaluations that extend beyond the environmental sciences to include social, economic, and political systems may also be necessary.[61–63]

Based on these challenges, we have identified several opportunities to conduct dam-removal science to better inform management decisions. Although our focus was on dam removal, the research gaps that we identified are strikingly—but perhaps not surprisingly—similar to those identified for the broader field of river restoration.[36,63,64] Thus, the opportunities that we propose for advancing dam-removal science largely echo recommendations made for river restoration in general.

First, we suggest that scientists work with dam-removal practitioners to identify regional and national sets of priority research questions to focus science on research that will advance practice. As an example, questions could be organized around common management concerns, such as the spread of invasive species (fishes and riparian vegetation) or the downstream effects of reservoir sediment erosion.[65] Second, to address these priority questions, there is a need for greater national- and regional-level research coordination that can facilitate the allocation of limited resources more efficiently and in a manner that provides stronger inference for applying results across a broader range of river systems in different geographic locations (e.g., Lindenmayer and Likens[41]). This national-level coordination may also promote long-term monitoring and holistic ecosystem-scale studies.

A third and final recommendation is to create a centralized database to store dam removal science information. Although this has been recommended in the past, both for dam removal[66] and river restoration in general,[36] a complete and centralized database for up-to-date dam removal information currently does not exist (but see the Clearinghouse of

Dam Removal Information; http://calisphere.org/collections/26143; accessed May 3, 2016). In particular, relational databases are needed in order to query dam removals and scientific studies relative to geospatial information (e.g., digital elevation models, land use, and hydrography). These databases would make it possible to examine the biogeographic context of dam-removal responses and to predict responses to future removals. Part of these efforts could also include identifying, analyzing, and interpreting relevant, but as yet unpublished data and gray literature, and ensuring that this information is readily available and effectively communicated to practitioners.

It is our hope that the information collected and analyzed in this article, although incomplete, can begin to address these database needs. For instance, the information contained within the USGS Dam Removal Science Database[27] and the American Rivers Dam Removal Database[4] is currently being translated into a dynamic and visual online database tool, termed the Dam Removal Information Portal or 'DRIP' (https://www.sciencebase.gov/drip/). This database can currently be used to visualize the location of dam removals included in the American Rivers database, summarize basic information on removed dams (e.g., dam height, year removed, metrics monitored), filter removed dams by different attributes (e.g., types of studies available), and provide links to published studies. This database has already been linked to the National Hydrography Dataset (NHD), and, in the future, it will be linked to other relevant geospatial data sets such as the National Water Information System (NWIS).

CONCLUSION

Scientists will increasingly be called upon to make predictions about how rivers will respond to dam removal and how long they may take to recover. Our analysis serves as an assessment of the current state of dam-removal science—information that can be used to inform the practice of dam removal. Although we identified numerous gaps in the research that might limit the application of science to decision making, these challenges can be confronted by articulating and prioritizing research needs and questions, facilitating regional and national coordination of research, and increasing the accessibility and communication of dam-removal science to researchers and managers, as well as the public. Accomplishing these tasks will facilitate feedback between researchers and practitioners needed to align science with management, and may help shift the perception of dam removal from that of a localized and opportunistic endeavor to a broader and more strategic nation-wide adaptive management experiment.

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