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Global Trends in Dam Removal and Related Research: A Systematic Review Based on Associated Datasets and Bibliometric Analysis

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Abstract: Dam removal has been increasingly reported globally and is becoming an important approach for river management, restoration and environmental conservation in damming rivers. However, current limited knowledge of global trends in dam removal and related research may be potentially biased in terms of the geographic distribution and organisms studied. Such bias could mislead dam removal planning and management in different areas and ecological conservation for different taxa. In this study, we quantitatively and qualitatively analyzed datasets of dam removal and publications of dam removal research using bibliometric methods. A total of 1449 dam removal documents were published from 1953 to 2016. Trends, current hotspots and future directions of dam removal research were identified. The results from this study reveal that dam removal largely occurred in the North America and Europe, and most of the removed dams were small and old dams. With respect to the topic analysis, more dam removal studies should focus on the responses of a wide range of organisms, not only fish, as well as the interspecies relationships, food webs and ecosystem structures and functions. Based on our findings, we also provide some suggestions for future dam removal planning and analysis.

Keywords: dam; demolition; literature; research topics; weir

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1 Introduction

Dam construction has a long history associated with human civilization (Wang et al., 2014) because dams play a vital role in flood control, agricultural irrigation, drinking water supply, electricity generation and aquaculture-based production (World Commission on Dams, 2000; Lehner et al., 2011; Bellmore et al., 2017). However, the public and scientists continue to criticize dams due to the negative side effects of dams on river environments and aquatic biodiversity (Baxter, 1977; Bunn and Arthington, 2002; Nilsson et al., 2005; Zhang et al., 2018). For example, a dam can impair a river ecosystem (Poff and Hart, 2002), decrease the energy inputs from upstream to downstream (Vannote et al., 1980), and even prevent the migration of aquatic animals (Larinier, 2000; FAO, 2001; Dugan et al., 2010).

During the past several decades, dam removal has been increasingly planned and implemented (Wang et al., 2014; Bellmore et al., 2017; Foley et al., 2017) to allow rivers to return their natural states as an efficient approach to river restoration (Bednarek, 2001; Katopodis and Aadland, 2006). Numerous studies have found that reconnected rivers can strongly improve water quality (Mullens and Wanstreet, 2010; O'Connor et al., 2015; Bohrerova et al., 2017), release sediment and energy to downstream areas (Cheng and Granata, 2007), and increase both habitat diversity and aquatic biodiver-

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sity (Kang and Kazama, 2013; Magilligan et al., 2016; Ding et al., 2018). For instance, two dams (Great Works and Veazie Dams) in the Penobscot River, Maine, USA, which were removed to open thousands of miles of upstream spawning habitat for Atlantic salmon (*Salmo salar*), shortnose sturgeon (*Acipenser brevirostrum*) and other types of sea-run migrant fish in the main river and tributaries (Klima, 2014). However, dam removal is intrinsically complicated, and the expected outcome may not occur. Notably, socioeconomic, ecological, cultural-historical, political and safety factors should be taken into consideration (Angermeier, 2008; Lejon et al., 2009). The potential risks of dam removal can be divided into five categories: life risks, economic risks, technological risks, environmental risks and social risks (Born et al., 1998; Hart et al., 2002). For instance, the remnants of dams can be detrimental to future navigation (The H John Heinz III Center, 2002). To date, the ecological consequences of dam removal have been minimally studied due to the lack of long-term monitoring pre- and post-dam removal (Brewitt, 2016). Most dam removal cases and studies were conducted in developed countries and areas, such as America and European countries, and only a small percentage of removals have been scientifically evaluated (Bellmore et al., 2017). Therefore, our limited knowledge of dam removal and its restoration effectiveness may be potentially biased by relying on these cases and studies. Such bias could mislead dam removal planning and management in different areas.

An overall understanding of existing dam removal studies and important trends is urgently needed and essential for establishing river restoration strategies globally. Such an understanding can be achieved based on a powerful bibliometric analysis of the existing literature. Bibliometrics analysis has been successfully applied to extract useful information from a large number of scientific outputs and identify global trends in multidisciplinary research fields (Liu et al., 2011, 2016; Tao et al., 2015). In this study, we conducted a bibliometric analysis of dam removal studies. The main objectives of the study were as follows: 1) to map the distribution of dam removals in terms of the publications in each country, publication type, authors and subject; 2) to predict hot areas and topics in future dam removal studies; and 3) to provide some suggestions for future dam removal planning and analysis.

2 Data and Methods

In this study, nine datasets on dam removal were collected (Table 1): the United States Geological Survey (USGS) Dam Removal Science Database (2015); American Rivers Dam Removal Database (2016); European Rivers Dam Removal Database (2016); The United Kingdom River Restoration Project Database; Low-Head Dam Removal Project Database; France, Spain and United States Dam Decommissioning Database; and other dam removal project databases. Due to the multiple sources of data and various geographic coordinate systems used (e.g., WGS1972, WGS1984 and NAD1983), the spatial location of each removed dam was corrected by consistently using the Robinson (world) Coordinate System. When location information was missing, we searched Google Earth™, the Global Reservoir and Dam (GRanD) database and the literature to identify the location of the dam. Additionally, other supplemental information was used to supply missing attributes. Still, some of the basic information (i.e., the date of the dam removal) could not be determined. Attributes included the name of the dam (alternative name), name of the impounded river, name of the main basin, name of the nearest city, height of the dam in metres, age of the dam in years, latitude/longitude, and year (not further specified: year of construction; year of completion; year of decommissioning). Moreover, a global polygon layer, basic metadata information and projection information were provided in ESRI shapefile format with accompanying XML (.shp.xml) and ASCII (.prj) files. Each shapefile consists of five core files (.dbf, .sbn, .sbx, .shp, and .shx files). The above information was integrated to map the distribution of dam removal using ArcGIS 10.4.1.

The information from documents used in this study was mainly obtained from four databases: the Web of Science, Google Scholar, Scopus and the United States Geological Survey Publication Warehouse. Our search covered the papers published from 1953 to 2016, the search terms used to search titles, abstracts and keywords were ‘dam remov*’ and ‘river OR stream’. All full results were imported into EndNote X7 for further analysis. EndNote X7 is an industry standard software tool for publishing and managing bibliographies, citations and references on Windows and Macintosh computers (Brouwer et al., 2014). Duplicate documents were removed. Document information, including publication

Table 1 List of the major datasets of global dam removal

Datasets	Contribution	Description	Source/URL
USGS Dam Removal Science Database	Primary	Summaries of documented dam removal science, dam characteristics, dam-removal date. Publication Date: 2015	http://doi.org/10.5066/F7K935KT
American Rivers Dam Removal Database	Primary	An interactive map of USA dam removals, with coordinates, date of removal, and dam height when data available. Update Date: March 2017	https://www.americanrivers.org/threats-solutions/restoring-damaged-rivers/dam-removal-map.
Europe Rivers Dam Removal Database	Primary	An interactive map of Europe dam removals, with coordinates, date of removal, and dam height when data available. Update Date: March 2017	http://damremoval.eu/
France, Spain and USA Dam Decommissioning Database	Primary	Dam removals information of France, Spain and USA. Update Date: March 2017	http://www.rivernet.org/general/dams/decommissioning/decom3_e.htm
NHDES Dam Removals Project Database	Primary	Dam removals project data: planned, completed and under Consideration. Update Date: March 2017	http://www.des.nh.gov/organization/divisions/water/dam/damremoval/index.htm
UK River Restoration Project Database	Primary	An interactive project map of River Restoration Centre's (RRC)	http://www.therrc.co.uk/uk-projects-map
Low-Head Dam Removal Project Database	Primary	A Summary of Existing Research on Low-Head Dam Removal Projects	http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=1287
R Packages 'dams'	Support	Dams in the United States from the National Inventory of Dams (NID). Update Date: November 5, 2016	https://github.com/jsta/dams
Global Reservoir and Dam (GRanD) Database	Support	Summaries of dam attributes, such as damming data, dam of main use and dam characteristics etc.	http://sedac.ciesin.columbia.edu/data/set/grand-v1-dams-rev01
Other Database	Support	Including literatures, government documents and other web sources etc.	

Note: USGS: The United States Geological Survey, USA: The United States of America, NHDES: New Hampshire Department of Environmental Services, UK: The United Kingdom

year, author name (s), journal title, article title, keywords, abstract, country, document type, and author (s) address (es), were stored for further analysis. Documents from Northern Ireland, Wales and England were regrouped as being from the United Kingdom. The IF reflects the influence of the academic journal, while the h index, which was introduced by Hirsch (2005), can be applied to characterize the number of highly cited papers in a journal. Boxplots with illustrating the heights and ages of removed dams, analyses of topic words and distributions of disciplines were created using the ggplot2 package in R software (Wickham, 2016), Voyant tools (Online: https://voyant-tools.org/) and Sci2 tool (York, 2014), respectively.

3 Results

3.1 Global trends of dam removal

During the past half century (1950–2016), 3869 dams (including dams of unknown removal date) on rivers or streams have been progressively removed throughout the world. As illustrated by the distributions of publications and authors, most of the recorded dam removals (1408 or 36%) were distributed in America. Dam removal generally occurred ahead of publication and became increasingly common over time. Specifically, only 22 dams were demolished in the United States and the UK from the 1950s to 1960s (Figs. 1a and 1b). From the 1970s to 1980s, the number of removed dams reached 155, mainly in North America, with a few in Finland and Australia (Figs. 1c and 1d). Then (in the 1990s–2010s), the number of dams removed increased exponentially, and removal expanded to Southeast Asia, including South Korea, Japan, and China (Figs. 1e–1h). While some of the dam removal dates were not available, the growing trend of dam removal was very clear.

Boxplots (also known as box-and-whisker diagrams) with jittered scatterplots overlaid on the heights and ages of removed dams were mapped, as shown in Fig. 2. The boxes contain some raw height and age data for dams in each decade. Outlier points were plotted individually to provide more information regarding the heights and ages of removed dams of the same bar segments. The most extreme values of height and age of removed dams were 210 m (Glines Canyon Dam, Elwha River, Washington, USA; lifespan of 1911–2011) and

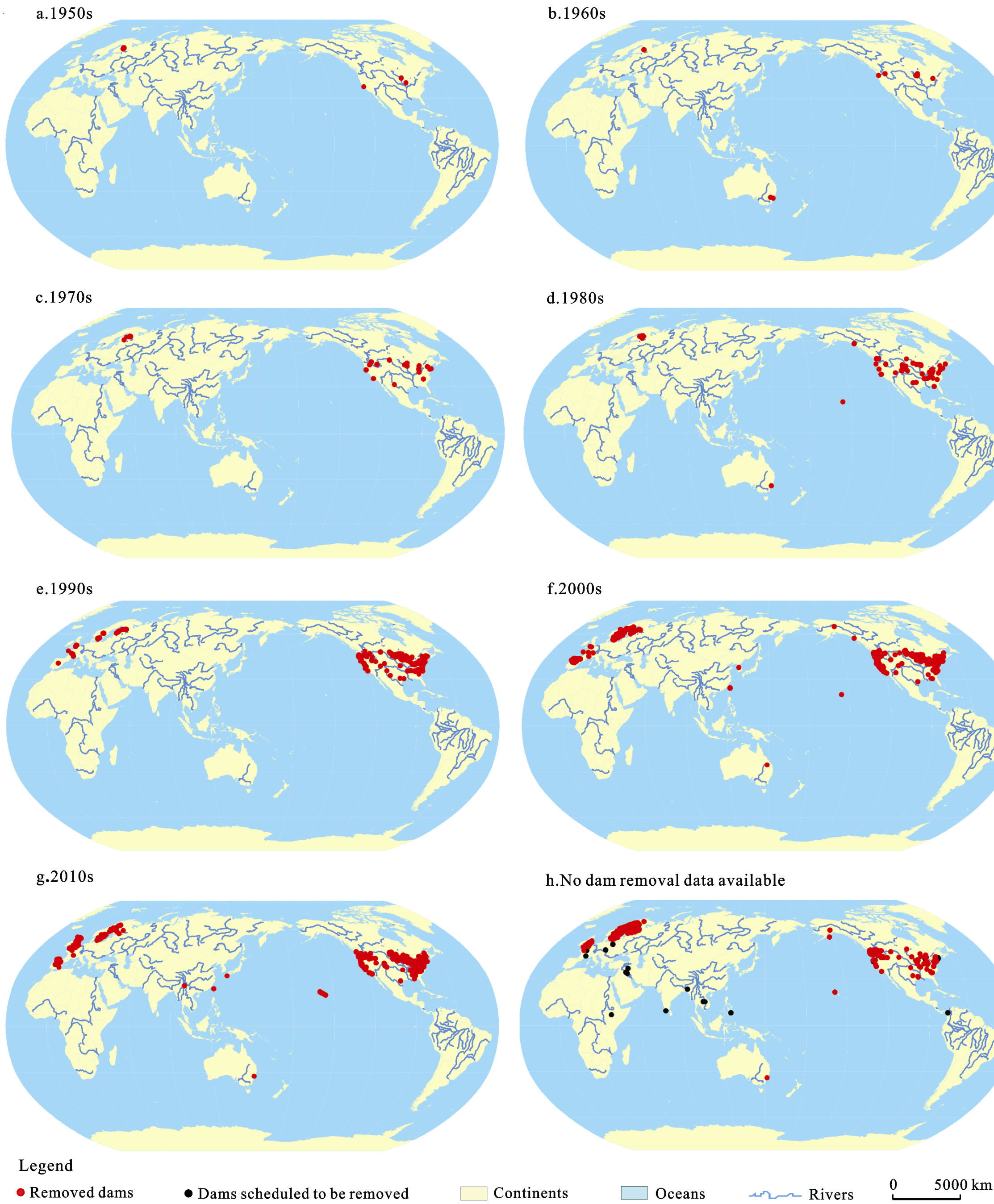

Fig. 1 Global geographic distribution of the removal of 3917 dams based on available data, including both removed dams (3869, or red dots, 99.9 % of all dots) and dams scheduled for future demolition (48, or black dots, 0.01% of all dots), (a)–(g) are from the 1950s to 2010s and (h) is for no available dam removals date

446 years (Chesaning Dam, Shiawassee River, Michigan, USA; lifespan of 1563–2009), respectively. In addition, the results demonstrated that the mean height of removed dams decreased and the mean age of them increased: the median height of removed dams fluctuated slightly (with a range of 0.5–55.0 m) in the 1950s–1990s and was significantly different from median heights of 6.0 m (0.5–25.0 m) in the 2000s and 8.0 m (0.4–28.0 m) in the 2010s (Fig. 2a). Additionally, the upward trend in median age of removed dams was very clear from the 1950s to the 2010s (Fig. 2b). Overall, the heights and ages of removed dams were mainly concentrated in the range of 0.4–55.0 m and 1–199 years, respectively.

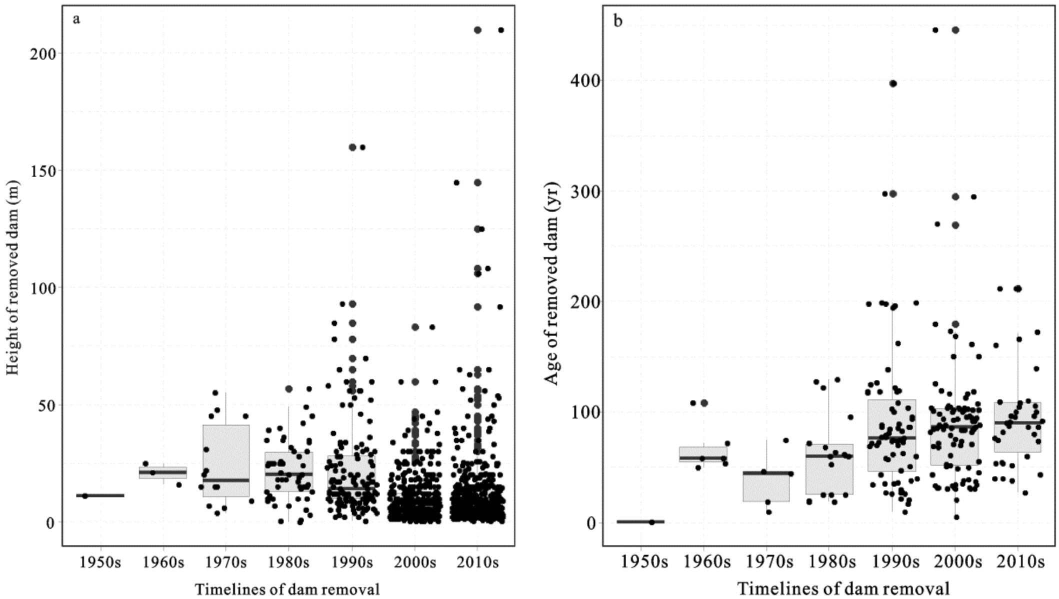

Fig. 2 Boxplots with jittered scatterplots overlaid on (a) the heights of removed dams and (b) the ages of removed dams in the 1950s–2010s

3.2 Publications of dam removal research

A total of 1449 documents about dam removal were published from 1953 to 2016, and the majority of them were written in English (1401, or 96.69% of all publications). No publications were found before 1953. Five document types were retrieved (Fig. 3). The most common publication type was journal article (1188, or 81.99% of all publications), followed by conference proceedings, reports, thesis and books, which accounted for 8.97%, 5.31%, 1.93% and 1.79% of the total, respectively. Fig. 3 shows the global distribution of publication productivity and the authors of dam removal research from 1953 to 2016. The most productive country was the United States in terms of both the publication number (987, or 68% of the total) and author number (1009, or 66% of the total). Other countries, such as Canada, Sweden, Spain, Finland, China, Australia, Japan and Brazil, also made notable contributions to dam removal research.

The discipline distribution of 1188 journal articles was mapped, as shown in Fig. 4. A total of 165 sub–discipline nodes were identified and aggregated into 12 main disciplines of science. Dam removal research has become a multidisciplinary field spanning biology, earth sciences, biotechnology, infectious disease, math and physics, chemistry, humanities, social sciences, and other disciplines (Fig. 4). Biology; earth science; and chemical, mechanical and civil engineering were the top three most popular disciplines, and considerable overlap was observed among these three disciplines.

Published research on dam removal appeared in 149 journals across a wide range of SCI categories (e.g., Environmental Sciences, Water Resources and Ecology, *etc.*), and the top 20 most active journals (which accounted for 29.3% of 1188 journals) are summarized in Table 2. *River Research and Applications* (Journal Citation Report abbreviated title RIVER RES APPL) ranked first and published 64 (or 4.42% of 1118 journals) articles on dam removal. Geomorphology published the second most articles (44, or 3.04%), followed by the *Journal of Environmental Management* (Journal Citation Report abbreviated title J ENVIORN MANAGE) (33, or 2.28%), *Transactions of the American Fisheries Society* (Journal Citation Report abbreviated title N AM FISHMANAGE) (30, or 2.07%) and *Water Resources Research* (Journal Citation Report abbreviated title WATER RESOUR RES) (30, or 2.07%). With respect to the number of citations per publication (CPP), *BioScience* was the leading journal with 177.40, followed by the *North American Journal of Fisheries Management* (89.15) and *Journal of Environmental Management* (72.61). Journals with high CCPs also had high IF scores, which indicates that these two indicators are highly correlated.

3.3 Research trends of major topics

In terms of keyword analysis, the period before 1996 was not displayed due to the discontinuity of the occurrence of most keywords. The frequency counts for the top 10 keywords in the past two decades are shown in Fig. 5. Although those search terms (e.g., dam removal, river or stream) were the most frequently used topic words, they failed to reveal research hotspots; thus, they were excluded from the topic word analysis. Fig. 5 indicates clear increases or decreases in the usage of certain words. With the increasing number of publications, 'sediment (s)' studies increased steadily from 1996 to 2013 and exponentially in 2014; then, the trend slightly declined. Studies of 'fish (es)', 'habitat (s)', 'flow', 'channel (s)', 'restoration (s)', 'model (s)', 'species', 'salmon (s)', and 'management (s)' exhibited a similar trend. The topic word "sediment (s)" ranked first and occurred 3030 times, and the next most common topics were 'fish (es)' (1707), 'habitat(s)' (1348), and 'flow' (1288).

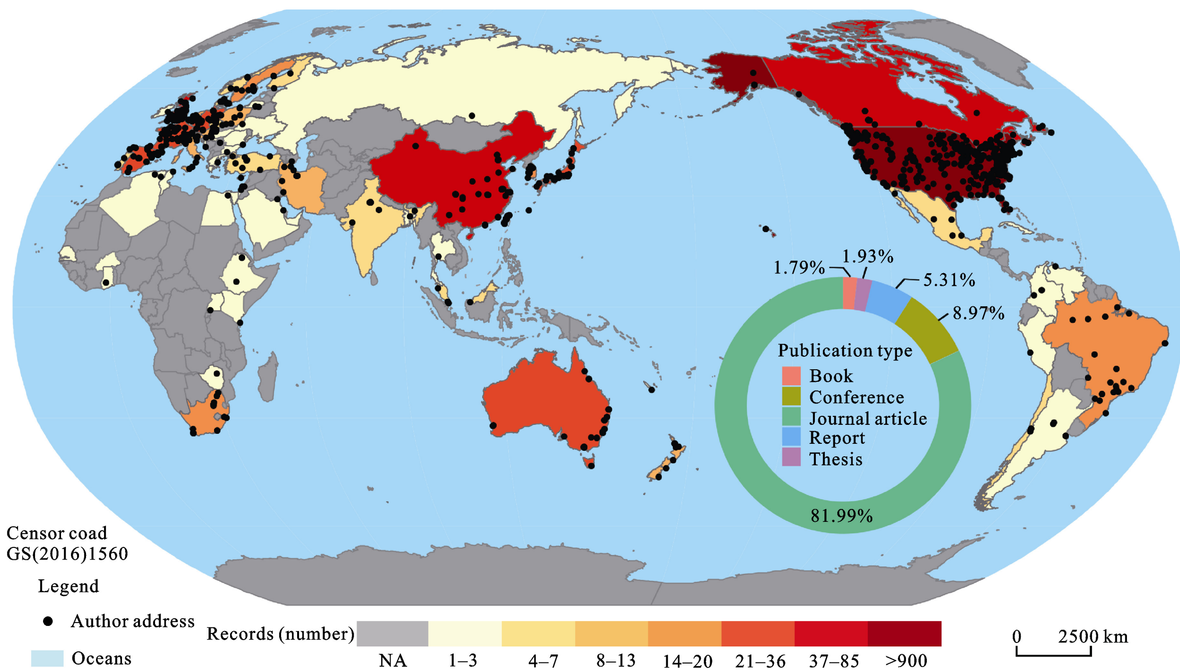

Fig. 3 A world map of productive regions and the global spatial distribution of authors from 1953 to 2016 and the literature classified by publication type in percent

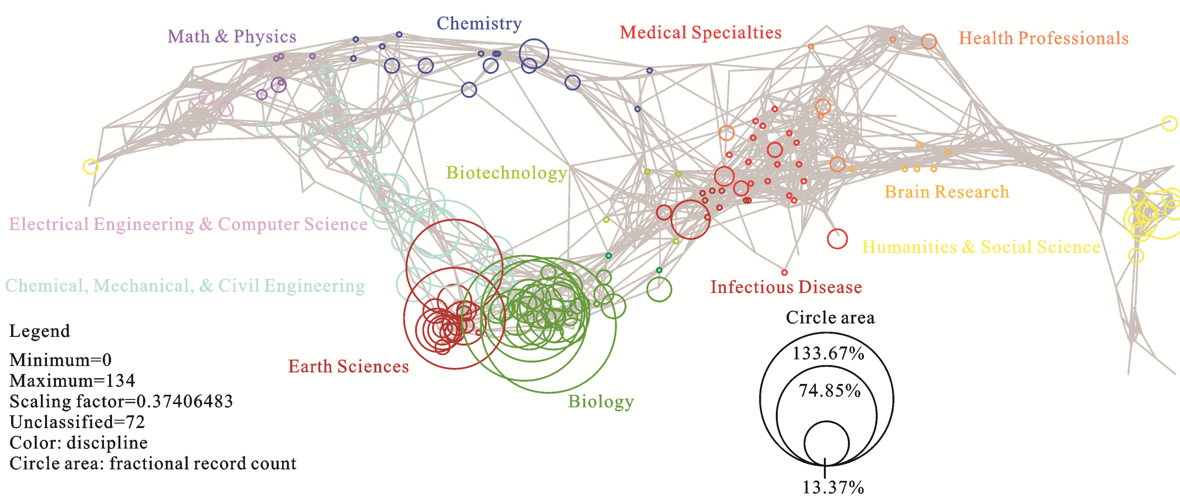

Fig. 4 The visualization of 165 sub-disciplines and 12 major disciplines of dam removals studies, minimum and maximum data values are the number of fractionally assigned records; circle area are proportional to the number of fractionally assigned records

Table 2 The top 20 most productive journals on dam removal research from 1953 to 2016

JCR abbreviated title	Categories (R/T); Q	TP (%)	TC	CPP	IF	h-index
RIVER RES APPL	Environmental Sciences (102/225); Q2 Water Resources (22/85); Q2	64 (4.42)	1782	27.84	1.98	23
GEOMORPHOLOGY	Geography, Physical (12/49); Q1 Geosciences, Multidisciplinary (34/184); Q1	44 (3.04)	2032	46.18	2.81	23
J ENVIRON MANAGE	Environmental Sciences (54/225); Q1	33 (2.28)	2396	72.61	3.13	19
T AM FISH SOC	Fisheries (21/52); Q2	30 (2.07)	543	18.10	1.47	12
WATER RESOUR RES	Environmental Sciences (35/225); Q1 Water Resources (5/85); Q1 Limnology (1/20); Q1	30 (2.07)	1599	53.30	3.80	23
NORTHWEST SCI	Ecology (139/150); Q4	29 (2.00)	772	26.62	0.41	16
HYDROBIOLOGIA	Marine and Freshwater Biology (33/104); Q2	23 (1.59)	723	31.44	2.05	15
N AM J FISH MANAGE	Fisheries (30/52); Q3	23 (1.59)	1159	89.15	1.01	13
J AM WATER RESOUR AS	Engineering, Environmental (28/50); Q3 Geosciences, Multidisciplinary (93/184); Q3 Water Resources (34/85); Q2	20 (1.38)	663	33.15	1.66	13
ECOL ENG	Ecology (50/150); Q2 Engineering, Environmental (17/50): Q2 Environmental Sciences (66/225); Q2	17 (1.17)	475	27.94	2.74	10
CAN J FISH AQUAT SCI	Fisheries (7/52); Q1 Marine and Freshwater Biology (17/104); Q1	16 (1.10)	955	59.69	2.44	11
FRESHW SCI	Ecology (55/150); Q2 Marine and Freshwater Biology (18/104); Q1	14 (0.97)	655	46.79	2.43	11
ECOL APPL	Ecology (24/150); Q1 Environmental Sciences (26/225); Q1	12 (0.83)	778	64.83	4.25	12
J GREAT LAKES RES	Environmental Sciences (107/225); Q2 Limnology (6/20); Q2 Marine and Freshwater Biology (37/104); Q2	12 (0.83)	287	23.92	1.91	10
BIOSCIENCE	Biology (11/86); Q1	10 (0.69)	1774	177.40	4.29	10
EARTH SURF PROC LAND	Geography, Physical (9/49); Q1 Geosciences, Multidisciplinary (23/184); Q1	10 (0.69)	253	25.30	3.51	8
FRESHWATER BIOL	Marine and Freshwater Biology (11/104); Q1	10 (0.69)	560	56.00	2.93	10
J HYDROL	Engineering, Civil (5/126); Q1 Geosciences, Multidisciplinary (33/184); Q1 Water Resources (6/85); Q1	10 (0.69)	380	38.00	3.04	9
PLOS ONE	Multidisciplinary Sciences (11/63); Q1	9 (0.62)	119	13.22	3.06	6
RESTOR ECOL	Ecology (72/150); Q2	8 (0.55)	315	39.38	1.90	8

Notes: JCR, Journal Citation Report; R, journal rank in category; T, total journals in category; Q, quality in category; TP, total publications; percentage (%), percentage of publications for a certain journal; TC, total citation counts; CPP, citation per publication; IF, impact factor in 2015

4 Discussion

4.1 Geographic distributions and characteristics of global dam removal and the associated trends

The geographic distributions of removed dams and river biodiversity hotspots rarely align (Myers et al., 2000; Vörösmarty et al., 2010; Marchese, 2015; Fig. 1). Dams threaten zones of aquatic biodiversity in all the major rivers of undeveloped, developing and developed countries (Vörösmarty et al., 2010). However, a campaign to remove over 4000 dams occurred in the North America and Europe (Fig. 1). The obvious gap in dam removal between developing and developed countries is potentially because that developing countries have to prioritize economic development rather than environmental conservation (Born et al., 1998). Old and functionless dams are around the world. In developing countries, limited funding is more likely to be used for new dam

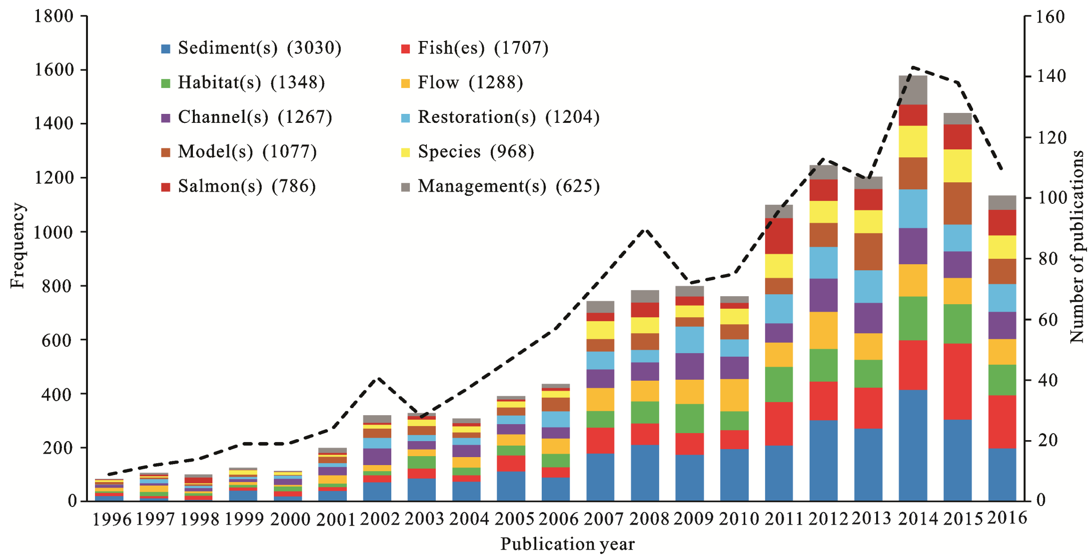

Fig. 5 Frequency count for the ten most frequently used topic words (total frequency of occurrence) in 1996–2016

construction, but not to remove these old dams (Born et al., 1998; Zarfl et al., 2015). Second, less developed regions have higher water resource requirements for drinking and agriculture than do developed regions due to their fast-growing populations (Alcaraz et al., 2015).

The maximum and minimum values of the heights and ages of removed dam have become increasingly polarized, resulting in the overall compression of box-plots and the growth of outliers (Fig. 2). The results suggest the driving factors of dam demolition are the loss of dam function and the aging structure, and potentially associated with the increasing public awareness of river health importance (Stanley and Doyle, 2003). Most dams removed in the past half century were small, low-head and run-of-river dams (Grant, 2001; Fig. 2); thus, removal in the predictable future will likely involve more of these relatively modest structures, but even large dams may be removed due to their limited lifespan (up to 80% of dams will be 50 years old by 2020 according to O'connor et al., 2015).

4.2 Current and future of hot topics and areas

Keyword analysis can reveal the popular topics in a specific research area (Mane and Börner, 2004). The most popular topics associated with dam removal were related to environmental change and biodiversity conservation. The first popular topic was 'sediment', which exhibited highest frequency of occurrence (Fig. 5). A dam can cut off the transportation of sediment from upstream to downstream, and sediment deposition can occur in water impoundments due to accumulation (Ackers and White, 1973; Wohl and Cenderelli, 2000). Sediment accumulation in front of a dam can threaten the function of the dam and create the need for dam removal. When a dam is removed, the first environmental consequence is sediment flushing, and the restored 'flow' regime changes the river 'channel' (Magilligan et al., 2016). Other frequently used keywords, such as 'fish', 'habitat', 'restoration', 'species' and 'salmon', indicate that the second most popular topic associated with dam removal is habitat restoration for aquatic organisms and the river ecosystem (Pohl, 2002). Fish, particularly salmon, was a key taxa associated with dam removal (Service, 2011; Brewitt, 2016). In addition, dam removal poses a challenge for river 'management' (Hart et al., 2002; Fig. 5), particularly in transboundary rivers (Dudgeon, 2003). Currently, we lack knowledge and experience in river management post-dam removal (Rollet, 2014).

The above analysis also indicates that the majority of studies focused on the effectiveness of dam removal for fish restoration, particularly salmon restoration. Therefore, future researches could involve other aquatic organisms, such as phytoplankton, algae, macrophytes, zooplankton and benthic invertebrates. Based on the distribution of dam removals in terms of the area, height and age, North America and Europe will continually to be the core areas of dam removal and research, we expect to observe increasing trends in Asian countries such as China and Japan in the near future, but likely not in countries in Africa (Zarfl et al., 2015), because dam removal and associated studies were highly correlated with the economic development level and the existing number of dams (Smith, 2006). Additionally, removal in the predictable future will likely involve more of these relatively modest structures, and even large dams.

4.3 Suggestions for future dam removal research

4.3.1 Drivers for dam removal

The dismantling of a dam is intrinsically complicated, socioeconomic, ecological, cultural-historical, political and safety factors should be taken into consideration (Angermeier, 2008; Lejon et al., 2009). Based on previous studies, reasons for dam demolition include structural obsolescence, safety considerations, ecosystem restoration, recreational opportunities, and cost-saving (The H John Heinz III Center, 2002). Among which, safety considerations, ecology restoration and cost-saving are the main drivers for dam removal in the United States, accounting for 97.9% (Wang et al., 2015). Our results also indicated that the loss of dam function and the aging structure are drivers for dam removal around the world (Fig. 2). However, what is not yet clear about the reasons of dam removal for each country, since each country varies considerably in terms of political, economic and cultural backgrounds.

4.3.2 Ecosystem response to dam removal

Dam removal can not only affect sediment transportation in rivers but also other physical and chemical factors, such as the flow regime, temperature, and nutrient transport (Born et al., 1998; Cheng and Granata, 2007). Understanding the changes in these factors is critical for further river management. For example, more studies should focus on the mobilization processes of nitrogen, phosphorus, organic and mineral contaminants (Shuman, 1995; Kang and Kazama, 2013). Extensive monitoring data could provide essential information to synthetically understand the environmental change in response to dam removal and to inform future dam removal planning. In comparison to short-term monitoring projects, long-term projects, though expensive, should be encouraged because river ecosystem restoration takes a long time (Halsing and Moore, 2008).

According to the keyword analysis, most studies have concentrated on the effectiveness of dam removal for fish restoration, particularly salmon restoration. Therefore, previous studies essentially ignored other aquatic organisms, such as phytoplankton, algae, macrophytes, zooplankton and benthic invertebrates. Primary producers provide food sources and shelter for consumers (Schneider, 2007) and are of great significance to river restoration and biodiversity maintenance (Zhang et al., 2011). The restoration effectiveness of dam removal may vary considerably depending on the type of organisms involved (Shafroth et al., 2002; Mclaughlin, 2013). Therefore, more dam removal studies should focus on the responses of a wide range of organisms, not only fish, as well as the interspecies relationships, food webs and ecosystem structures and functions.

4.3.3 Early strategies for restoring river biodiversity after dam removal

Habitat fragmentation due to dam construction is a primary driver of the biodiversity decline in rivers (Wu et al., 2003). Additionally, fragmentation combines with other stressors, such as climate change, land use change and biological invasion, to complicate the restoration of river ecosystems after dam removal (Neeson et al., 2015; Gangloff et al., 2016). To date, scientists have not found an effective method of restoring river biodiversity after dam removal. It is imperative that institutions and stakeholders use existing knowledge to alleviate this issue by implementing conservation, management and restoration strategies in an adaptive fashion (Dudgeon, 2010). The early strategies for river ecosystem restoration after dam removal could include establishing protected areas (PAs) of significance to river biodiversity and implementing management plans for these PAs (Raghavan et al., 2016). In addition, removing the remnants of dams to make flow regimes more natural is important (Stanley and Doyle, 2003).

4.3.4 Tradeoff between human water security and aquatic biodiversity restoration

Approximately 80% of the global population lives in zones where either the human water security or biodiversity is threatened (Vörösmarty et al., 2010). Water resources are essential not only for human survival and development but also for biodiversity maintenance (Richter et al., 1997; Vörösmarty et al., 2010). Is there any closed relationship between ‘dam removal’ with ‘water security and aquatic biodiversity restoration’? If yes, what kind of relationship should be mentioned and how to find out the solution to keep balance between these requirements?

5 Conclusions

In this study, we quantitatively and qualitatively analyzed publications and datasets of dam removal research using bibliometric methods. 3869 removed dams in rivers or streams are mostly small and old ones in the past half century. The results demonstrated that the mean height of removed dams decreased and the mean age of them increased. In the last two decades, the number of dam removal increased exponentially and removal expanded from the North America and Europe up to Southeast Asia, including South Korea, Japan, and China. Additionally, a total of 1449 dam removal documents were published from 1953 to 2016. *River Research and Applications*, *Geomorphology and Journal of Environmental Management* were most active journals in this field. The United States was the most productive country in term of both publication number and author number. The analysis of topic words also indicated that the most popular area was sediment (s), followed by fish (es), particularly salmon (s), and habitat (s). With respect to the topic analysis, more dam removal studies should focus on the responses of a wide range of organisms, not only fish, as well as the interspecies relationships, food webs and ecosystem structures and functions. Although we searched from a wide range of sources, there were still some dam data unavailable, which could cause the results were slightly inconsistent with the true situation in some countries Based on our findings, we also suggest some future research directions for dam removal, including drivers for dam removal, ecosystem responses, early conservation strategies after dam removal, and the tradeoff between human water security and aquatic biodiversity restoration.

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