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Removing Dams, Constructing Science: Coproduction of Undammed Riverscapes by Politics, Finance, Environment, Society and Technology

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ABSTRACT: Dam removal in the United States has continued to increase in pace and scope, transitioning from a dam-safety engineering practice to an integral component of many large-scale river restoration programmes. At the same time, knowledge around dam removals remains fragmented by disciplinary silos and a lack of knowledge transfer between communities of practice around dam removal and academia. Here we argue that dam removal science, as a study of large restoration-oriented infrastructure interventions, requires the construction of an interdisciplinary framework to integrate knowledge relevant to decision-making on dam removal. Drawing upon infrastructure studies, relational theories of coproduction of knowledge and social life, and advances within restoration ecology and dam removal science, we present a preliminary framework of dams as systems with irreducibly interrelated political, financial, environmental, social, and technological dimensions (PFESTS). With this framework we analyse three dam removals occurring over a similar time period and within the same narrow geographic region (the Mid-Columbia Region in WA and OR, USA) to demonstrate how each PFESTS dimension contributed to the decision to remove the dam, how it affected the process of removing the dam, and how those dimensions continue to operate post removal in each watershed. We conclude with a discussion of a joint research and practice agenda emerging out of the PFESTS framing.

KEYWORDS: Dam removal, infrastructure, restoration ecology, praxis, USA

ENTERING THE AGE OF DAM REMOVAL

For the first time in US history, the annual number of documented dam removals has exceeded the number of documented dam constructions (American Rivers, 2016; NID, 2016; Grabowski et al., *in preparation*). Thus, 15 years after the 2002 special issue in BioScience heralding the beginning of the 'dam removal era' (Babbit, 2002), the United States appears to have an annual net loss of dams. Such a dramatic shift in river management reflects broader socioeconomic changes and the maturation of environmental interest groups into national-scale political forces (Lowry, 2003; McCool, 2012), who increasingly recognise the importance of the social, political, and cultural dimensions of biophysical systems in need of restoration (NRC, 1996).

Within this context, dam removals have evolved from a 'normal' dam safety engineering intervention (Wildman, 2013) to a cornerstone of river and riparian wetland ecosystem restoration strategies (American Rivers et al., 1999). As attested to by this special issue, a research agenda focused on the biophysical impacts of dam removals (e.g. Tullos et al., 2016; Magilligan et al., 2016; Bellmore et al., 2016; Tonitto and Riha, 2016) has expanded to include the social and political origins and consequences of removals. Cross-scale analyses of social, political, and cultural factors operating across economic sectors (McCool, 2012), as well as place-based micro-political, experiential, and relational dimensions of dam removals (Fox et al., 2016) and their historical and institutional contingencies (Magilligan et al., 2017) have refined our understanding of why dam removals do or do not occur. And yet, despite the well-documented need for inter-sectoral and interdisciplinary approaches for analysing dam removals (Graf, 2003), a conceptual framework for synthetic analysis of both academic and experiential knowledge still does not exist. Without such synthesis, science-heavy managerial attitudes threaten to replicate long-understood problematic modes of technocratic governance of ecological infrastructure projects (Scott, 1998; Carse, 2012). Additionally, we remain limited in predicting or identifying causal factors leading to dam removals versus other management options (with Lowry, 2003 and Magilligan et al., 2017 as notable exceptions).

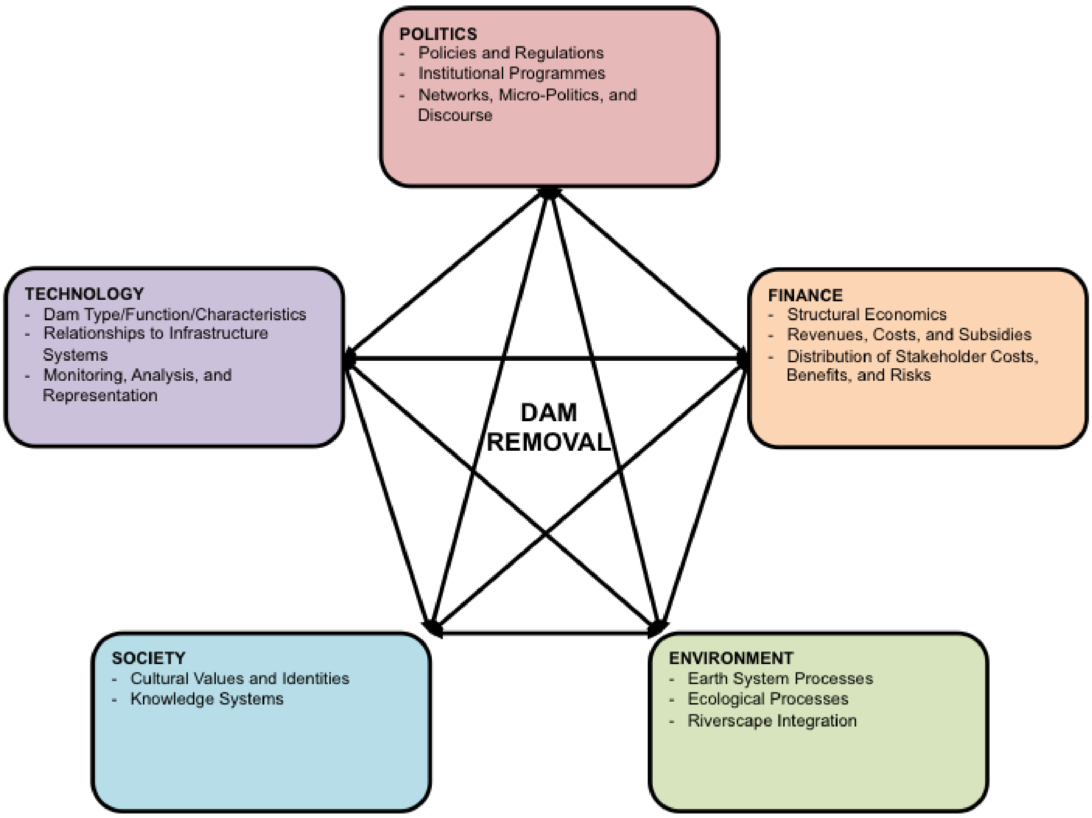
In this paper, we engage in three major tasks. First, drawing upon existing literature, we propose a conceptual framework for integrating existing knowledge around dam removal through a Political-Financial-Environmental-Social-Technological Systems (PFESTS) lens. With PFESTS, we also seek to provide a platform for integrating academic, practitioner, and community knowledge and perspectives in dam removal decision-making processes. PFESTS provides a relational way of synthesising knowledge for improving practice (Deloria Jr., 2003), which hinges upon understanding how each dimension of PFESTS can be understood as a composite of specific components. Second, we discuss relevant components of each dimension of PFESTS, and briefly discuss how to address knowledge gaps and improve dam removal practice in each dimension. Lastly, we illustrate the analytical value of this framework through three case studies of the Condit, Marmot, and Powerdale dam removals in Southern Washington and Northern Oregon, USA. We choose these case studies because despite their geographic and temporal proximity and similar overarching policy process (hydroelectric relicensing), each case highlights distinct issues. We provide tables identifying relevant factors in each dimension, as well as a narrative description of the PFESTS for each case before, during, and after removal. We conclude with a discussion of how these three removals provide insight into the broader applicability of the PFESTS framework in contributing to future research and practice.

DAMS THROUGH THE PFESTS LENS

Dams have long been understood as civil engineering works embodying ideas about progress, development, and modernity, ideas underpinned by beliefs about appropriate relationships between human society and the natural world (Worster, 1985; Lee, 1994; Pritchard, 2011). Dam removal likewise serves an important symbolic role in restoring the natural world from harms caused by contemporary industrialised civilisations (Abbey, 1975; Babbit, 2002; DamNation, 2015); and has generated extensive studies of hydro-geomorphology, riverine ecology, and cost benefits of dam building and removal (reviewed within Tullos et al., 2016 and Bellmore et al., 2016). In addition to these biophysical studies, a recognised need for interdisciplinary analysis (Born et al., 1998; McCool, 2012) has linked project complexity with policy analysis (Lowry, 2003), and engaged social, scientific, and economic dimensions from the practitioner perspective (Bonham, 2008). In parallel, emerging dam engineering literature has started to think about dams as systems linked to social, economic, and environmental systems (Regan, 2010; Ho et al., 2017).

Dam removals could be studied through existing coupled and human natural systems frameworks such as Socio-Ecological Systems [SES] (Collins et al., 2011), to identify feedbacks between social and ecological processes, or Socio-Enviro-Technical Systems [SETS], to understand the role of technologies and the social power of technical expertise (Grabowski et al., 2017). However, field work of the authors continues to find that both SES and SETS frameworks tend to obscure, rather than make explicit, the political forces pushing removals at relevant scales (e.g. national policies, federal agency activities, state programmes, and local politics), and the financial calculus of dam owners and overseeing agencies. Therefore, we argue that dams should be seen through the prism of PFESTS – Political-Financial-Ecological-Social-Technical Systems (displayed in Figure 1), a framework developed for improving ecological restoration practices (Grabowski et al., 2016).

Figure 1. Dam removal through the PFESTS lens.



Note: While all dimensions and components are interdependent, the strength of the connection depends upon the context of the dam removal project. This figure serves as a schematic to highlight the major components within each dimension discussed in section 3.

The PFESTS framework presented here thus extends work in SES and SETS by drawing upon work in Political Ecology and Economy to highlight the Political and Financial dimensions of decision-making. Secondly, we draw upon Social Studies of Science / Society and Technology Studies to ground scientific analyses in social reality (Latour, 2010), making it clear that it is *impossible* to perform apolitical scientific labour. By expanding upon Bruno Latour's work with insights from Swyngedouw (2010), we go beyond the question of 'is scientific practice socially constructed?' to the more pertinent and trickier questions of 'how well is our science constructed, for whom, and to what ends?'

Through PFESTS, we provide a tool for 1) building reflexivity, political savvy, and social awareness into existing dam removal science dominated by technical approaches, b) better identifying the full range of participatory and collaborative efforts, technical expertise, and funding necessary for any given dam removal, and c) improving our ability to identify likely candidates for removals through the PFESTS lens. In the following section, we provide a definition of each PFEST dimension, explain its connections to dam removal, highlight key components of each dimension in terms of existing knowledge, and identify ways of improving both dam removal research and practice.

P: POLITICAL DIMENSION OF DAM REMOVALS

Definition of political

We define the political dimension in two parts. The first pertains to who gets to determine the 'correct' course of action for any given group of people (or to paraphrase Ranciere (2015) – the first political question pertains to who constitutes the political class, and who must be content to simply reproduce their lives). The second, more nuanced portion of this definition pertains to the processes by which certain parties take on authority and others do not. Taken together this definition refers to both who have decision-making power relative to other parties, and how they come by it.

Importance of the political to dam removal

Those who have participated in a high-profile dam removal process often refer to the ways in which decision-making was 'politicised' regarding the deals that had to be cut between parties to reach agreement on the proper course of action (Bonham, 2008). In contrast, many small dam removals, occurring for public safety purposes, have had little fanfare or public outcry (Born et al., 1998), and thus are political in the sense that federal and state policies have manifested in black-boxed programmes of dam inventorying and safety assessments, funds for dam removal or rehabilitation, and legal frameworks that assign liability for dam failure to dam owners. To simplify discussion of the political, we categorise existing knowledge into three tangible components: policies and regulations (Bowman, 2002); programmes of particular organisations, including agencies, institutions, and businesses, non-governmental organizations, and their representatives (Born et al., 1998; Mogren, 2014); and interpersonal relationships, micro-politics, and discourse affecting people’s attitudes on removal (Baker et al., 2013; Fox et al., 2016).

Information on components of the political dimension

Policies and regulations

Much of the complexity in dam removal projects comes from the nuanced and overlapping nature of policies and regulations that govern infrastructure, society, and rivers. Policies and regulations regarding dams can be broadly classified into those associated with the dam itself, those stemming from the regulations affecting rivers more generally, treaty rights and other agreements between sovereign nations that regulate operations, and those affecting economic sectors with strong linkages to dams.

At the national level, notable dam failures have resulted in a reactionary policy approach to dam management manifesting in the National Dam Safety Program (Rogers, 2012), creating a National Inventory of Dams (NID) by the US Army Corps of Engineers [USACE] for all dams over 25 feet (ft) tall or impounding >50 acre-feet (unless under 6 ft tall – around 90,000 dams), requiring emergency management plans for all high hazard dams (ASDSO 2014). At the state level, the NDSP provides funding for inventorying, and potentially removing, dams, although requirements are variable from state to state, creating incompatibilities for comparative analysis between states (Grabowski et al., in preparation). The Federal Water Power Act of 1920 created the Federal Energy Regulatory Commission [FERC] to regulate and coordinate the development of non-federal hydroelectric power projects in the United States, the licensing processes of which have led to the largest dam removals to date. The Endangered Species Act [ESA] and the Wild and Scenic Rivers Act of 1968 pertain to dams affecting endangered species and those in specially administered rivers. Impacts on water quality are also regulated under the Clean Water Act of 1972 [CWA], and play a significant role in some dam removal decisions. Lastly, dams are regulated under the Coastal Zone Management Act of 1972, which may become increasingly important with wider recognition of the relationship between retained dam sediments and coastal resilience (Syvitksi et al., 2005). The broader policy dimensions linking dams to other economic sectors (Hawley, 2011) display even more complexity, as policies pertaining to one sector, like the farm bill, have profound implications for the demand of dam services, including demand for irrigation water, electricity, and navigational services from large publicly financed and operated systems (McCool, 2012).

While comprehensive reviews of regulations affecting dam removals exist (see Bowman, 2002; Hydropower Reform Coalition, 2016), few have examined fundamental issues of jurisdiction and/or sovereignty as and their influence on claims over appropriate use of land and waterways. *U.S. vs. Washington*, otherwise known as the 1975 Boldt Decision, provided sovereign co-management over fisheries to tribal governments. This continues to require enormous efforts on the part of tribes to be enforced (Guarino, 2013), and, in the case of the Columbia River, harms to fisheries and tribal societies remain largely unmitigated and uncompensated (Ulrich, 1999). Even more poignantly, the universal right to self-determination of Indigenous Peoples has become increasingly important in asserting jurisdiction and rights over traditional lands and resources, which may have profound implications for infrastructural management (Alfred 1999). Additionally, dealings between the US and Canadian governments, e.g. the Columbia River Treaty, regulates the number of dams, level of flow, and sale of energy.

Institutional actions

The complex and somewhat contradictory regulations outlined above are enforced by a diverse set of local, state, and federal agencies, often in conflict with one another. These institutional networks vary depending on dam function, with multipurpose dams (>24% of dams (NID, 2016)) tying together a larger number of institutional interests than single purpose dams. Aside from the agencies described above, the US Department of Agriculture [USDA], Bureau of Reclamation, Department of Defence, and the Tennessee Valley Authority own and operate a significant number of dams throughout the country, though over 64% of dams in the USA are privately owned (NID, 2016). Both the US Fish and Wildlife Service [USFWS] and National Marine Fisheries Service [NMFS] are required to provide input into FERC licensing processes and to partner with the Environmental Protection Agency, US Geological Service, and state environmental departments to manage mandates of the ESA and the CWA. The now defunct Coasts and Communities grant program administered by NOAA and USFWS was instrumental in pushing along early dam removal for restoration throughout the United States (Lowry, 2003). Conversely, the USDA owns numerous dams and provides support for water resources development, conservation programmes, and irrigation dam financing. Aside from state safety statutes, state regulations can require specific permits for dam construction, water storage, and operations. Some of these constrain the impacts of dam removals themselves, such as the Oregon Revised Statutes pertaining to hydropower decommissioning, preventing conversion of hydropower water rights to instream use should they "injure the rights of another party" (ORS, 2015). Additionally, state-level programmes seeking to restore rivers can be significant players in dam removal projects, such as the Oregon Watershed Enhancement Board, and the Salmon Recovery Funding Board in Washington. Overall, institutions translate policy and regulations into actions, and the ways they do so depend largely upon the scales at which they operate (Vogel, 2012). Lastly, state and federal programmes and agencies designating and protecting structures of historical significance can serve to protect dams from removal.

Networks, micro-politics, and discourse

While it is tempting to see agencies as having blanket jurisdiction, all decisions surrounding dam removal are made by individuals balancing their own interests with their institutional affiliation, operating in both formal governance networks (Mogren, 2014), and informal social networks within which individuals influence other individuals, typical of infrastructure governance in general (Eakin et al., 2017). As Fox et al., demonstrate in their review of the contestation over dam removals in New England, individual-level relationships are where history, identity, and ideas of nature become concrete and significant for decision making. These findings highlight the importance of context, discourse and rhetoric in shaping policy decisions, both at that individual and group level and how the media disseminates emotionally compelling narratives of both removal advocates and opponents to a broader public (Jørgensen and Renöfält, 2013).

Application to dam removal decision-making

Improving research and addressing knowledge gaps

Key research questions remain as to the consequences of policy shifts across scales on public processes of dam management and dam removal. While it is obvious that specific agency programmes have pushed removals, we need better research on how conflicting agency and institutional agendas can be resolved most effectively to minimise post-removal conflict. Aside from such an action-oriented agenda, we also need more research on how networks of institutions operate around dams to enforce their conflicting mandates. Another key research area pertains to how post-removal environmental impacts affect both other dams within the system in terms of shifting regulatory oversight for any remaining endangered species or water quality issues. A key political-financial question for many removals and restoration programmes also pertains to who reaps the immediate economic benefits of restoration programmes (Whitelaw and Macmullan, 2002).

Improving dam removal practice

Appeals to objectivism and reductionism, be it environmental claims, or more objective economic analyses, reveal a naiveté in the political economy of infrastructure management which has always defended its public legitimacy via appeals to objective analyses of the public good (Lee, 1994; Pritchard, 2011; McCool, 2012). To improve the uptake of science in highly politicised decision-making contexts, we should avoid making absolutist claims as to the necessity and impacts of dam removal. Rather, we need to situate science within the political context of decision-making, recognise both its strategic value and the risks inherent in using science as a tool for political mobilisation. Such a practice goes beyond improvements to 'science communication' – improving practice entails continuing to build coalitions of stakeholders who, further empowered by sound science, can both exert pressure on existing political processes and facilitate the creation of new ones through existing institutional channels and direct action.

F: Financial dimensions of dam removal

Definition of financial

The financial dimension of PFESTS is defined by the systems of managing and accounting for direct monetary flows of dams and removals. As for any enterprise or infrastructure system, financing refers to the ways in which capital can be raised, direct costs associated with design, implementation, operation and maintenance (O&M), what revenues are generated and how they are tied back in to different enterprise functions, subsidies and taxes associated with dams, the assignation of financial liability, the projections of future costs and revenues, and the out-of-pocket costs of compliance with regulations.

Importance of the financial to dam removal

While there has been limited analysis to date of the financial dimensions of dam removal within the restoration community, it is clear that financial considerations are relevant before, during, and after removal decisions. However, economic analyses of removals, while identifying broader impacts, rarely identify how financial flows affect operator decision-making (Rye, 2000). Dam operators' inability to financially comply with regulations is often mentioned as a key driver of removals, and yet it is rarely, if ever, formally analysed. Here, we propose to simplify the above definitional considerations to address 1) the structural economic context of dam financing, 2) actual costs, revenues and subsidies for dam operations and removal, and 3) the distribution of realised costs and benefits from dams and their removal for their stakeholders.

Information on components of the financial dimension

Structural economics

Dam finances hinge upon their role in the structure of the local, regional, national and international economy, all of which are affected by dam removals (Kruse and Scholz, 2006). For example, hydropower dams respond to global energy prices, flood protection infrastructure often requires regional inter-agency coordination and financing, and local recreational dams may be financed privately. Dam finances also include historical impacts, sunk costs, and future projections; the evaluation of what goods and services dams produce remains sensitive to the temporal window utilised for analysis, as well as who has and who will bear the costs of the dam (as evidenced in FERC estimates for economic viability of hydroelectric projects). Historical adjustments of economic structures by dams are particularly poignant for many indigenous peoples who consistently voiced opposition to dam construction, and to whom reparations have not been forthcoming despite the increasing visibility of removals for restoring human-river relationships (Ulrich, 1999; Fisher, 2010). Thus, how one conceives of the appropriate spatial and temporal scale of dam finances fundamentally influences how one justifies dam removal or continued operation (Whitelaw and Macmullan, 2002; Hawley, 2011; McCool, 2012).

Revenues, costs, and subsidies

Given that removals usually take place in the face of a change to normal operations, we must understand the regular revenues and costs of O&M in relation to financial costs associated with removal. There are the administrative costs of dam removal processes (e.g. legal costs, organisational person-hours devoted to the project), knowledge costs (e.g. feasibility studies, specialised analyses, consultants), and costs associated with the labour and materials of repairing, modifying or removing the dams. Flows of revenue into the dam can be highly regulated and tightly coupled to performance, as in rates for electricity, or largely informal and weakly coupled, as in homeowner association fees or local tax revenue going into a general budget. Revenue streams can also be impacted by macroeconomic trends, such as when hydroelectric dams utilised for manufacturing become defunct due to technological revolutions in electricity generation and decline of manufacturing in the so-called developed world. Feasibility studies and assessments of the hydrologic, geologic, economic, social, and ecological components of restoration often come from federal and state agencies, although environmental non-government organisations (NGOs), tribal governments, and local governments can all be involved in paying for knowledge generation around dam removals. Congressional financing for removals can occur through partial grant financing from participating agencies (including dam safety funds or ecological-mitigation funds), or through changes in regulations affecting the operator's finances (e.g. allowed rate increases). Dams owned by private individuals may be susceptible to changes in markets and may have greater financial uncertainty than publicly owned infrastructures or those owned by large corporations.

Distribution of stakeholder costs, benefits, and risks

Whether a stakeholder accepts or disapproves of a dam removal hinges upon the actual and perceived costs and benefits resultant from a dam or its removal. Robust projections of anticipated stakeholder costs are extremely challenging as there are inherent subjectivities in post-removal financial projections. To a property owner, dam removal may be perceived as a risk to lake front property values, while post-project property values may rapidly increase along newly created river frontage with increased lot sizes, which may in turn adversely affect other owners by increasing property taxes. As the impacts of a dam reverberate through watersheds and sociopolitical systems, the ways in which economic activities of individuals not directly coupled with the dam are affected become felt and can serve as a basis for increased perceived certainty around the impacts of dam removals in other contexts (Johnson and Graber, 2002).

Application to dam removal decision-making

Improving research and addressing knowledge gaps

Scholarship in the political ecology of restoration urges us to remain critical in understanding the financial beneficiaries of emerging restoration economies (Lave et al., 2010). For example, while there is potential for small-scale, locally based collaborative watershed restoration efforts to boost local employment economies (Nielsen-Pincus and Moseley, 2013), complex removal projects often require most of the labour to come from other regions across the state and country (Rozance et al., *in preparation*), or from companies historically involved in dam construction and maintenance. This use of 'outsider' labour can impact public support of the project. Conversely, money for dam removals and restoration projects that goes back into forest industries, or engineering and contracting firms historically engaged in infrastructure projects for extractive purposes, can simultaneously build political support for removals and provide employment in areas with declining shares of natural resources-based employment, but also create conflicts around who is perceived to benefit the most from dam-removal projects. While the moving water recreation industry certainly appears to benefit from removals (McCool, 2012), care should be taken when making economic arguments as to net benefits, as other recreational interests may be displaced. Thus, similar to how large-scale public investments in dam infrastructure may have simply shifted economic activities such as farming from one part of the country to another (Hawley, 2011), dam removals may also shift economic activities from one sector to another (Whitelaw and Macmullan, 2002). More research is needed on how the finances of dam operators affect removal decisions, the relative costs of removals versus other rehabilitation options, and how economic activities are affected by removals at a variety of spatial, temporal, and social scales.

Improving practice

Dam removal advocates must pay critical attention to the feedback between political and social conflict and complexity and the administrative costs of removal projects. Once a dam has been slated for removal, studies that look at flows of dam removal funding can shed light on other elements of PFESTS. As these projects can be costly and variable (mean and standard deviation of removals reporting costs in Washington State is 2.6 and 5 million USD, respectively – Grabowski et al., *in preparation*), accountability on administrative overhead, deconstruction costs, and labour issues can impact public trust and support on future projects. Dam removal projects should therefore strive to increase transparency about the financing of projects and where money goes during the removal process. This can bolster support for removals as project costs and benefits can be more accurately defined and therefore defended as appropriate. Additionally, changes in the financial fortunes of enterprises connected to dammed and undammed rivers also need to be transparent to justify the social financial benefits and costs of removals.

E: ENVIRONMENTAL DIMENSIONS OF DAM REMOVALS

Definition of environmental

We define the environmental dimensions of dam removals as pertaining to basic earth processes (climatic, hydrological, and geomorphological processes), ecological processes (populations, communities and ecosystems, including the influence of human-led restoration efforts), and how the relationship between the two becomes integrated by the 'riverscape' (Fausch et al., 2002).

Importance of the environmental to dam removal

The environmental expectations of dam removals cannot be easily teased apart from their political, financial, social, and technological dimensions. While many dam removal organisations have touted the ecological benefits of removing dams, actual ecological impacts of dam removals involve trade-offs between ecological states (Stanley and Doyle, 2003), which are often subjectively determined (Hull and Robertson, 2000). Environmental expectations surrounding dam removal are directly tied to how these infrastructures and ecosystems are perceived and valued by the environmental managers, scientists, local stakeholders, and community members taking part in the process (Escobar, 1998; van Riper et al., 2017). Dam removals as restoration interventions often operate with the goal of recovering pre-dam environmental conditions and the desired ecological services (Palmer et al., 2014; Magilligan et al., 2016). However, the ways in which financial, political, and regulatory rationales and ongoing activities interact with environmental realities, will determine whether lost ecological connections and functions are re-established.

Information on components of the environmental dimension

Earth system processes

As hydraulic infrastructures, dams fundamentally alter and rely upon climatic hydrological patterns for their basic functions, and the interplay between their structural attachment to local geology and hydro-climatic forces as enacted through design and operations determines how safe and effective a dam is over time (Regan, 2010). In contrast to the impacts of dam removals, the impacts of dams on flow regimes (the magnitude and timing of high flows, modification of diurnal flow regimes, decreases in baseflow, changes in river chemistry and temperature) and the resultant impacts on channel geomorphology (reduced bedload transport, increased channel incision, reduced floodplain development and main-channel connectivity) have been known for quite some time (Graf, 2006). Thus, much of the knowledge of how dam removals may affect earth system processes has emerged out of studies of dams' impacts on those same systems. And while we know that we must adequately account for the diversity of river system responses to dam removals of different types (Poff and Hart, 2002), how dams have enabled land use activities within their basins makes simple 'before and after' comparison of dam impacts on earth processes difficult if not impossible.

Ecological processes

Ecological research on dam removals tends to focus on responses in fish community assemblages, habitat availability for migratory and anadramous fish, and transformations from lentic to lotic ecosystem structures (Bednarek, 2001). Studies have also attempted to integrate analyses of river ecosystem responses at basin scales involving numerous small dam removals (Raabe, 2012), and examine the impacts of large-scale restoration programmes (Bennett et al., 2016). Narrowing the ecological scope to the river itself, we know that changes within fish community structure influence the basic physical, chemical, and biological properties of streams; one well-documented example being the positive feedbacks between increasing anadromous returns and the size and number of offspring (Janetski et al., 2010). Similarly, while we have known for some time that anadromous fish (particularly Pacific salmon) provide nutrients to terrestrial systems (Gende et al., 2002) and terrestrial ecosystems subsidise river food webs (Richardson et al., 2010), the extent and magnitude of those connections vary greatly from system to system. In order to better assess overall impacts of dam removals, we need to improve the integrative abilities, connectivity, and ecological and geographic extent of science around dam removal, for which we can build off of existing work on habitat and process connectivity.

Riverscape integration

The environmental impacts, including the ecological and earth system processes, of dam removals depend upon both exogenous watershed factors and complex in-stream processes, all of which are acted upon by the other dimensions of PFESTS. Since dams participate in transformations of land, such as providing irrigation water, controlling flooding, and historically enabling logging, mining, milling and manufacturing activities, dams impact landscapes and not just rivers, and in turn watershed scale land use characteristics also influence fundamental properties of river systems (Allan, 2004). Studies attempting to integrate these various influences have generally relied upon integrative biophysical constructs such as the watershed or more recently, the 'riverscape' (Fausch et al., 2002). The riverscape concept allows one to examine how riverine conditions are driven by both landscape and within channel processes. Understanding undammed landscapes requires thinking about how the removal of hydraulic infrastructures influences the landscape conditions influencing river ecosystems as well as within river processes.

Application to dam removal decision-making

Improving research and addressing knowledge gaps

Biophysical uncertainties must be better understood, such as how migratory fish communities (McKernan et al., 1950; Van Hyning, 1968), system-level habitat diversity (Rosenfeld et al., 2000), and ecological agents in the broader riverscape (e.g. directly through beavers in Pollock et al., 2004 and indirectly through wolves in Roemer et al., 2009) respond to and impact dam removal. Additionally, parsing uncertainties in the biophysical processes affected by dam removals (documented in Bellmore et al., 2016; Tullos et al., 2016; Tonitto and Riha, 2016) to social, political, financial, and technological changes in the riverscape such as planning processes around urban development, or agricultural intensification or change, remains a key research agenda. Given that habitat-based models (such as the Ecosystem Diagnosis and Treatment model) remain the scientific basis for planning diverse types of restoration activities, we would do well to analyse how they relate to actual measurements of ecological function such as trophic structure (in particular of algae, zooplankton, and invertebrates) and ecological productivity. Analysing and communicating such contingency in the environmental dimensions of dam removals stands in contrast to previous studies primarily seeking to provide certainty as to the impacts of removals (Poff and Hart, 2002; Tullos et al., 2016; Tullos personal communication), but remain critically important.

Improving practice

During the dam removal process, it is important to take a step back and evaluate why the dam is being removed, the expected outcomes, and how/if these expectations fit with the reality and uncertainty of what is currently understood about these complex and dynamic systems. In addition, it is key to question how outcomes are being valued and by whom. Acknowledging these linkages, expectations, and uncertainties will in turn create a more informed dam management and removal processes.

S: SOCIAL DIMENSIONS OF DAM REMOVAL

Definition of the social dimension

We define the social dimension in terms of how individuals and communities relate to one another and create collective or individualistic experiences of the world (Becker, 1982), as well as the way these relationships form and are influenced by robust social structures such as institutions (Weber, 1946; Giddens, 1984), and political economies (Marx, 2008). This definition encompasses how individuals and communities relate to one another based upon individual and collective identities, specific formal and informal relationships that structure social networks, and how knowledge of the world is or is not transmitted through these networks.

Importance of the social to dam removal

Like all infrastructure interventions (Bowker and Star, 1999), dam removals embody complex social processes in terms of how and why they are performed, what social relationships they change, the new forms of social life produced by undammed landscapes, and the feedbacks between those new social realities and the impetus for further removals, restoration activities, or modifications to hydraulic infrastructures.

Different groups of people have different views of the appropriate use of rivers by humans. The management actions taken to achieve each of these visions are often contradictory. Ultimately, social and political processes negotiate these contradictions, embedding them into policies that guide the building and removal of dams.

Information on components of the social

Cultural values and identities

Although many stakeholders in dam removal projects ostensibly represent institutions and organisations (such as federal, state, local, and/or tribal agencies, business interests, or homeowners' associations) each has an individual identity and worldview constrained or reinforced by the cultures they participate in (Mogren, 2014). In many cases, the ways in which personal and collective identity is (un)attached to a dam drives the ways in which the dam is valued (Rye, 2000). Additionally, identity and values can form the underlying psychological motivation to engage in decision-making processes, or undertake political projects of mobilisation and organisation either for or against removal (Fox et al., 2016; Magilligan et al., 2017)

Knowledge systems

Knowledge systems represent a robust body of work providing useful insight into the relationship between expertise, legitimacy and the framing of infrastructure value by examining which social actors are able to influence and participate in the knowledge systems driving decision-making (Bowker and Star, 1999; Jasanoff, 2004; Miller et al., 2010; Carse, 2012; Larkin, 2013; Munoz-Erickson, 2014). In contemporary society, scientific knowledge dominates the ways in which we collectively understand

and interpret the world around us (Ozawa, 1991; Knorr-Cetina, 1999). Scientific framings of dams as primarily technical and environmental, with the underlying assumption that if dams are removed pre-dam environmental conditions and the desired ecological services will return (Palmer et al., 2014; Magilligan et al., 2016), require a certain set of assumptions about society-nature relationships. In this sense, dam removals do not differ dramatically from other ecological restoration work suffering from a 'lack of social-imagination' (Hull and Robertson, 2000). Choices about how to frame the environment, even those perceived to be 'apolitical', have power, and stem from inevitable differences and rhetorical value of claims as to the 'natural' (Rayner and Hayward, 2013). Often, restoration actions value the historic (first) nature over the present nature, and disregard the complex historic, current, and future socio-ecological dynamics, which may lead to unexpected ecological restoration outcomes.

The current decision-making process around dam removal prioritises information produced by federal and state agencies, although work performed by consultants is often used by municipal governments and NGOs to vie for legitimacy in dam decision-making. Agency scientists and decision-makers often view traditional knowledge of rivers with scepticism, even when their interests may align with traditional Indigenous knowledge holders (Blackstock, 2005), or other forms of vernacular knowledge. In many cases, western science in the form of archaeology and anthropology make traditional ecological knowledge claims, appropriating and legitimating that knowledge in the decision-making space (Alfred and Corntassel, 2005; Zent, 2012). How knowledge transfer occurs depends on the social relationships of the knowledge system, and can benefit traditional Indigenous knowledge holders or rob them of voice and identity. On rivers where dams have been removed, post-removal monitoring, particularly of sediment and fish, may benefit greatly from the inclusion of vernacular knowledge as possessed by fishermen and boaters, knowledge which generally also must be translated into scientific terms to be considered legitimate by governing institutions.

Application to improving dam removal decision-making

Improving research and addressing knowledge gaps

In the context of dams, it is important to consider the ways sociocultural systems frame our views of the natural world, including views and assumptions about rivers, riparian areas, and floodplains. Ideas about 'nature' serve as a rhetorical resource within discourse (Rayner and Hayward, 2013), with profound implications for management strategies (Cronon, 1996; Hull, 2002), and social life (Hartmann, 1998; Swyngedouw, 2010).

Thus, key research questions remain as to how stakeholder worldviews, values, and identities influence perceptions of the symbolic and material value of dam removals. Similarly, we need more research on the practical significance of how environmental systems are conceptualised by stakeholders in ways which guide both the construction of technical information about removals and the interpretation and uptake of different types of information about removals. Another major area of research should address how organisational cultures interact and evolve during dam removal decision-making processes, and how these relate to shifting political mandates and new financial realities at local to national scales.

Improving practice

When thinking about how and why dams come to be removed we must remember that dams are built as infrastructure systems by specific groups of people for particular purposes; dams are also removed by specific groups of people for different purposes. When social appeals to expertise are made to resolve conflicts over dam removal, the knowledge systems participating in dam removal become apparent both as sources of authoritative information on how and why a dam should be removed and its potential impacts, and also sites of contestation between values over what constitutes legitimate knowledge. Thus, while it may not be possible or desirable to 'manage' social interactions between stakeholders in dam removal decision-making processes, scientists and practitioners engaged in those processes should at least understand the importance of avoiding triggering rhetoric which exacerbates pre-existing cultural and social conflicts.

T: TECHNICAL

Definition of technical

We define the technical dimension of PFESTS in terms of both the physical technologies of dam building, dam removal, and restoration practice (e.g. materials, tools, equipment), the technologies of representing dams and rivers (e.g. data collection practices, tools for analysing and modelling), as well as the softer technologies of governance (Bowker and Starr, 1999; Carse, 1999; Agrawal, 2005) that accompany all technical systems.

Importance of the technical to dam removal

Understanding dams as technological infrastructure systems performs a variety of functions in the analysis of dam removal decisions. First, it clarifies the ways in which experts and knowledge systems portray the technologies of dam construction, operation, and removal, and the ways these portrayals impact the likelihood and practice of dam removal. Additionally, understanding dams as technological infrastructure systems can demonstrate what impacts of dam removal are likely to be felt in the rest of the infrastructure linked to the dam. Finally, the ways in which impacts of dams are 'known' are increasingly mediated through particular technologies of collecting data and monitoring post-removal outcomes, analysing those data, and ultimately presenting them to stakeholders. Whether these technical practices and representations align with the grounded experiences of those affected by dam removal often determine their future viability and involvement in dam removal projects.

Information on components of the technical

Dam types, functions, characteristics and removal methods

Dam type and size both significantly influence the likelihood of its removal (Grabowski et al., *in preparation*) as well as its removal method and costs. Even dams of the same type can have significant variation in construction style and quality, significantly influencing dam longevity (Charlwood, 2009). Likewise, dam functions or purposes, including those with multiple functions can also be subjectively defined, and underlies issues with consistent documentation of what types of dams have been removed (Grabowski et al., *in preparation*). Some dam functions will be completely lost upon dam removal, others can be and often are easily replaced through other means (such as the use of pumps for irrigation and water supply withdrawals). The methods for removing dams may also affect the timing and likelihood of dam removal, e.g. the short-term impacts of rapid reservoir drawdown causing conflict between project stakeholders. In this sense, the impacts and costs of a dam removal fundamentally depend on the technology employed in designing and constructing the dam, as well as its connections to other infrastructure systems.

Relationships to infrastructure systems

Thinking of dams as embedded within larger infrastructure systems (Regan, 2010) requires us to carefully analyse the scale at which a dam removal will have impacts, as certain linkages may preclude a social appetite for dam removal (e.g. extensive built development in floodplains downstream of flood control dams). These connections can cut both ways however, as dams serve as significant sources of risk to downstream human communities in the event of failure, and higher hazard dams face increased monitoring scrutiny and potentially increased likelihoods of removal (Ashley, 2004). The same holds true for hydroelectric dams, which must compete financially with other sources of electricity generation for revenue, but which can also provide below national market rate power for local consumers, which may require subsidies to achieve consensus for dam removal (as in the case of the Elwha Dam removals – NPS, 2016).

Technologies of monitoring, analysis, and representation

The ways in which society and the environment are known increasingly depend on technologies ordering phenomena into units of accounting within a particular disciplinary framework (Latour, 1999). Thus there is no single class of objects 'dams', rather, referencing Nancy Cartwright (1999), we have a 'dappled world' of dams, where different data sources, while having internally consistent quantitative descriptions of dams, are often incompatible as they are not only subjectively constructed based upon the motivations, technical/disciplinary training, world view and personal idiosyncrasies of the individual and/or data compiling agency, but also fragmented by the technologies and policies of data storage and retrieval. For instance, the NID has become classified and key pieces of it, including dam hazard ratings, conditions, and locations, are not accessible to non-USACE employees (USACE personal communication).

Application to improving dam removal decision-making

Improving research and addressing knowledge gaps

While technological factors are significant and of concern to the dam safety community attempting to understand relationships between dam ages and dam failures (Regan, 2009), they have received little attention with the dam removal science community which has sought ecological classifications of dams based upon reservoir and drainage basin characteristics (Poff and Hart, 2002). Overcoming these technical silos would allow dam removal scientists to better understand why and how particular dams need to be removed, knowledge held by many dam removal practitioners but not translated into the academic literature.

Even less is known about how different dam designs affect the cost and nature of dam removal, which requires expertise like dam construction but also new forms of knowledge related to controlled demolition. A few different removal strategies have been publicly tested, and are currently being studied by a USGS-led dam-removal synthesis workgroup (Powell Center Working Group, 2016), but more systemic information should be collected on the technologies of deconstructing dams and how they relate to technological characteristics of dams. Even more fundamentally, we are constrained in linking case study level insights with systemic analysis of dam removal by the lack of data consistency around removals at both the state and national scale. Creating consistent databases of dams and removals for both comparisons between existing and removed dams, as well as understanding variance within removals should remain a top research priority.

Improving practice

The technical dimension can improve dam removal practice by improving methods of analysing and representing scientific information regarding the impacts of dam removal in public processes. We should also seek opportunities to improve technical databases representing dam conditions to identify potential synergies between public safety dam management and restoration objectives. Lastly, by evolving a dam-removal practice, we can increase public support for dam removals, as existing practice has served as a source of conflict in prior decisions.

CASE STUDIES

Three case studies below highlight the interdependencies of PFESTS as they apply to dam removals in the Pacific Northwest. These three dam removals, occurring in 2008 (Marmot), 2010 (Powerdale), and 2011 (Condit), all resulted from FERC re-licensing processes within the same narrow geographic area, influenced by ongoing negotiations over endangered species in the Columbia River Basin. Marmot and Condit received substantial media attention, shifting the national discourse around dam removal. On the other hand, Powerdale is more representative of a broader class of small hydroelectric facilities with lesser symbolic value, but profound impacts on rivers and their communities. While ultimately all three dams were removed because the operator could not justify the relicensing expenses, each case highlights specific considerations that dramatically altered the PFESTS of dam removal. The Marmot case highlights the role of large local institutional players in facilitating removals, as well as the contingency of environmental impacts based upon social and political contestations over appropriate technologies of environmental management. The Condit case highlights not only the importance of representations of dam removal technologies to immediate stakeholders, but also the interplay between stakeholder conflicts and project costs. Powerdale, with its post-removal conflicts over appropriate in-stream flow requirements, highlights the social contingency of dam removal impacts on both environmental and social systems in highly technologically modified landscapes.

Powerdale Dam, Hood River Basin (HRB), Oregon

Powerdale Dam was a 6000 kW (powering ~3000 modern households) hydroelectric combination concrete roller gate and earth embankment dam that began operation in 1923. The dam diverted water to a powerhouse three miles downstream just one and a half miles from the river's current mouth on the Bonneville Pool of the Columbia. PacifiCorp, a private regional electric utility company, had initially planned on renewing the dam's FERC licence in 1998, a plan that was the preferred alternative for FERC. However, in 1999 the Mid-Columbia Evolutionarily Significant Unit of Steelhead was listed under the ESA, which alongside a 1998 Thermal Total Maximum Daily Load regulatory process, provided regulatory teeth in opposition of continued operations. After input on the draft environmental assessment from the NMFS, the Oregon Department of Fish and Wildlife [ODFW], and the Confederated Tribes of the Warm Springs [CTWS] who have treaty fishing rights on Hood River, and five other stakeholders, FERC's updated licence conditions, finalized in 2002, imposed costs that would render the project uneconomical for PacifiCorp. Costs were imposed both by operational changes required to meet state water quality standards and upgrading fish screens and passage.

The subsequent settlement process proceeded rapidly with involvement from several federal agencies, NOAA, the State of OR, CTWS, and other non-governmental organisations including American Rivers and reached an agreement in 2003. The settlement process had large consequences for the longer-term impacts of the dam removal. FERC issued an environmental assessment for the settlement agreement later that year, and accepted surrender of the licence in 2005. The project included removal of the main dam structure and partial removal of the flow-line to the powerhouse. In 2003, FERC granted a retroactive and temporary continuation of the licence to continue operation for revenue generation until 2010, although the 2006 flood partially destroyed the flowline preventing further power generation and public access to the dam site. Prior to removal, ODFW and CTWS conducted extensive monitoring work to ascertain baseline fish populations bypassing the dam via a working fish ladder.

The Hood River Watershed Group [HRWG], a regionally recognised pragmatic and collaborative watershed council consisting of representatives from all major watershed stakeholders facilitated the transfers of lands on which the dam, flowline, and powerhouse were situated. Land was transferred both to Hood River County, and the Columbia Land Trust (CLT) for its conservation value and access for public recreation, which continues to be negotiated by public processes (HR News, 2017). Secondly, conflicts over how to treat released water rights remain in negotiation. Following decommissioning, PacifiCorp converted the 500 cubic-feet/second water right from the Powerdale Dam project to in-stream water rights held in trust by the Oregon Water Resource Department (OWRD) using a 1932 priority date jeopardising junior water rights in low-flow years (which have become increasingly common). Since that time, OWRD issued a proposed final order of a partial conversion of in-stream water rights, which has been contested by NOAA, CTWS, and two other parties, and is still being negotiated without public involvement. Considerable statutory ambiguity in the OR statutes means that this case could set an important legal precedent for post removal of in-stream flow requirements in the state. Because of these ongoing political and social contestations reverberating far upstream of where the dam used to stand, large uncertainty remains around the ultimate impacts of dam removal on one of the world's most productive orchard regions and Indigenous salmonid fisheries.

Marmot Dam Complex – Big Sandy and Little Sandy Dams, Sandy River Basin (SRB), Oregon

On the opposite slope of Mount Hood/Wy'east in Northern Oregon, lies the Sandy River, aptly named for the enormous volume of fine glacial sediment it transports. The 22 MW Marmot dam complex owned by Portland General Electric was composed of a large roller-compacted concrete dam (47 ft high, 195 ft long) on the main stem of the Sandy River, diverting water several miles to the Little Sandy Dam (a 15.75 foot high diversion dam) through the Little Sandy River. Water from the Little Sandy was moved to Roslyn Lake, a popular recreation spot for the local community, which served as a staging pond for a powerhouse on the Lower Bull Run River within the Sandy Watershed. When the FERC licence came up for renewal in 2004, it became quickly obvious to PGE that the costs of compliance demanded by other relicensing parties (including NMFS and USFWS) of protecting salmon, listed as threatened under the ESA in 1999, meant that relicensing was not financially viable, even with recent improvements to fish passage. Parties to relicensing came to a settlement shortly thereafter with the aid of a professional mediation organisation. One of the major parties to the FERC relicensing process, and the lead entity on the Sandy River Basin Watershed Plan (which funded numerous analyses utilised within the FERC process), was the City of Portland, which manages the existing dams on the Bull Run River as the main source of the city's water supply. The city was engaged in its own regulatory compliance process through the creation of the Bull Run Water Supply Habitat Conservation Plan in order to maintain its incidental take permit which allows an entity to adversely influence endangered species under the ESA, as well as comply with CWA regulations pertaining to the temperature impacts of the water supply system on the Lower Sandy.

Removing the dam on the main-stem Sandy River opened several miles of river to white water recreation, although with limited access points, the opened section of river has not become a major destination for anglers or boaters. A small but vocal number of fishermen represented by the Native Fish Society engaged in a public and legal battle against ODFW, alleging that hatchery strays previously sorted at the Marmot Dam complex have now been enabled to spawn and dilute the genetics of wild stock throughout the upper Sandy River Basin. These contestations have engaged numerous scientific analyses on fish population genetics, as well as adding new regulations regarding the number of hatchery fish released into the basin (Handleman, 2014). As in the case of Powerdale, dam removal has increased scientific uncertainty around the status migratory fish in the basins, and unlike Powerdale, has increased the use on habitat-based models in restoration planning processes.

Table 1. Powerdale Dam removal: Major considerations for each major component of PFESTS.

Political	**Financial**	**Environmental**	**Social**	**Technological**
Policies and regulations	***Structural econ. context***	***Earth processes***	***Cultural values + identity***	***Dam characteristics***
Thermal TMDL included dam operations ESA listed species FERC process – 1998-2005 Treaty fishery on ceded land OWRD water rights in conflict	Decreasing energy prices due to natural gas boom; continually low prices due to Federal Columbia River Power System (FCRPS) Increasing share of economic activity of recreation and real estate Land use dominated by orchards and timber forests	High gradient, glacially fed stream, mixed snow and rain dependency Low summer flows during dry season Naturally variable temperature regime Dynamic channel with complex incision-deposition regime Dam not a barrier to sediment/bedload transport	Removal marketed as improving habitat and conservation value Public site access diminished post dam removal Widely acknowledged demographic change Tribal fishery in upper river, large recreational fishery	6000 kW concrete roller gate dam built in 1923 River diverted along mixed wood and steel flow-line to downstream flood-prone power plant
Institutional actions	***Revenues, costs, subsidies***	***Ecological processes***	***Knowledge systems***	***Infrastructure connections***
CTWS Fisheries co-management with OR. Dept. of Fish and Wildlife Extensive funds available from BPA for CTWS restoration budgets Columbia River Basin Fish Accord (CRBFA) context Opposing government agency interests (e.g. OWRD vs ODFW on in-stream flow issue)	Significant Operations and Maintenance costs – Flow line, Roller gates, and Powerhouse flooding due to high flow events Marginal economic returns Funding available for feasibility studies Willing party for land transfer and appropriate tax structure	Downstream juvenile fish passage an issue Historical loss of off-channel habitat Lack of Large Woody Debris Jointly managed fish hatchery significantly influences population counts	Disjunct data sets of federal, state, county, and irrigation districts of river conditions Coordination by Hood River Watershed Group (HRWG) and SWCD provides education and training Recognised need by federal agencies for improved data analysis and dissemination Tribal acceptance of technical approaches New collaborative group for forest management provides extensive public engagement/ outreach	Electricity replaced with coal power Basin thick with irrigation infrastructure Numerous other small FERC licensed hydropower facilities operate under different licence processes Railroad continues to own and operate tracks in conservation easement – complicates public access

Networks and micropolitics	***Stakeholder distribution***	***Riverscape integration***		***Technologies of representation***
Highly charged in-stream flow conflicts continue Cultural divide in management philosophy between tribes and settlers Hood River Watershed Group coordination of plans, activities, and priorities	Numerous stakeholders seeking to steward river resources Irrigated agriculture faces potential losses from instream water rights No single monetary beneficiary from removal Recreational area access diminished	Ongoing concerns of river pesticide and metal concentrations Irrigation withdrawals profoundly affect summer flow Landscape impacts on stream temperature actively studied		Fish population counts less certain Dam removal initiated alternative monitoring programmes Long running flow gauge near bottom of basin

Table 2. Marmot Complex Dam removal: Major considerations for each major component of PFESTS.

Political	**Financial**	**Environmental**	**Social**	**Technological**
Policies and regulations	***Structural econ. context***	***Earth processes***	***Cultural values + identity***	***Dam characteristics***
ESA-listed species FERC process 1997-1999 Assessment of navigability City of Portland – ESA-mandated Habitat Conservation Plan significant Limited wild, scenic, and recreational designations	Decreasing Energy Prices due to natural gas boom, continually low prices due to FCRPS Continued expansion of wind power by owner Land use dominated by vacation homes, timber forests, and wilderness	High gradient, glacially fed stream, mixed snow and rain dependency Low summer flows Naturally variable temperature regime Dam retaining significant sediment Flooding of residences remains major issue	Professional mediation firm hired for settlement agreement process Widely acknowledged demographic change Strong recreational fishing community Lower river experiences high metropolitan recreation pressure	Two concrete dam 22MW complex w holding pond and long flowline built b/w 1908 and 1912 and removed in 2008 Minor part of diverse energy portfolio
Institutional actions	***Revenues, costs, subsidies***	***Ecological processes***	***Knowledge systems***	***Infrastructure connections***
ODFW hatchery conflict with NGOs NMFS, ODFW, USFS, BLM all in favour of removal	Significant O&M costs Upgrades for fish passages inadequate Marginal returns prior to	Downstream fish diverted into flowline/holding pond (100% mortality) Historical loss of off channel	Non-overlapping data sets of federal, state, city, NGOs of stream temps and conditions Coordination by SRBP	Major tributary downstream of Bonneville Dam Holding pond provided water to local wells – PGE not found

BLM accepts land transfer CRB Fish Accord context	FERC relicensing Funding available for feasibility studies from city	habitat Lack of LWD Fish hatchery	No collaborative group for forest management Limited/No tribal input E. Multnomah Soil and Water Conservation District provides training and technical assistance for landowners	liable for maintaining groundwater levels Power lost replaced by grid purchases (primarily wind, coal, and natural gas)
Networks and micropolitics	***Stakeholder distribution***	***Riverscape integration***		***Technologies of representation***
Sandy River Basin Partners led by city coordinate federal, state and city agency activities Sandy River Basin Watershed Council facilitates citizen involvement in restoration/environmental advocacy	Recreational access major issue City of Portland had most to gain from removal USD20 million cost passed on to rate payers	~1/3 of basin remains dammed with no fish passage – temperature and flow concerns at mouth Lower basin conflicts over development and industry Basin-wide significant restoration actions		Fish population counts less certain EDT model dominates projected impacts of restoration Long-running flow gauge changed by removal Extensive modelling of sediment transport

Table 3. Condit Dam removal: Major considerations for each major component of PFESTS.

Political	**Financial**	**Environmental**	**Social**	**Technological**
Policies and regulations	***Structural Econ. context***	***Earth processes***	***Cultural values + identity***	***Dam characteristics***
ESA-listed species Water quality issues FERC process began in 1991, ongoing Settlement process caught in the middle of FPA Modification / inexperienced FERC Wild and scenic river designated in 1986 above reservoir, National Scenic Area below dam	Decreasing energy prices due to natural gas boom; continually low prices due to FCRPS Watershed land use largely agricultural and forested, increasingly residential pressure Strong recreation economy Tribal economic reliance on fishery	High gradient, bedrock, glacially fed stream; dependency on mixed snow and rain Consistent summer flows in mainstem High quality cold water habitat, with some tributary, some temperature issues Dam had significant sediment retained	Significant cultural conflicts noted Widely acknowledged demographic change World-class boater Mecca On-going failures of justice around in lieu site at mouth of river Loss of reservoir community 'commons'	Concrete dam (125 ft high) completed in 1913 – 14.7 MW No fish passage

Institutional actions	***Revenues, costs, subsidies***	***Ecological processes***	***Knowledge systems***	***Infrastructure connections***
Land transfer still pending Lake home owners pressed county governments to intervene pre and post settlement Strong Yakima Nation presence Ongoing retrocession and co-management issues CRB Fish Accord context Loss of Cons Dist. director	Significant O&M costs Fish passage extremely expensive due to geologic constraint Funding available for restoration from YN, PCSRF, SRFB Extensive consulting and legal fees added due to adversarial relationships	Limited off-channel habitat Lack of LWD Fish hatchery discontinued prior to removal discussions Dam at river mile 3.3 – opened >32 miles of fish habitat	Fundamental disagreements about sediment concerns despite modelling Multi-stakeholder engagement in education and outreach efforts Disagreements over habitat quantification Underwood Conservation District provides education and training for land / river stewardship	City water source pipe overhauled at river crossing river crossing) and domestic well issues (needed re-drilling) Power lost replaced in company portfolio by coal plant upgrades Original power sold to paper mill in lower Columbia Local Public Utility District (LPUD) purchasing old transmission lines
Networks and micropolitics	***Stakeholder distribution***	***Riverscape integration***		***Technologies of representation***
No current management and planning coordination body (failure of WRIA 29b process) – informal efforts ongoing Virulent conflicts in public meetings Many organisations acting in concert/conflict Annual Riverfest festival brings together river community	Reservoir side cabin owners leasing land from PacifiCorp – ongoing issues around land transfer – a few cabins condemned due to soil instability post removal Commercial rafting industry booming Direct costs of removal passed to utility electric customers Treaty tribal fishers blocked from river access	Temperature and flow concerns at mouth Increasing residential development pressure, on-going agriculture and forestry issues Basin-wide significant restoration actions		Extensive modelling underestimated sediment transport Long-running flow gauge changed by removal Fish population monitoring projects on-going

One of the primary impacts of the Marmot removal appears to be allowing the City of Portland to cost effectively maintain the legality of its water supply system with regard to endangered species and water-quality concerns.

Condit Dam, White Salmon River Basin (WSRB), WA

Condit Dam was completed in 1913, roughly three miles from the river's current mouth on the Bonneville pool across the Columbia from Hood River, Oregon. Within a year of construction, floods destroyed the dam's fish ladders, and after an unsuccessful replacement attempt, the owner paid mitigation fees to the state of WA instead of replacing them. The dam's impacts on fisheries was noted, and subject to intensive legal scrutiny during compensation processes for the Federal Columbia River Power System (Ulrich, 1999), and Indigenous People living at the mouth of the White Salmon were forced by the damming of the Columbia River to move again to an 'in-lieu' of traditional access site at the present river mouth, and remain largely uncompensated (Fisher, 2010). With the dam's FERC licence expiring in 1993, PacifiCorp (the same operator of the Powerdale Dam) initially sought relicensing for the project in 1991, only to be mired in a contentious process for years. This process resulted in a 1999 settlement agreement, updated in 2005, and a final one in 2010 with Skamania and Klickitat counties that had successfully slowed removal through asserting local jurisdiction, which PacifiCorp repeatedly fought invoking federal law. Although PacifiCorp initially intended to renew the licence to operate, by 1996 it was obvious that revenues from the project could not exceed costs of financing NMFS-required fish passage. Much of the conflict focused on the removal plan to rapidly dewater the reservoir, as well as the loss of cultural ecosystem services related to the reservoir, mobilising local stakeholders, notably residents owning cabins but leased from PacifiCorp lands, and the White Salmon Steelhead Fishermen, concerned about loss of habitat below the dam, to petition local and state government representatives to defend their interests. Skamania and Klickitat counties hired lawyers and paid consultants to challenge state-level permitting for the dam removal, and added over USD3.3 million in costs to the dam removal process (Becker, 2006). These lengthy legal battles continue to have significant social and political ramifications, and may have contributed to the failure of the State Water Resource Inventory Planning Process. On October 26, 2011, after PacifiCorp obtained all necessary permits, a tunnel drilled at the base of the dam was dynamited, rapidly draining the reservoir and transferring an unanticipated amount of sediment downstream, blocking a boat ramp at the in-lieu fishing site.

Presently, a Yakama Nation project of dredging a channel and building a boat ramp is being paid for by funds set aside in the settlement agreement. Additionally, some fears of lake residents were realised with erosion from the former reservoir site requiring bank stabilisation, several wells drying up, and some damage to foundations of former houses close to the lake resulting in condemnation and removal (Pesanti, 2016). Meanwhile salmon and steelhead have returned to river reaches above the dam. The White Salmon area serves as a Mecca for a global whitewater kayaking scene, and the commercial whitewater industry on the White Salmon continues to boom. However, no watershed-level coordination body exists to balance competing concerns around maintaining the quality of water resources in the basin and regional residential development pressures continue to increase. On former Pacificorp lands, stakeholders are seeking to resolve issues of ownership and river access, as well as continuing to manage ecological restoration of the former dam site. At the same time, ongoing monitoring efforts by the USGS, YN, the Underwood Conservation District, and others are seeking to determine the impacts of removal on migratory fish populations within the basin (Jezorek and Hardiman, 2017). How dam removal has affected river governance remains an active topic of research in the basin.

Discussion and conclusion

Our PFESTS framework provides a useful tool for integrating existing knowledge around dam removals, understanding and improving decision making, and guiding future research. Of primary interest to this special issue, we highlight how the impacts of dam removals themselves are socially and politically contingent. We offer PFESTS as a framework to synthesise existing knowledge, inform future research efforts, and improve dam-removal practices.

From our descriptions of PFESTS dimensions and relevant components we have provided a cohesive set of considerations for analysing how each PFESTS dimension co-produces the other, and what steps we can take to build off existing knowledge to improve dam-removal practices. Our case studies illustrated how dam removal is driven by the interactions of PFESTS dimensions. Going forward we hope to inform both 'thick' descriptions of individual removals and how they are situated within larger policy and planning processes, as well as provide a basis for comparative research on dam removals at the local, state, national, and international level.

Overall, we need an invigorated discussion between different elements of the dam-removal community (e.g. dam-safety professionals, water-resources-development policy makers, restoration practitioners, and affected communities) to more clearly articulate normative goals around dam removal. Effectively removing dams thus requires a re-engagement with both core-democratic principles around public processes and a renewed appreciation of Indigenous Peoples' relationships with rivers in the Americas. Restoring nature requires restoring and evolving human relationships with ecosystems; how we do so will determine if the dam-removal era will continue to accelerate, or be momentary blip in the history of human river relations.

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