



Research

Incorporating climate change into restoration decisions: perspectives from dam removal practitioners

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ABSTRACT. Incorporating climate change into conservation and restoration decisions is increasingly important for natural resource managers and restoration practitioners to effectively address the underlying drivers of ecosystem change. Small dam removal is an example of a restoration tool that may offer multiple socioeconomic and ecological benefits in streams, including promoting climate resilience. With the pace of dam removals increasing, practitioners and researchers are well-poised to incorporate climate change into future dam removal decisions. Therefore, we surveyed dam removal practitioners across 14 states in the eastern United States to understand current practices of small dam removals, factors driving restoration decisions, and how climate change knowledge is incorporated into these decisions. We also aimed to identify barriers to and opportunities for knowledge exchange between practitioners and researchers. Of the 100 respondents, most (79%) consider climate change in their dam removal decisions to some extent. Despite this, many reported a lack of clear, relevant, and accessible data linking small dam removal to climate resilience benefits. Dam removal practitioners also indicated that they most often rely on climate change information garnered from conversations with colleagues, rather than from scientific research products. These results suggest that the co-production of relevant, salient research questions and readily accessible and interpretable research products (e.g., technical summaries, open access articles) may encourage practitioners to incorporate climate change science more consistently and efficiently into dam removal decisions. These findings may also translate to other stream restoration efforts to inform knowledge exchange and improve restoration outcomes in a changing climate.

Key Words: *climate change; dam removal; decision making; survey; translational science*

INTRODUCTION

Natural resource managers and restoration practitioners are increasingly interested in incorporating climate change impacts into conservation planning and decision making (AFWA 2022, Wilkening et al. 2022). Many practitioners recognize that current project prioritization and restoration approaches, as well as predictions about project outcomes, may not be appropriate given expected changes in habitat quality and quantity, species ranges, and socioeconomic vulnerabilities due to climate change (Leadley et al. 2010, Yocum et al. 2022). This shift toward considering climate change is also evident in global recommendations (e.g., IUCN 2020 Motion 009), regulations (e.g., Executive Order No. 14008 2021), and planning documents (e.g., U.S. State Wildlife Action Plans) that either encourage or require consideration of climate change impacts in infrastructure and conservation decisions (AFWA 2022). For sensitive freshwater river systems, which often experience ongoing local anthropogenic pressures that overlap with climate change, calls from researchers to incorporate climate change science into river restoration planning and design have also been increasing (Seavy et al. 2009, Perry et al. 2015, Skidmore and Wheaton 2022). Despite these calls, it is unclear to what extent, if at all, climate change is currently being incorporated into river restoration decisions, and what knowledge may be useful to guide proactive restoration for a changing climate.

Surveys of natural resource managers have been used to elucidate gaps between scientific research production and management needs, sometimes termed the “knowing-doing gap” (Knight et al. 2008). This gap may manifest in the production of research not

relevant to practitioners, practitioners not using research because of limited access to scientific articles or data, or mismatches in scale or approach between research and management efforts (Fazey et al. 2014). Surveys have proven to be useful tools with which to gather information on the state of a resource management or restoration practice (Matzek et al. 2014) and to inform the development of research programs (Enquist et al. 2017). For example, surveys conducted among invasive plant managers and river restoration practitioners suggest that personal observations in the field, rather than scientific research products, substantially inform the design and implementation of a management strategy or restoration project (Bernhardt et al. 2007, Matzek et al. 2014). Direct input from practitioners may be critical to advance the science to meet the practice of restoration, particularly through the lens of climate resilience (Fuller et al. 2019, Grantham et al. 2019). For research to better support practitioners, and for restoration decisions to be transparent and grounded in well-supported science, a translational approach may be taken that calls for early and iterative collaboration between scientists and stakeholders (Enquist et al. 2017). Deliberately engaging with the intended end-users of scientific information before the information is produced allows both scientists and practitioners to direct research products toward a final form that is actionable and relevant (Hallett et al. 2017).

In this study, we focus on a specific river restoration approach, dam removal, that is globally increasing in prevalence (Schiermeier 2018, American Rivers 2022) attributable to both practical safety and cost reasons, as well as environmental motives (O’Connor et al. 2015, Magilligan et al. 2016). Small dam removal

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projects (≤ 15 m tall) conducted in low order streams (1st to 4th) represent the majority of removals in the U.S. (Bellmore et al. 2017, Foley et al. 2017, Habel et al. 2020) because many of these structures are no longer used for their original purpose (e.g., powering mills) and have limited utility for power generation or flood control (Magilligan et al. 2016). Evidence of the social-ecological consequences of this aging infrastructure is building (e.g., Pohl 2002, Bellmore et al. 2017, Vahedifard et al. 2021), and river restoration practitioners have championed small dam removal as a tool to improve ecological integrity of rivers and ameliorate negative impacts to public safety, water quality and quantity, and species and habitats (American Rivers 2002).

Small dams and climate change both interact with human safety and stream ecosystems (water quality and quantity, physical habitat, and species; Table 1). Small dams may have individual effects that are additive to climate change effects (e.g., cumulative increases in stream temperature), or may interact with climate change, leading to synergistic impacts. For example, reduced flow rates due to small dams may compound with climate-induced warming, resulting in lower dissolved oxygen (Table 1). As such, dam removal may increase the ecological resilience of stream ecosystems in the face of climate change by facilitating faster recovery of biota from climate-induced disturbances (Gunderson 2000), increasing access to thermal and flow refugia, and reducing overall temperatures (Seavy et al. 2009, Ho et al. 2017; Table 1). Similarly, reducing safety and flooding risks to local communities and increasing economic benefits through removal projects may also increase community resilience to climate change (Vahedifard et al. 2021; Table 1). With the average age of U.S. dams over 50 years old (ASCE 2021) and new funding sources designated for dam safety and removal projects (e.g., Infrastructure Investment and Jobs Act, 2021), the pace of dam removals is expected to increase in the coming years (Grabowski et al. 2018). This expected increase in dam removals presents an opportunity for practitioners, researchers, and communities to manage and restore river systems for ecological and community benefits that persist into an uncertain future.

The expanding prevalence of dam removal, coupled with a growing understanding of climate change impacts on rivers (Perry et al. 2015, Wu and Johnson 2019), has also led to changes in the political context for dam removal projects. There has been a recent boom in U.S. environmental legislation requiring consideration of climate change in development and infrastructure projects, which often include dam removals (e.g., Massachusetts Executive Order No. 569, 2016), and dam removal is considered a key component of climate resilience (e.g., U.S. Twenty-First Century Dams Act S. 2356, 2021). Globally, there are calls to protect rivers as corridors in a changing climate and to remove dams for biodiversity, habitat, and natural infrastructure restoration (e.g., UNFCCC 2021). Although climate resilience is an oft-cited benefit of dam removals in these and other public communications (e.g., American Rivers 2022), it currently remains unclear if and how practitioners integrate climate change information into dam removal decisions. Here, we focus on two types of climate change information as it relates to river restoration: (1) empirical and modeled data related to baseline or future climatic conditions (e.g., distribution of thermally sensitive taxa, projected annual maximum discharge; and (2) quantitative or qualitative links between restoration actions and resilience

metrics (e.g., reduced likelihood of flooding stemming from dam removal; Table 1). Application of these two types of information in restoration decisions may range from cursory mentions of warming waters in permit applications to the use of streamflow projections in engineering design plans (Perry et al. 2015). Thorough and deliberate incorporation of climate change research into dam removal decisions may lead to increased likelihood of project success and longevity and may help prepare communities and rivers for potential impacts of climate change.

Through a survey of dam removal practitioners in the northeastern U.S., we aimed to better understand the links between dam removal science and practice in a changing climate. Specifically, our objectives were to (1) understand current practices of dam removals and factors driving decisions; (2) understand if and how climate change information is incorporated into these decisions; and (3) identify barriers to and expand on opportunities for knowledge exchange among practitioners and researchers. Although this study focuses on links between practitioners and researchers, these groups represent only a small subset of a network of players in the dam removal world, including affected communities, businesses, policy makers, and regulators. Facilitating knowledge exchange throughout this network may help move the practice of dam removal into the future and can serve as further guidance for the incorporation of climate change information into other restoration decisions.

METHODS

Survey sampling frame

We surveyed dam removal practitioners working in the 14 states served by the Northeast Climate Adaptation Science Center (NE CASC), which includes: Connecticut (CT), Delaware (DE), Kentucky (KY), Maine (ME), Maryland (MD), the Commonwealth of Massachusetts (MA), New Hampshire (NH), New Jersey (NJ), New York (NY), Pennsylvania (PA), Rhode Island (RI), the Commonwealth of Virginia (VA), Vermont (VT), and West Virginia (WV; Fig. 1). Collectively, there have been around 800 dam removals across these states from 1916 through 2022, with the most in PA (355) and the least in DE (3; American Rivers 2022). Starting with American Rivers dam removal project lists for 2018 to 2020, we generated a list of organizations that participate in dam removal projects, including local, state, tribal, and federal agencies, non-profit/non-governmental organizations (NGOs), and private companies. Within organizational websites, we searched for individuals whose job title or description relate to dam removal projects, suggesting involvement in dam removal decision making. We obtained contact information for potential participants from publicly available lists of project contacts and organizational websites, for a total survey population of 324 practitioners. This a priori development of a survey frame allowed for assessments of response rates and non-response bias (Bose 2001).

Survey development and distribution

We developed a survey using a web-based software (Qualtrics 2018, Provo, UT), with questions broadly focused on three topics: (1) current dam removal practices, (2) how climate change information is incorporated into dam removals, and (3) how knowledge is gained and shared. The survey included a mix of Likert scale, check-all-that-apply, ranked-response questions, and

Table 1. Examples of additive (+) and interactive (×) effects of climate change and small dams on social-ecological factors.

Category	Factors	Climate Change	Effect	Small Dams	Sources
Safety	Flooding	Increase in extreme precipitation events; altered timing of high flows	×	Aging structures may be at high risk of dam failure; impoundments may exacerbate flooding during high flows	Death et al. 2015, Fluixá-Sanmartín et al. 2018, Tabari 2020
	Harmful algal blooms	Extended dry periods and warming waters increase probability of cyanobacterial blooms	+	Reduced water velocity in impoundments and increase of nutrients may facilitate cyanobacterial blooms	Chapra et al. 2017, Ho and Michalak 2020
Water Quality	Stream temperature	Increase in air temperature and reduced cloud cover can increase stream temperature	+	Increase surface area exposed to solar radiation can increase stream temperature	Zaidel et al. 2021, Botero-Acosta et al. 2022
	Dissolved oxygen (DO)	Increase in stream temperature can decrease DO	×	Warming temperatures and reduced flow rate can decrease DO in impoundments	Chapra et al. 2021, Jane et al. 2021, Abbott et al. 2022
Water Quantity	Flow extremes	Increase in air temperature and reduced cloud cover; increase in extreme precipitation events	×	Increased surface area may lead to increased evaporation, resulting in net water loss from a system; downstream channel scour and entrenchment during high flows	Csiki and Rhoads 2010, Morden et al. 2022, Parmesan et al. 2022
Species & Habitats	Connectivity	More frequent/extreme periods of drought may lead to drying and loss of floodplain and longitudinal connectivity	+	Loss of connectivity due to physical barrier of dam, as well as habitat barrier created by impoundment	Doyle et al. 2005, Ward et al. 2020
	Migratory fish	Increase in physical stress due to warming waters at sea and in freshwater; altered spawn timing with changes in temperature and flow cues	×	Reduced access to spawning grounds; changes in spawning habitat	Mattocks et al. 2017, Tamario et al. 2019
	Freshwater fish	Increase in physical stress due to warming waters and lower DO; northward or elevational range shifts	×	Reduction in available habitat and/or appropriate water quality to support sensitive non-migratory species; dispersal limited; reduced genetic variability upstream may decrease survival and fecundity	Barbarossa et al. 2021, Donadi et al. 2021
	Invasive species	Range expansions of invasives expected, and warming may alter the rate of spread and impacts associated with aquatic invasives	×	Impoundments may create conditions favoring non-native species; conversely, dam removal may facilitate invasive species dispersal	Rahel and Olden 2008, Holcomb et al. 2016, Steel et al. 2019
	Biodiversity	Decreased water quality (e.g., increased stream temperature, reduced DO, release of contaminants) may impact biodiversity through reduction of sensitive species	+	Reduced biodiversity upstream of small dams due to dispersal and habitat limitations; reduced biodiversity downstream due to thermal or habitat alteration	Davies 2010, Fencel et al. 2017, Tickner et al. 2020

open-ended questions, with the sequences of response options randomized to reduce effects of order on responses (see Appendix 1). Questions were pre-tested with a subset of practitioners involved in dam removal via the think-aloud approach, and response options were assessed for completeness during this process (Ryan et al. 2012).

The online survey was distributed via email in November 2021 and concluded in January 2022. Two reminder emails were sent in December and January. The total response rate of completed surveys was 30.9% (n = 105). Returned surveys were considered complete if participants answered at least 70% of questions. Only survey respondents who self-reported as participating in dam removal project planning, defined as “anything ranging from giving input on design or implementation, or deciding where to focus restoration efforts, what techniques to use, how to allocate budget money, etc.,” were included in analyses (n = 100). No significant difference was found between the distribution of organization affiliation (e.g., NGO, state government, etc.) of those who were sent the survey and those who responded ($\chi^2 = 0.24$, df = 5, p = 0.999), suggesting responses are representative of a range of dam removal practitioner affiliations (e.g., NGO or state government; Bose 2001). No personally identifiable information was recorded, and responses were aggregated to further ensure anonymity.

Data analyses

For each question, sample size varied because the number of responses to individual questions varied, and some questions were presented to a subset of respondents based on previous answers.

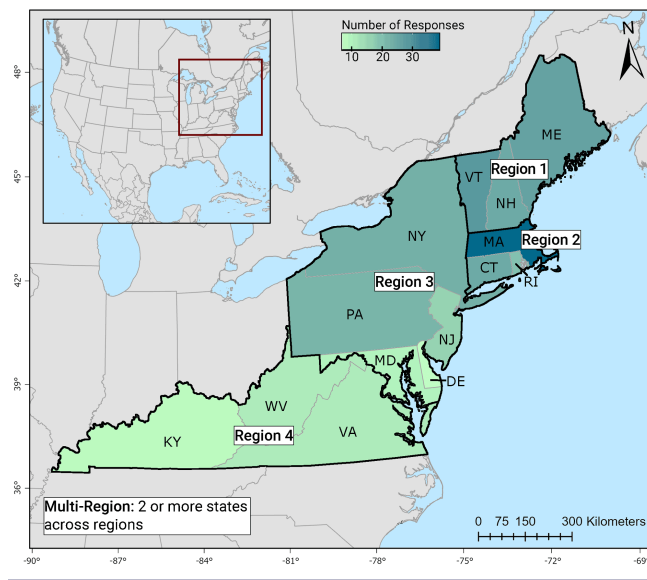
We therefore report the percentage of responses relative to the sample size for each question. Survey questions answered on a Likert scale or ranked scale were assigned a value of 1 to N number of response options and analyzed for comparisons between organizations/employers and regions using a Kruskal-Wallis Rank Sum Test (H), using a significance level ($\alpha = 0.05$) and controlling for the false discovery rate using the Benjamini-Hochberg adjustment. Respondents could select multiple states in which they conducted dam removal work; thus, we binned respondents into the following 5 regions and compared select responses across these regions: Region 1 (ME, NH, VT), Region 2 (CT, MA, RI), Region 3 (NY, NJ, PA, MD, DE), Region 4 (VA, KY, WV), and Multi-Region (2 or more states across regions).

RESULTS

Respondent demographics

Survey responses from 100 dam removal practitioners were included in these analyses. While the majority of respondents worked within the northeastern U.S. (Pennsylvania and north), all states within the NE CASC footprint were represented (Fig. 1). Most practitioners worked solely in 1 state (n = 70), 12 worked in 2–5 states, 14 worked in 6–10 states, and 4 worked across all 14 states included in this study. Respondents were well-distributed across regions, with 24 from Region 1 (ME, NH, VT), 21 from Region 2 (CT, MA, RI), 18 from Region 3 (NY, NJ, PA, MD, DE), 13 from Region 4 (VA, KY, WV), and 24 working across multiple regions. Most practitioners (38%) identified their primary role as project manager/coordinator, followed by program director (22%), biologist (13%), engineer (11%),

Fig. 1. States in the northeastern United States included in this study, which encompasses the Northeast Climate Adaptation Science Center (NE CASC) footprint. Color indicates where survey respondents conduct dam removal work. Participants could select more than one state in which they conduct dam removal work. Regions are defined by the heavy black lines. States are defined by the light grey lines. Regions and state abbreviations are as follows: Region 1 (Maine = ME, New Hampshire = NH, Vermont = VT), Region 2 (Connecticut = CT, the Commonwealth of Massachusetts = MA, Rhode Island = RI), Region 3 (New York = NY, New Jersey = NJ, Pennsylvania = PA, Maryland = MD, Delaware = DE), Region 4 (the Commonwealth of Virginia = VA, Kentucky = KY, West Virginia = WV), and Multi-Region (2 or more states across regions).

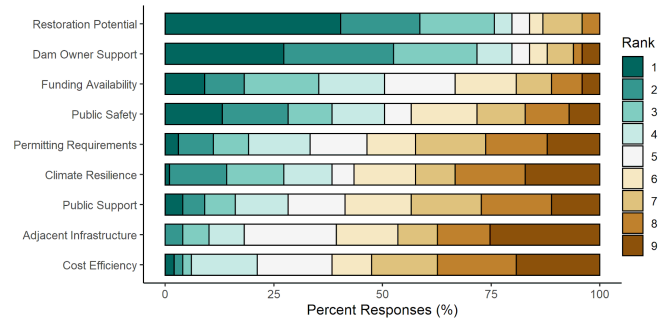


community advocate (8%), research scientist (4%), and other (4%), which included field assistants, funders, and regulators. Respondent employers ranged from NGOs (35%), state governments (29%), the federal government (12%), private/for-profit organizations (11%), tribal governments (5%), local government/municipalities (5%), and other (3%), which included universities and unidentified organizations. These practitioners had a wide range of experience with dam removals and were involved in anywhere from 1 to more than 100 dam removal projects over the course of their careers (mean = 17 ± 22.5 ; $n = 70$). The majority of respondents (68%) held a graduate or professional degree.

Factors influencing dam removal decisions

To understand current environmental stressors that dam removal practitioners are concerned with, participants were asked the extent to which stressors impacted organizational goals. The majority of respondents (55%) reported that habitat fragmentation impacts their organization's goals "to a great extent," followed by invasive species (33%), contaminants (30%), and warming temperature (29%). To understand what factors are important for consideration in dam removal projects, respondents

Fig. 2. Practitioners ranked the importance of various factors during the dam removal planning process. Factors were ranked in order of most (1) to least (9) important and are shown in descending order of average ranked importance. Data were collected from question 6 of the practitioner survey described in this paper.



were asked to rank factors by importance to dam removal project planning. Ecological restoration potential, dam owner support, and public safety were highly ranked across respondents (Fig. 2). Respondents from private/for-profit organizations ranked ecological restoration potential as less important than those affiliated with NGOs, federal, tribal, and local governments ($H(6) = 25.69$, $p = 0.002$), and ranked climate resilience as less important than did those affiliated with NGOs, and tribal and local governments ($H(6) = 22.13$, $p = 0.010$). Rankings did not significantly differ by region.

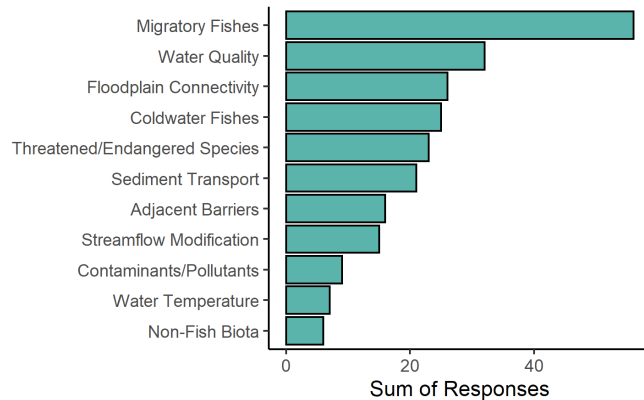
Important ecological factors in dam removal decisions

If ecological restoration potential was ranked within the top 5 important factors for dam removal decisions (83% of respondents), respondents were prompted to select the 3 most important ecological factors in their dam removal decisions. Migratory fishes ($n = 56$) and water quality ($n = 32$) were selected the most, and non-fish biota ($n = 6$) and water temperature ($n = 7$) were selected the least (Fig. 3). There were both affiliation and regional differences in the selection of important ecological factors. Specifically, respondents affiliated with local governments selected water quality as important more often than those with state or federal governments or private organizations ($H(6) = 20.55$, $p = 0.024$). Threatened and endangered species ($H(4) = 15.80$, $p = 0.018$) and non-fish biota ($H(4) = 16.75$, $p = 0.018$) were more often selected as important in Region 4 (VA, KY, WV) than in other regions. Additionally, coldwater fish was most often selected as an important factor driving dam removal decisions in Region 1 (ME, NH, VT), despite the indicated low importance of water temperature for dam removal decisions.

Links between climate change and river restoration

Sixty-one percent of dam removal practitioners stated that they personally were "extremely concerned" about the influence of climate change on rivers and their ecosystem services, and 27% stated they were "moderately concerned," which was similar to the perceived concern of their organizations (60% and 24%, respectively). Only one individual stated they were "not at all concerned" about climate change impacts on rivers. Climate concern did not differ between employers or regions. To better

Fig. 3. Practitioners selected the 3 most important ecological factors (out of 11) in their dam removal decisions. Ecological factors are ordered by total number of responses. Other factors identified through fill-in-the-blank included all fishes, non-migratory fishes, freshwater mussels, legacy sediment impairment, overall connectivity, upstream habitat quality, and wetland restoration potential. Data were collected from question 6a of the practitioner survey described in this paper.



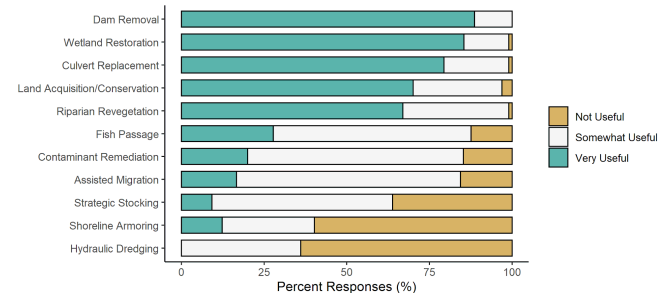
understand these concerns and the expected impacts of climate change, respondents were asked the extent to which certain ecosystem services provided by rivers would be impacted by climate change. Most respondents reported that flood regulation (88%), subsistence fisheries (67%), and recreational fisheries (64%) would be impacted to a “great” or “very great” extent.

Of 11 potential restoration or management actions, the large majority of respondents indicated that dam removal (89%), wetland restoration (85%), and culvert replacement (79%) would be very useful for climate adaptation of aquatic ecosystems, while most respondents felt that shoreline armoring (60%) and hydraulic dredging (64%) would not be as useful (Fig. 4). Other useful actions reported included sediment removal, building community awareness, and increasing floodplain connectivity. When asked how important dam removal is for helping rivers and riparian systems adapt to climate change, respondents reported that removal is extremely (69%) or very (22%) important for ecological resilience. For helping communities and people adapt to climate change, dam removal was indicated by 46% of respondents as extremely important and 38% of respondents as very important. Respondents from state governments, NGOs, and private organizations indicated dam removal is slightly more important for helping rivers adapt to climate change, while respondents from the federal government indicated dam removal may be more important for communities.

Gaps between climate science and the practice of dam removal

Despite the majority of respondents indicating dam removal as important for ecological and community resilience to climate change (91% and 84%, respectively), climate change information is not always incorporated into dam removal decisions, with 21% of respondents reporting that climate change information is rarely or never incorporated into dam removal decisions within their organization. This pattern did not vary based on respondent

Fig. 4. Practitioners indicated whether they felt certain restoration and management actions would be useful or not useful for climate adaptation of aquatic ecosystems. Data were collected from question 9 of the practitioner survey described in this paper.



employer ($H(6) = 11.33$, $p = 0.790$), but did vary significantly by region ($H(4) = 18.15$, $p = 0.001$), where climate change is more often considered in Region 2 (CT, MA, RI) and by those who work in multiple regions compared to the other regions. A range of answers emerged when asked why climate change is not incorporated in decision making; open-ended responses indicated that there is not a clear connection between climate change and dam removal, that dam removal is beneficial regardless of climate impacts, or that other issues (e.g., fish passage, water quality) are more pressing.

Knowledge exchange: current trends and future potential

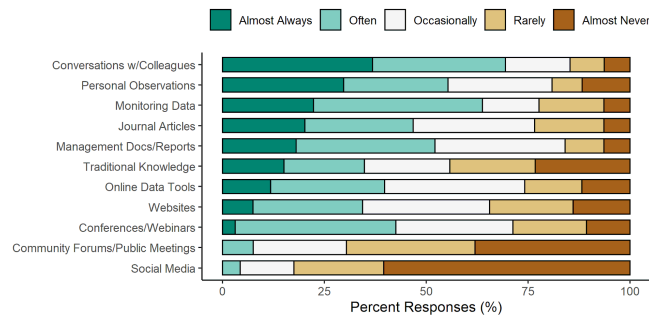
The majority of practitioners almost always or often obtained climate change information from conversations with colleagues (70%), personal observations (55%), or monitoring data (64%; Fig. 5). Public meetings and social media were almost never or rarely used by most (> 70%) respondents to obtain climate change information (Fig. 5). Peer-reviewed journal articles and online data tools were used always or often by less than 50% of the respondents, and respondents said that constraints on time (searching for, reading, or synthesizing data), access to journal articles, and a lack or perceived lack of useful or relevant research or data limited their use of these resources (Fig. 5). Respondents selected how they have communicated dam removal project outcomes in the past 5 years, and informal sharing with colleagues, community forums and public meetings, and contributing to internal reports or management documents were the most common forms of communication. Looking forward, respondents identified community vulnerability to climate change, flood forecasting, and climate impacts on stream temperature as very useful avenues for future research, while strategic stocking and assisted migration were indicated by most as not useful (Fig 6).

DISCUSSION

Trends in current dam removal practices

As others have found, dam removal decisions in the eastern U.S. are often driven by logistical reasons—including dam owner support, cost, and public safety—in addition to ecological restoration potential (Chaffin and Gosnell 2017, Magilligan et al. 2017, Grabowski et al. 2018), which may overshadow climate

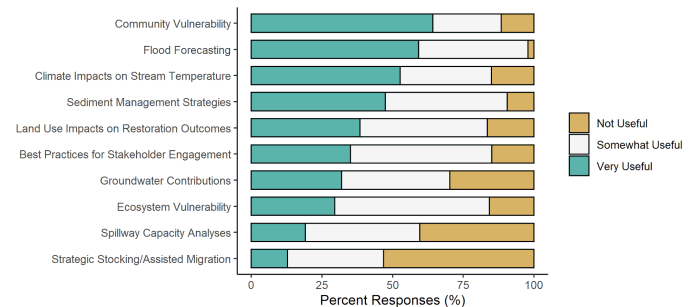
Fig. 5. Respondents indicated how often they consulted 11 possible sources for climate change data during the dam removal process. Data were collected from question 11 of the practitioner survey described in this paper.



change considerations. Broadly, migratory fish and water quality were considered important ecological factors driving dam removal decisions. Improved passage for migratory fish species—including river herring (*Alosa pseudoharengus* and *Alosa aestivalis*), American shad (*Alosa sapidissima*), and Atlantic salmon (*Salmo salar*)—is one of the most salient ecological benefits of dam removal. Migratory fishes are also a major avenue for funding, which may reduce the need for practitioners to consider climate change to be compliant with funding requirements. Additionally, improved water quality is an often-cited ecological driver of dam removals, although which parameters are expected to improve (e.g., dissolved oxygen, total suspended solids, contaminants, etc.) may vary by site. These priorities suggest that dam removal projects are often the result of immediate needs and opportunities, rather than deliberate and proactive preparation for climate change impacts (Hobbs et al. 2011, Tonkin et al. 2019).

Within these broad trends, we also determined regional and organizational differences among important ecological drivers of dam removals. For example, Region 4 (KY, WV, VA) contains a relatively high biodiversity of fish and non-fish biota, such as freshwater mussels, as compared to other regions in this study (Jenkins et al. 2015, Elkins et al. 2019), whereas Region 1 (ME, NH, VT) contains a high density of coldwater streams (Detenbeck et al. 2016). Regional stakeholders (e.g., Conservation Fisheries, Inc., Trout Unlimited, Eastern Brook Trout Joint Venture) are often invested in the restoration of ecologically, culturally, and recreationally important species, which may drive priorities and funding opportunities in these regions. Differences in agency scopes may also influence how climate change information is considered in dam removal decisions. Municipalities, which are often focused on individual dam removal projects, may rely on high-resolution, local-scale data (e.g., continuous temperature or streamflow monitoring, predictive modeling) for shorter-term impact assessments associated with a project. In contrast, state or federal agencies overseeing broad regions may employ large-scale spatial data (e.g., fish population assessments, global climate models) to evaluate long-term ecosystem dynamics and inform strategic plans for enhancing river resilience to climate change,

Fig. 6. Ten useful research topics from a practitioner's perspective identified through question 17 of the practitioner survey described in this paper.



particularly concerning migratory fish populations across multiple dams and watersheds. Results suggests that the perceived benefits of dam removals vary depending on the intersection of regional and agency priority ecosystems and taxa, and that dam removal as a restoration tool may be flexibly applied to achieve different ecological objectives (Poff and Hart 2002), including resilience to climate change impacts.

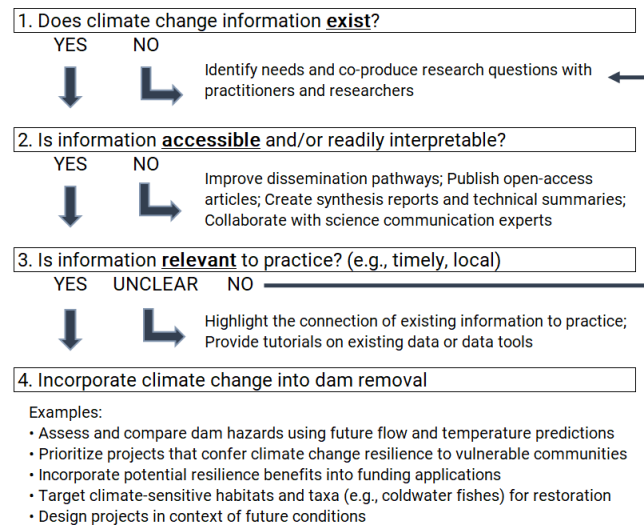
Barriers and opportunities for incorporation of climate change into dam removal decisions

Our survey results indicate that dam removal practitioners in the NE CASC region are generally concerned about climate change-related impacts to rivers and consider dam removal an important tool for helping both community and rivers adapt to a changing climate. Despite indicating dam removal as a useful tool for climate resilience, a recurring theme among responses was the lack of a concrete connection between the action of dam removal and climate change resilience. One respondent stated: “I feel like there can be a disconnect between verifying that climate change is in fact occurring locally and watershed-based planning on best management practices to improve climate resiliency/adaptability.”

Conversely, other respondents who did not explicitly incorporate climate information stated that the connections between climate and dam removals are already understood; that is, the benefits for climate resilience are included in dam removal decisions via the expected reduction of thermal impacts and increased connectivity to climate refugia. Although some respondents indicated climate change was a lower priority when ranked among other factors (e.g., safety), it may be better viewed as a supplement to existing priorities, working in conjunction to highlight more benefits of a project and tap into a broader array of resources.

These varying perspectives suggest that barriers to knowledge exchange between research and practice may be distinguished into three main themes, as proposed by the authors of this paper: existence, accessibility, and relevance. By engaging with these themes through the questions below, researchers and practitioners alike may begin to identify opportunities to better incorporate climate change information into dam removal decisions, leading to forward-thinking projects and more resilient social-ecological systems (Fig. 7).

Fig. 7. Series of questions that may help guide practitioners and researchers to identify where opportunities are available for improvements to knowledge exchange on the topic of climate change and dam removal, with broad examples for improvement.



1. Does the information needed by practitioners exist?

If the information needed by practitioners does not exist, research and data that support practitioner decisions may be identified through a translational ecology approach (Hallett et al. 2017), whereby researchers and practitioners develop relevant and useful research questions and products through relationship building and two-way communication (Meadow et al. 2015). In this study, dam removal practitioners indicated that research focusing on socioeconomic resilience to climate change, including community vulnerability analyses and flood forecasting, could be the most useful research avenues to pursue in the future. Practitioners also indicated that research explicating the links between dam removal and different facets of climate adaptation and resilience (e.g., reducing water temperatures, reducing flood risk, increasing persistence of coldwater taxa) could be useful. To facilitate actionable science production, trained research scientists may be hired and embedded within resource management agencies to serve as in-house scientists, in addition to trained resource managers. Formal links between decision makers and scientists at academic research institutions, like the U.S. Geological Survey's Cooperative Research Units and Climate Adaptation Science Centers and university extension programs, may also facilitate the production of actionable science, as well as contribute to scientific training programs for conservation and restoration professionals (Cook et al. 2013).

2. Is the information readily accessible?

Participants in this survey and other surveys of natural resource managers have indicated that paywalled research, or research that requires payment for access, is often inaccessible to them, reducing their reliance on primary literature (Bernhardt et al. 2007, Fazey et al. 2014, Cvitanovic et al. 2015, Beaury et al. 2020). Although

policies are changing toward reducing paywalls for publicly funded research (The White House, Office of Science and Technology Policy 2022), a first step for researchers seeking to produce actionable science could be to target open-access journals for publication of research findings. However, some practitioners indicated that a lack of time or expertise to both search for and interpret research publications limited their access to useful information. For example, one respondent stated, “[I am] not provided time in my work to do much of this type of research/review.” Another described how peer-reviewed publications are not typically written with practitioners in mind: “As a non-scientist, I don’t feel qualified to choose articles to base decisions on. If I had a good source of such, that would be different.”

These responses suggests that although open access publications may be necessary to increase access to climate change information, they may not be sufficient, and additional formats of dissemination may also be important to consider. Public data repositories, synthesis papers, one-page research summaries, or online articles may be useful avenues for increased accessibility of climate and dam removal knowledge. Beaury et al. (2020) found that research findings would be most accessible to practitioners through presentations at practitioner conferences, summarized research documents, and co-production of science. Respondents in this survey echoed these findings, with one stating: “Technical manuals and information provided at conferences are valuable since they distill information from articles into a more immediately useful format, and it is important that my work be implemented quickly and efficiently.”

Yocum et al. (2022) also suggest that researchers focus on producing “shovel-ready” data sets for immediate incorporation into existing conservation and restoration planning tools. In many cases, it may also be useful for researchers to relinquish the role of sole science communicators and instead partner with science translation experts to create materials that move evidence-based research into practice and are more accessible to end-users. This type of partnership has been prevalent in the public health sphere (e.g., Smith and Wilkins 2018), and is beginning to gain traction in research institutions (e.g., The Ohio State University Knowledge Exchange: <https://kx.osu.edu/>). Communication may also be enhanced through the involvement of a boundary organization that spans between research and management (e.g., The Nature Conservancy, American Rivers). Similarly, trained science communicators embedded within universities may help bridge communication gaps between researchers and end-users.

3. Is the information relevant to practitioners?

Existing research on the production of actionable science suggests that research that is most relevant to practitioners is timely, local, and salient (Sarewitz and Pielke 2007, Hart and Calhoun 2010). State-level regulations and permitting processes can drive the scale and scope of dam removal programs, suggesting state-level research products and guidance documents may be most useful. For example, a dam removal project manager may be more likely to incorporate climate change information into the project if local or state-level stream temperature projections are readily available in a commonly used spatial resolution and format. If no such information exists, research questions may then be developed to address the identified information gaps. However, there may also

be cases where relevant information does exist, but the direct connection to practice is obscure. One respondent stated: “There may be a lot of research on climate change out there, but I don’t personally encounter a lot that directly relates to river restoration.”

Highlighting clear connections between expected impacts of climate change and dam removal—either through synthesizing and disseminating existing research (e.g., Table 1) or by developing new research questions—may help practitioners target dams with greater climate resilience benefits, apply for a broader range of funding opportunities, and communicate more transparently with the public.

Potential benefits of improved knowledge exchange

Dam owner willingness, public safety, cost, and ecological restoration potential remain strong motivators for dam removal (Pohl 2002, Grabowski et al. 2018, Sneddon et al. 2022). However, explicitly incorporating climate change information (e.g., data, projections, resilience metrics) into dam removal planning and implementation may have several benefits. From a practical perspective, clearer evidence demonstrating climate resilience benefits of dam removal may unlock previously inaccessible funding opportunities for projects, as funders consider climate change resilience as a key issue in the upcoming years. Additionally, safety risks that are assessed using historical data may not be reflective of future conditions influenced by a changing climate (Tullos et al. 2021, Buhl and Markolf 2023), putting into question the true number of dams that may be hazardous to public safety and infrastructure. The incorporation of downscaled climate model projections into hydrologic models may be critical for accurate assessments of dam risks and impacts (Fluixá-Sanmartín et al. 2018). Projections of future stream temperature may also be useful for practitioners to identify streams that may benefit the most from dam removal by providing access to coldwater or flow refugia where climate-vulnerable taxa (e.g., coldwater or migratory species) may persist (Ebersole et al. 2020). Locally relevant data may help inform greater watershed-based management of both individual species and sensitive ecosystems in the context of climate change, and potentially improve community resilience by reducing flooding or safety risks. These examples, among others, highlight ways in which dam removal can better serve as a proactive strategy to enhance ecological and community resilience to climate change. Identifying areas for further study and improvement may be useful before, rather than after mandates are implemented.

CONCLUSIONS

Call to researchers

These survey results suggest that more accessible, interpretable, and relevant research that explicitly demonstrates links between climate change and small dam impacts, and that local to regional scale studies could be most useful to practitioners. Additionally, research that focuses on community vulnerability to climate and dam impacts could help inform decision making. Restoration research emphasis is expanding from a physical science domain to a transdisciplinary arena, which incorporates social science (Perring et al. 2015, Knapp et al. 2019), and this trend is reflected in our survey results as well. Finally, research questions developed in collaboration with local and regional practitioners and

communities may prove to be fruitful. Although peer-review publications are important to progress the science of dam removals, research products may also be provided in readily available forms, such as technical papers, one-page documents, or publications in open access journals. Ultimately, the onus is on researchers to turn “data” and “information” into knowledge that can be readily shared with and used by practitioners.

Call to practitioners

Our survey results point to the predominant use of personal and observational knowledge in dam removal decisions, and primary exchange of information through conversations with colleagues. Because this knowledge is held by individuals rather than institutions, and dependent on the capacity, knowledge, and personalities of state or organizational actors (Sneddon et al. 2022), these institutions may be vulnerable to loss of critical knowledge because of retirements or job transitions. Formalizing this knowledge into guidance documents, publicly available reports, or peer-reviewed publications may help progress the science, as well as the practice, of dam removal, and insure against knowledge loss. Additionally, although community vulnerability was indicated as a very useful avenue of future research, practitioners also indicated that information was rarely obtained from public forums, suggesting an asymmetry in knowledge exchange between the practitioners and the public. Formally incorporating local and traditional ecological knowledge into dam removal decisions may be necessary to fully realize the goal of understanding community vulnerability and resilience (Fazey et al. 2014, Szalkiewicz et al. 2020).

Future directions

Dam removals represent one restoration decision among many options, and the results from this survey may be used as a starting point for incorporating climate change into other pressing natural resource management decisions. Here, we present a framework for identifying barriers and opportunities for incorporating climate change into conservation and restoration decisions that emphasizes the co-production of knowledge and collaboration between researchers and practitioners. This framework may be useful as more agencies and organizations recommend or mandate that climate change be considered in conservation, management, and infrastructure decisions.

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Data Availability:

The data that support the findings of this study are openly available in Science Base at <https://doi.org/10.21429/s2pe-ww46>.

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Appendix 1

Supplemental information for *Incorporating climate change into restoration decisions: Perspectives from dam removal practitioners*

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Appendix 1

*Survey distributed over email using an online survey software (Qualtrics 2018, Provo, UT).

Consent

You are being invited to participate in a study being conducted by researchers from the University of Massachusetts Amherst. You were selected to participate in this study because of your potential involvement in river restoration and dam removal projects. The purpose of this study is to understand how climate change is currently integrated into dam removal projects and to understand gaps between scientific data production and needs of practitioners. If you agree to take part in this study, you will be asked to complete an online survey. This survey will ask about your organization's current dam removal practices, and your personal perspectives on dam removal, river restoration, and climate change. It will take approximately 15 minutes to complete.

You may not directly benefit from this research; however, we hope that your participation in the study may help to guide future research to best meet the needs of restoration practitioners. Your answers in this study will remain confidential, and we will minimize any risks to breach of confidentiality by not collecting individually identifiable information and by aggregating responses prior to analyses.

If you have questions about this project, you may contact the researchers at _____. This research was reviewed by IRB and determined to be exempt under 45 CFR 46.104. If you have any questions concerning your rights as a research subject, you may contact the University of Massachusetts Amherst Human Research Protection Office (HRPO) at _____.

Your participation in this study is completely voluntary and you can withdraw at any time. You are free to skip any question you choose.

By clicking "I agree" below you are indicating that you are at least 18 years old, have read this consent form and agree to participate in this research study.

Please print a copy of this page for your records.

- I agree
- I do not agree

Please complete this survey from your perspective as an individual (i.e., not the perspective of your employer), unless otherwise specified.

Q1) To what extent is dam removal project planning, monitoring, management, or implementation part of your current or past work?

- To no extent
- To a little extent
- To some extent
- To a great extent
- To a very great extent

Q2) What best describes your current role? Select all that apply.

- Program Director
- Project Manager/Coordinator
- Community Advocate

- Biologist
- Engineer
- Field Assistant
- Research Scientist
- Other

Q3) What best describes your employer?

- Local government
- State government
- Federal government
- Tribal government
- Non-profit organization
- Private/for-profit organization
- Other _____

Q4) In which of the following state(s) do you primarily work? Select all that apply.

- Maine, Massachusetts, New Hampshire, Vermont, Rhode Island, Connecticut, New Jersey, New York, Pennsylvania, Delaware, Maryland, Virginia, West Virginia, Kentucky

Q5) To what extent, if any, do you feel the following environmental stressors currently impact your organization's mission or goals?

	To no extent	To a little extent	To some extent	To a great extent	To a very great extent
Warming temperatures	•	•	•	•	•
Habitat fragmentation	•	•	•	•	•
Channelization	•	•	•	•	•
Invasive species	•	•	•	•	•
Extreme precipitation	•	•	•	•	•
Land use change	•	•	•	•	•
Contaminants	•	•	•	•	•
Sediment issues	•	•	•	•	•
Other: _____	•	•	•	•	•

Q6) When your organization becomes involved in a dam removal project, how important or not important are the following factors during the removal process? Drag to rank factors in order of most (1) to least (9) important.

- Funding availability
- Public support
- Cost efficiency
- Ecological restoration potential
- Public health & safety
- Adjacent infrastructure
- Climate resilience
- Permitting/regulatory requirements
- Dam owner support

Q6a) You indicated that the ecological restoration potential was an important factor in the dam removal process. What are the 3 most important ecological factors in your dam removal?

- Coldwater fishes
- Migratory fishes
- Non-fish biota
- Threatened or endangered species
- Floodplain connectivity
- Water temperature
- Streamflow modification
- Sediment transport
- Water quality
- Contaminants and/or pollutants
- Adjacent or proximate barriers
- Other _____

Q7) How concerned or not concerned are you and your organization about the influence of climate change on rivers and their ecosystem services?

	Not at all concerned	A little concerned	Somewhat concerned	Very concerned	Extremely concerned
You	•	•	•	•	•
Your organization	•	•	•	•	•

Q8) To what extent, if any, do you feel the following ecosystem services provided by rivers will be impacted by climate change?

	To no extent	To a little extent	To some extent	To a great extent	To a very great extent
Fisheries (recreational)	•	•	•	•	•
Fisheries (subsistence)	•	•	•	•	•
Water for consumptive use (drinking, domestic, agriculture)	•	•	•	•	•
Water for non-consumptive use (hydropower, transportation)	•	•	•	•	•
Flood regulation	•	•	•	•	•
Nutrient cycling	•	•	•	•	•
Recreation (non-fishing)	•	•	•	•	•
Cultural relationships with nature	•	•	•	•	•
Other: _____	•	•	•	•	•

Q8a) On what timescale do you think these ecosystem services (above) will be impacted by climate change to a great extent? Slide to select a time range.

- 0-5 years, 5-10 years, 10-20 years, 20-50 years, 50+ years, N/A

Q9) Which of the following actions do you feel are useful for climate adaptation of aquatic ecosystems?

Drag actions to group and rank by usefulness.

- Wetland restoration
- Dam removal
- Riparian revegetation
- Strategic stocking
- Assisted migration of species
- Culvert replacement
- Contaminant remediation
- Land acquisition and conservation
- Shoreline armoring
- Hydraulic dredging
- Fish passage installation

Q10) How often, if at all, is climate change currently incorporated into dam removal decision making at your organization?

- Never
- Rarely
- Sometimes
- Often
- Always

Q10a) If previous response = Never/Rarely: You mentioned your organization does not incorporate climate change in dam removal decisions. What do you believe is the primary reason for this?

Fill in blank _____

Q10b) If previous response = Sometimes/Often/Always. At what stage of the dam removal project is climate change science incorporated into decision-making? Select all that apply.

- Project scoping
- Project selection
- Fundraising/grant writing
- Coordination/partnership building
- Design/engineering
- Permitting/regulatory
- Construction (i.e., removal of structure)
- Restoration (i.e., post-removal actions)
- Monitoring

Q11) When obtaining scientific information on climate change impacts to river resources for use in the dam removal process, how often do you use the following sources?

	Almost Never	Rarely	Occasionally	Often	Almost Always
Websites	•	•	•	•	•
Social media	•	•	•	•	•

Management documents/technical reports	☐	☐	☐	☐	☐
Online interactive databases/tools	☐	☐	☐	☐	☐
Observations from personal experience	☐	☐	☐	☐	☐
Data obtained from monitoring	☐	☐	☐	☐	☐
Peer-reviewed journal articles	☐	☐	☐	☐	☐
Conversations with colleagues	☐	☐	☐	☐	☐
Conference or webinar attendance	☐	☐	☐	☐	☐
Other _____	☐	☐	☐	☐	☐

Q11a) If previous question response = Never/Rarely for journal articles. You mentioned that you do not or do not often consult peer-reviewed journal article for information on climate change impacts. Which of these reasons, if any, explain your answer? Check all that apply.

- ☐ I don't have time to search for articles
- ☐ Articles take too long to read
- ☐ The articles use too much jargon
- ☐ I don't have access to those kinds of articles
- ☐ I don't find them relevant or useful to my work
- ☐ Other _____

Q11b) If previous question response = Never/Rarely for Online interactive databases/tools. You mentioned that you do not or do not often consult online interactive databases/tools for information on climate change impacts. Which of these reasons, if any, explain your answer? Check all that apply.

- ☐ I don't have time to search for data
- ☐ I don't have time to synthesize data
- ☐ I don't know of online databases relevant to my work
- ☐ I don't find them useful to my work
- ☐ They are not user-friendly
- ☐ Other _____

Q12) To what extent do you agree or disagree with the following statement: "Scientific research agendas regarding climate change and rivers accurately represent the needs of managers and practitioners." Comments may be included below.

- ☐ Strongly disagree
- ☐ Disagree
- ☐ Neither agree nor disagree
- ☐ Agree
- ☐ Strongly agree

Q13) Which, if any, of the following metrics have you or your organization used to assess dam removal outcomes? Check all that apply.

- ☐ Biological metrics
- ☐ Vegetation metrics

- Water temperature
- Water quality
- Connectivity (e.g., length, complexity)
- Contaminant concentrations
- Stream flow metrics
- Hazard potential
- Recreational use metrics (e.g., # visitors)
- Aesthetics
- Flood mapping
- Public support/engagement
- Other _____

Q13a) How would you rank the usefulness of these metrics (above) in understanding dam removal effects on climate change resilience? Drag to rank the metrics in order of most (1) to least (11) useful.

Q14) How important, if at all, do you feel that dam removal is for helping streams and riparian systems adapt to climate change?

- Not at all important
- Slightly important
- Somewhat important
- Very Important
- Extremely important

Q15) How important, if at all, do you feel that dam removal is for helping communities and people adapt to climate change?

- Not at all important
- Slightly important
- Somewhat important
- Very Important
- Extremely important

Q16) To what degree do the following factors limit or not limit your success in incorporating climate change into dam removal projects?

	Does not limit success	Rarely limits success	Sometimes limits success	Often limits success	Always limits success
Organizational priorities	•	•	•	•	•
Obtaining funding	•	•	•	•	•
Personnel	•	•	•	•	•
Policies/regulations	•	•	•	•	•
Access to information	•	•	•	•	•
Availability of relevant information	•	•	•	•	•
Uncertainty in climate change impacts	•	•	•	•	•

Public perception of climate change	•	•	•	•	•
Other: _____	•	•	•	•	•

Q17) Which of the following research topics should be prioritized to best aid you in dam removal project planning or implementation? Group topics by priority level (low, moderate, high).

- Flood forecasting
- Climate impacts on stream temperature
- Sediment management strategies
- Best practices for stakeholder engagement
- Groundwater contribution to stream temperature
- Ecosystem vulnerability to invasive species
- Land use impacts on dam removal outcomes
- Community vulnerability to climate change
- Spillway capacity analyses
- Strategic stocking and assisted migration
- Other _____

Q18) Which of the following have you or your organization used to communicate project outcomes in the past 5 years? Select all that apply.

- Produced internal report for government agency or funding source
- Wrote or contributed to an article for a non-scientific audience
- Wrote or contributed to a peer-reviewed publication
- Presented at a scientific meeting/symposium
- Added data to an online database or mapping tool
- Shared data with managers informally
- Shared outcomes in a public forum
- Contributed to an online newsletter or webpage
- Shared information with journalists
- Other _____

Q19) About how many dam removal projects have you been involved in over the course of your career?

- Fill in blank.

Q20) What is your highest level of education?

- Some high school
- GED or alternative credential
- High school diploma
- Associate degree
- Bachelor's degree
- Professional degree beyond bachelor's degree
- Master's degree
- Doctoral degree

Q21) Please provide any additional feedback on this survey.