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Removing Dams, Constructing Science: Watershed Restoration Through A Socio-Eco-Technical Systems Lens

by

Zbigniew Jakub Grabowski

A dissertation submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy
in
Environmental Sciences and Resources

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Abstract

Ecological conservation and restoration in the anthropocene must struggle with overlapping drivers of biodiversity and cultural loss; ruptures of the ecological environment mirror ruptures of human relationships with nature. And yet technology cannot remove humans from nature; technological and infrastructural reconfigurations of nature create new vulnerabilities and risks for humans and ecosystems alike. How can conservation and restoration science productively grapple with complex infrastructure systems and decision-making processes as biophysical and social drivers of ecosystem change?

Using dam removals in the USA and in the Mid Columbia River region of the Pacific Northwest, this dissertation develops a conceptual framework for Social, Environmental, and Technological Systems (SETS), and applies it at three spatial and temporal scales to the practice of dam removal as a river restoration strategy. Drawing upon existing data sets, as well as biophysical, document, survey, and interview data this dissertation addresses how dam removals have functioned in the context of the social histories of river restoration programs, examines how these restoration programs must continue to renegotiate the human relationships with nature through the infrastructure systems that enable certain forms of existence while precluding others.

Of particular interest is how restoration programs have increasingly functioned to deliver novel infrastructure solutions, while ignoring longer-term changes in ecological structure and function due to infrastructure development; in other words, the infrastructural work of restored ecosystems, and the infrastructural blind spots of restoration programs.

How restoration planning considers, or does not consider, infrastructural blind spots, is indicative of not only the biophysical drivers of threatened and endangered species loss, but also the political dynamics of decision making at large, and the power-knowledge relationships constituting legitimate and relevant knowledge in the decision making space.

In the Pacific Northwest, there appears to be a tipping point of social convention in centering treaty rights and obligations vis-à-vis ongoing processes of colonization and institutionalized scientific expertise. Ecological restoration will only be successful if it addresses both engineered infrastructures and social justice.

Dedication

For my mother, without whom none of this would be possible.

For dad, who at the beginning of this process took one last trip on the big aeroplane in the sky, but has nevertheless remained along for the ride.

For my daughter Oona, for in her is the future.

And for all things wise, wonderful, bright, beautiful, great, and small (thanks James Herriot), may we find peace and harmony through this time of upheaval and change.

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I am also grateful to my many mentors over the years, direct and indirect, and I am proud to walk in the footsteps of many who have traversed the paths of knowledge wherever it may take them.

I also have nothing but the deepest gratitude for my loving partner, Sara Swetzoff, and my daughter Oona Grabowska, to whom this work is dedicated: may the subsequent generations learn from the mistakes of the past, and improve on the successes of the ancestors.

Blessings to the land of Nch'I Wana – may the land be beautiful, bountiful, and biodiverse in perpetuity.

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Introduction: Systemic and Reflexive Knowledge in the new Conservation Science

Biodiversity loss worldwide continues due to the synergistic effects of habitat destruction, climate change, and a host of other anthropogenic stressors (Barnosky et al. 2011), a loss so rapid and significant it constitutes a global change in its own right (Chapin iii et al. 2000). Globally freshwater species have declined at a far faster rate than their terrestrial counterparts (Dudgeon et al. 2006). These ecological declines are not surprising, as aquatic ecosystems, and riverine ecosystems in particular, are highly sensitive to landscape level changes, directly compete with a variety of human domestic, agricultural, and industrial uses of water and space, and integrate human physical and chemical alteration of the environment (Allan 2004). These biodiversity losses interlock with very human concerns in water resource management, including the relationships between land use and management and water quality, the sustainable management of ground and surface water resources, built development in floodplain and wetland habitat (Dudgeon et al. 2006, Defries et al. 2012).

In the Pacific North West of the United States, the pre-eminent crises of conservation that combines both terrestrial and aquatic issues is the crisis of Salmon. Despite being sustainably managed for thousands of years, in less than 150 years of colonization and industrialization, salmon fisheries have been over-exploited in the rivers and the seas, and seen widespread habitat destruction due to physical, chemical, and biological factors (NRC 1996). In addition, extensive dam, irrigation, power transmission, and transportation infrastructures have not only physically displaced habitats and species, but enabled new human uses of the landscape inimical to salmon co-habitation, which ironically have themselves now come under threat due to increasingly global drivers of anthropogenic climate change (Mote and Salathe 2010; Chang and Psaris 2013).

All of these drivers of ecosystem decline can be plausibly linked back to the installation of colonial and explicitly imperial modes of defining and managing the natural world, transporting a logic of maximum exploitation and industrial regularity indicative of high modernist approaches to river management (Pritchard 2011, White 2011, Worster 1985) to a diverse landscape previously typified by seasonal variability and diversity in human-ecological relationships (Hunn and Selam 1991; Fisher 2010; Jacob 2013; Beavert 2017). Thus the biological losses of concern for conservation science, are accompanied by profound social and cultural disruptions, events such as the cultural, ecological, epistemological, and biological genocides occurring during the ongoing colonization of the so called 'Americas, (Deloria, 2003). These events cannot be separated fro the rise of centralized state bureaucracies that disrupted customary ways of relating to and governing nature typical of the advent of modern and high modern forms of industrialized society (Jacoby 2001, Scott 1998, Hess 1995), which have been increasingly subsumed under the rhetoric of the 'anthropocene' (Zalasiewicz et al. 2008). Contemporary conservation is thus thoroughly embroiled in the conflicts of what types of knowledge are best used to manage the environment, which can be broadly divided what James Scott (1998) calls ‘metis,’ or place based knowledges, and ‘techne,’ or abstractable generalizable knowledge of ‘how things work.’

Biocultural rupture, ecological decline, and infrastructural transformation however are not totalizing forces, they have all stimulated social reactions to preserve ecosystems, often through spurring novel political coalitions confronting, resisting, reforming, and evolving physical infrastructures, land uses, and overall systems of river governance (Lowry 2003; McCool 2012). These new coalitions and collaborations must also face the obduracy of social and technological infrastructures embedded within land and hydroscapes (Star 1999; Miller et al. 2008), the ways in which managers and decision makers can address dispersed processes of land use and climate change (Hoyer and Chang, 2014), which may very well depend upon their ability to work together with a common language and understanding (Granek et al 2010). Building such a common understanding, and understanding how such multi-vocal knowledge practices can manifest in practical changes to current management systems often requires reflexive and collaborative research practices (Spoon 2014).

Placed in the current social context, shifts in the focus of river management have occurred alongside broader social changes; disillusionments with the promises of modernity, resurgent practices of indigenous governance reclaiming autonomy, self-determination, and cultural and spiritual environmental practices, and a broader turn towards the creation of multi-lateral, decentralized, and non-regulatory forms of environmental governance indicative of 'environmentality' (Agrawal and Lemos 2007). From such a vantage point, all environmental 'problems' simultaneously become negotiated by social forces operating in concert with and counter to technological trajectories.

The main question this dissertation seeks to answer, is have these social movements genuinely led to transformative forms of river governance, or has the techno-managerial approach to conservation and restoration remained supreme? To answer this question I trace the evolution of new systemic forms of organizing knowledge around the design and management of infrastructural systems; explicitly exploring them as co-produced by social, environmental, and technological forces (Chapter 1). I then go on to apply this line of thinking to examine at a high level the evolution of dam removal practice in the United States (Chapter 2). Chapter 3 digs deeper into three fairly high profile dam removals to understand how they were produced by multi-scalar political and financial forces along with their more broadly defined SETS domains, setting up an appeal to examine the lived experiences of individuals engaged in collaborative forms of river governance affected by the process and outcomes of dam removal in chapter 4.

Overall, this dissertation charts new terrain in the vital questions of the 21st century – can humans learn to transform their core infrastructural systems to preserve the integrity of their ecological well being, and do so in a way which is socially just and honors the agreements and wisdom of indigenous ways of knowing and relating to the land.

References for Introduction:

Agrawal, A., & Lemos, M. C. (2007). A greener revolution in the making? Environmental governance in the 21st century. *Environment: Science and Policy for Sustainable Development*, *49*(5), 36-45.

Allan, J.D. 2004. Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution, and Systematics* 35(1): 257-284.

Barnosky, A. D., Matzke, N., Tomiya, S., Wogan, G. O., Swartz, B., Quental, T. B., ... & Mersey, B. (2011). Has the Earth's sixth mass extinction already arrived?. *Nature*, *471*(7336), 51.

Beavert, V. R. (2017). *The Gift of Knowledge/Ttnuwit Atawish Nchinchimam: Reflections on Sahaptin Ways*. University of Washington Press.

Chang, H., & Psaris, M. (2013). Local landscape predictors of maximum stream temperature and thermal sensitivity in the Columbia River Basin, USA. *Science of the Total Environment*, *461*, 587-600.

Chapin iii, F. Stuart, Erika S. Zavaleta, Valerie T. Eviner, Rosamond L. Naylor, Peter M. Vitousek, Heather L. Reynolds, David U. Hooper et al. "Consequences of changing biodiversity." *Nature* 405, no. 6783 (2000): 234.

DeFries, R. S., Ellis, E. C., Chapin III, F. S., Matson, P. A., Turner, B. L., Agrawal, A., ... & Lambin, E. (2012). Planetary opportunities: a social contract for global change science to contribute to a sustainable future. *BioScience*, *62*(6), 603-606.

Deloria, V. (2003). *God is red: A native view of religion*. Fulcrum Publishing.

Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z. I., Knowler, D. J., Lévêque, C., ... & Sullivan, C. A. (2006). Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological reviews*, *81*(2), 163-182.

Fisher, A.H. 2010. Shadow tribe: The making of Columbia River Indian identity. Seattle, WA: University of Washington Press.

Granek, E. F., Polasky, S., Kappel, C. V., Reed, D. J., Stoms, D. M., Koch, E. W., ... & Aswani, S. (2010). Ecosystem services as a common language for coastal ecosystem-based management. *Conservation Biology*, *24*(1), 207-216.

Hess, D. J. (1995). *Science and technology in a multicultural world: The cultural politics of facts and artifacts*. Columbia University Press.

Hoyer, R., & Chang, H. (2014). Assessment of freshwater ecosystem services in the Tualatin and Yamhill basins under climate change and urbanization. *Applied Geography*, *53*, 402-416.

Hunn, E. S., & Selam, J. (1991). *Nch'i-wana," the big river": Mid-Columbia Indians and their land*. University of Washington Press.

Jacob, M. M. (2013). *Yakama rising: Indigenous cultural revitalization, activism, and healing*. University of Arizona Press.

Jacoby, K. (2014). *Crimes against nature: Squatters, poachers, thieves, and the hidden history of American conservation*. Univ of California Press.

Lowry, W. R. (2003). *Dam politics: Restoring America's rivers*. Georgetown University Press.

McCool, D. (2012). *River republic: The fall and rise of America's rivers*. Columbia University Press.

Miller, T. R., Baird, T. D., Littlefield, C. M., Kofinas, G., Chapin III, F. S., & Redman, C. L. (2008). Epistemological pluralism: reorganizing interdisciplinary research. *Ecology and Society*, *13*(2).

Mote, P. W., & Salathe, E. P. (2010). Future climate in the Pacific Northwest. *Climatic change*, *102*(1-2), 29-50.

National Research Council (NRC). (1996). *Upstream: salmon and society in the Pacific Northwest*. National Academies Press.

Pritchard, S. B. (2011). *Confluence: the nature of technology and the remaking of the Rhône* (Vol. 172). Harvard University Press.

Scott, J. C. (1998). *Seeing like a state: How certain schemes to improve the human condition have failed*. Yale University Press.

Spoon, J. (2014). Quantitative, qualitative, and collaborative methods: approaching indigenous ecological knowledge heterogeneity. *Ecology and Society*, *19*(3).

Star, S. L. (1999). The ethnography of infrastructure. *American behavioral scientist*, *43*(3), 377-391.

White, R. (2011). *The organic machine: The remaking of the Columbia River*. Hill and Wang.

Worster, D. (1985). Rivers of empire. *Water, Aridity, and the Growth of the American West,* New York: Pantheon Worster.

Zalasiewicz, J., Williams, M., Smith, A., Barry, T. L., Coe, A. L., Bown, P. R., ... & Gregory, F. J. (2008). Are we now living in the Anthropocene?. *GSA Today*, *18*(2), 4.

Chapter 1: Infrastructures as socio-eco-technical systems

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Need for Interdisciplinarity in Infrastructure Studies

Infrastructure plays a key role in 21st century sustainability challenges related to burgeoning populations, increasing material and energy demand, environmental change, and shifts in social values. Social and political controversy over infrastructure decision making will continue to intensify without robust interdisciplinary and inter-sectoral dialogue over national-scale and local-scale infra- structure trajectories. Alongside large investments in physical and social systems, the infrastructure community—including planners, engineers, public works specialists, financiers, and sustainability scientists—needs to articulate a 21st century vision addressing the interrelated technological, social, and environmental dimensions of infrastructure systems. Such a vision needs to address existing systems in the industrialized world and new systems in countries seeking to improve human welfare through infrastructure development.

Infrastructure systems—discussed here as primarily those integrating the built environment (Jones et al. 2001; Pulselli et al. 2007), transportation (Greene and Wegener 1997), power generation and distribution (Jacobson and Delucchi 2009), food production and processing (Food and Agriculture Organization of the United

Nations 2011), manufacturing (Jovane et al. 2008), water delivery (Gleick 2003; Muller et al. 2015; Palmer et al. 2015), and waste treatment (Melosi 2008)—underpin the unprecedented material wealth of contemporary human society. These technological systems have developed alongside extensive social infrastructure including specialized knowledge and expertise housed in institutions, informal knowledge systems of operation and maintenance, and a broader system of governance and regulatory politics setting budgetary priorities, policy directions, and regulatory certainty. In combination with these policy processes, user behavior and demographic change influence the demand and maintenance costs for infrastructure services, both of which have an identified overall investment need of $3.6 trillion (ASCE 2013), $2 trillion of which is needed by 2027 (ASCE 2017). Because infrastructure relies on environmental inputs to function, channels and protects society from environmental forces, and impacts environmental systems, attitudes about technology and appropriate human–nature relationships set the goals for long-term infrastructure sustainability. They do so through both a social willingness to pay for infrastructure systems and a social consciousness of and desire for specific types of systems. Shifting environmental conditions, including climatic changes and dispersed atmospheric pollutants, are exacerbated by the externalities of present infrastructure systems and the technologies they support. The extent of these shifts is rarely apparent until systems become overwhelmed (Gross 2010; Perrow 1999). For example, in the case of Hurricane Sandy, siloed sys- tem management created unforeseen vulnerabilities propagating through critical infrastructure systems (Klinenberg 2013, Comes and Van de Walle 2014), serving as an example of cascading failure (Rinaldi et al. 2001), as well as affecting system restoration (Sharkey et al. 2015). At the same time, infrastructure systems and the technologies and behaviors they enable serve as sources of risks and costs to public and environmental health; 8 of 10 people now live in urban areas with excessive air pollution primarily due to transport, manufacturing, and energy generation (WHO 2016).

How has contemporary infrastructure practice come to this point? The modern infrastructure ideal of large, networked systems such as power generation, information technology, and transport (Duenas-Osorio et al. 2007; Haimes and Jiang 2001; Winkler et al. 2011) has enabled lowered unit costs and greater accessibility while splintering social and environmental systems (Graham and Marvin 2001). In response, discourse on appropriate technology, emphasizing cost efficiency on both the supply side and the demand side of infrastructure thinking (Basu and Weil 1998), and work on inverse infrastructures examining self organizing forms of user-generated infrastructures (Egyedi and Mehos 2012) advocate for an improved fit between technological capabilities and social goals across scales.

Current infrastructure thinking must therefore address two fundamental challenges, one physical and one social. Physically, infra- structure must continue to evolve in design, implementation, and operations and maintenance in a world changing due to the impacts of infrastructure systems and the human activities they enable. Socially, the infrastructure community must acknowledge the in- inherently political nature of infrastructure systems in order to overcome siloed decision-making processes around single systems. Such an understanding requires embracing the added intellectual challenge of understanding how social perception and values frame the parameters of desirable infrastructure development.

Reimagining Infrastructures as Social, Ecological, and Technological Systems

One answer to overcoming these challenges in infrastructure discourse is to catalyze broader social engagement within existing processes of infrastructure planning, design, operations, and management. Established infrastructure decision-making processes appear contained within narrow domains of expertise, subject to a large degree of physical and social inertia (Hall 2016). To foster public engagement, the infrastructure community needs to high- light the broad and cross-sectoral role infrastructure decision- making plays in escaping unsustainable development trajectories (Karlsson 2014), as well as its potential to alleviate inequality in income and access to economic opportunity, as is being taken up by numerous current policy propositions. Providing defensible analysis of those claims, however, requires a strong interdisciplinary framework capable of illuminating the interrelated dimensions of the almost invisible but necessary support systems of contemporary life (Edwards 2003).

This paper provides a conceptual framework for facilitating dialogue around infrastructural systems as irreducibly interdependent social, ecological, and technological systems (SETs). Such a complex SETs framework facilitates the integration of infrastructure knowledge and practice on two fronts. The first involves the integration of different forms of expertise, shifting the emphasis in infrastructure research away from academically siloed or specialist- led programs to one engaging the infrastructure design, implementation, management, and research communities to frame problems and solutions collaboratively. Secondly, the authors emphasize the need for better process integration, whereby design, implementation, and management processes integrate technological systems with social and ecological systems. The framework herein simultaneously allows for the interdisciplinary analysis of the (uneven) economic benefits of infrastructure development while thinking more carefully about the environmental and social impacts of infra- structure (Monstadt 2009) by expanding on the idea of infrastructure ecosystems (Pandit et al. 2015). The infrastructure community must acknowledge that the negative impacts of infrastructure, previously considered as externalities, have transitioned from being simply impacts on the environment, to increasingly being felt as stresses on human systems, including risk to life and property, in- creased maintenance and operations costs, declining service levels, and disruptions to social life. The community must also acknowledge that there are enormous opportunities for increasing planning and design effectiveness through a more integrated approach to re- duce costs, decrease system down-time, and maximize cobenefits of joint systems operation and maintenance.

As part of thinking about the true costs and benefits of infra- structure, infrastructure systems science requires a more equitable process for articulating infrastructure's goals and design considerations. Just as the sociotechnical imaginaries of the New Deal gave rise to such examples of modernity as the Tennessee Valley Authority and the Bonneville Power Authority, the authors envision a New Green Deal, which formulates a socially equitable vision of ecological sustainability to guide technological progress (Barbier 2010; Jones and Conrad 2008). Such a vision adds to the current national dialogue on the need for large public investment in infrastructure (Infrastructure Week 2016).

This paper articulates the notion of infrastructure systems as socio-eco-technological systems, a framework entangling the social, ecological, and technological as dimensions of a system, rather than a series of component pieces. Dimensions must be viewed relationally, allowing the treatment of infrastructure systems as interdisciplinary objects variably constructed from differing social, ecological, and technological forces; in this sense, technologies serve as hybrids of socialized cognitive processes and the material world they inhabit. Thus SETs allow for analyzing and evaluating the impacts of different methods of analysis and system representation of infrastructure science on infrastructure governance [see Manuel-Navarrete (2015) for socio-ecological systems research examples]. Through such a practice these authors hope to provide a framework to simultaneously analyze the impacts of conceptual models of infrastructure systems on infrastructure decision making and engage in the infrastructure community to improve them.

Social dimensions of infrastructure comprise embedded social networks, tacit knowledge, discourses, institutions, policy, and planning in and around infrastructure systems in their imagining, implementation, and maintenance. This dimension includes the normative goal-setting processes of planning, associated analysis and apportionment of costs, risks, and benefits, and the role of regulations and subsidies in guiding technological change. Both the process and the outcomes of infrastructure planning must be equitable in order to maintain long-term involvement and to facilitate social, ecological, and financial returns on infrastructure investments.

For example, in the context of climate change, energy-intensive transportation, manufacturing, housing, and energy extraction infrastructures stemming from late-nineteenth-century inventions have created risks that threaten their continued function. Although it is tempting to view such problems as primarily technological, they are intrinsically social systems, being conceived by social actors (Jasanoff and Kim 2013), and they set the backdrop of individual social worlds and physical realities of the environment. Such a socialization of infrastructure through an exploration of its sociopolitical dimensions illuminates infrastructure's nature as a "total social fact" [after Marcel Mauss (1966) in Edgar and Sedgwick (1999)] because the study of infrastructure weaves together a diverse array of social lives, and the nature of infrastructure from the perspective of the individual can be used to expose the nature of society [after Bowker's infrastructural inversions (1994) in Star (1999)]. Such a perspective mirrors that of Alexander's (1977) idea of the lattice, in which interwoven and overlapping social, technological, and ecological systems combine to create the emergent urban experience. The way that people interact with infra- structure through use, operation, planning, financing, maintaining, and regulating all contribute to its manifestation as a physical phenomenon and bound the opportunities for physical system integration and decentralization (Derrible 2017). By taking these social processes into account, key operational and financial uncertainties can be exposed early on and compensated for, positively impacting longevity and functionality.

Ecological dimensions of infrastructure are composed of ecological structures (i.e., organisms, populations, communities, and ecosystems—generally networks of plants, animals, microbes, and so on), functions (i.e., primary productivity, food web interactions, carbon and nutrient cycling), and behaviors (e.g., squirrels nesting in transformer boxes, dam-building beavers) that make up, contribute to, and threaten infrastructures. Many of these ecological features and processes manifest independently of human intention, although they are enhanced or hindered by human activities and built infrastructures. This includes attempts to protect, maintain, and enhance existing and restored ecological elements providing ecosystem services, improved human well-being, urban function, and a stable global climate. Ecological networks and actors should be afforded the same consideration as social actors by being pro- tected from harm, encouraged in their contribution to infrastructure function, and not just treated as potential sources of risk or uncertainty.

Much of the urban ecology literature has focused on humans' negative first-order impacts on pre-human nature (Grimm et al. 2000; McKinney 2006). This is usually understood in terms of urbanization's impact on individual organisms, and organisms' ability to inhabit urban space. Within urban ecology, scholarship has moved toward analyzing ecology of the city, which includes analysis of how sociopolitical processes shape urban ecosystems, rather than the previously dominant tradition of urban naturalism, which focused on the spatial patterns of plants, animals, insects, and so on, which now is referred to as ecology in the city (Collins et al. 2011; Grimm et al. 2000). Both ecology in the city and ecology of the city lend themselves to a valuation of urban ecosystems in terms of the ecosystem goods and services provided to humans (Gaston et al. 2013), largely focusing on health (Lee and Maheswaran 2011; Tzoulas et al. 2007), higher-order cognitive abilities (Kahn 1999), and regulation of the environmental quality and function of the urban environment via the use of green infra- structure (Amati and Taylor 2010).

Aside from explicitly using ecological processes to perform infrastructural work (as in the case of green infrastructure), infra- structure serves an ecological role in transforming possibilities for material, energy, and information flow throughout the urban system and beyond (Kennedy et al. 2007; Sahely et al. 2005). Infrastructure function also is dependent upon ecological flows operating in and around it. It is up to the infrastructure community to beneficially integrate these ecosystem processes or inevitably face them as sources of risk and operational constraint at local to global scales. Calls for infrastructure investment should internalize such ecological considerations both in terms of direct impacts on eco- logical patterns and processes and system-level feedback such as impacts on climate and hydrology.

Technological dimensions of infrastructure are composed of the physical technologies (e.g., hardware, steel, concrete, rebar, cable, plant, equipment, and tools) and knowledge systems (e.g., data generation and management, software, and operating instructions) of an infrastructure network, including both expert-engineered and informal work. This dimension includes the linkages between disparate infrastructure systems and their complex adaptive system nature (Rinaldi et al. 2001), therefore acknowledging the interdependent functionality of existing technological systems (e.g., necessary interactions between electricity, information technology, financial infrastructure, and mass transit). Technology and

its developmental pathway cannot be seen as a value-neutral object. Rather, technology has embedded material and social con- sequences in terms of how it is managed, how it reshapes social life, and its inherent ecological interdependency and impacts.

Technological innovation can have direct and indirect impacts on infrastructure function, including ways of representing infra- structure systems through data, models, and media. For instance, the widespread use of GPS technology combined with advanced information systems has revolutionized understandings of commuter behavior and given rise to the smart city ideal (Batty et al. 2012) as well as its associated problems (Gabrys 2014). However, information technology management can only go so far in re- solving on-the-ground infrastructure problems; physical design constraints provide outer limits to system adjustment, and the relationship between the two provides fertile ground for research. This relationship between macro and micro technology (Crawford and French 2008; Edwards 2003; Kemp 1994) constrains and high- lights the relationship between consumer-scale technological innovation and systemic innovations in larger infrastructure systems, often by affecting user behavior, demand for infrastructure services, and avenues for service delivery and unit costs.

Five Critical Considerations Illuminated by SETs

Five critical considerations emerge from a SETs framing (Fig. 1) and provide a novel way of thinking about the infrastructure life- cycle. These are (1) setting infrastructure goals, (2) addressing complexity and scale, (3) understanding ecological-technological hybridity, (4) operating resiliently, and (5) system evolution.

These considerations are implicit in all infrastructure projects but are often taken for granted and thought to take place outside the arena of infrastructure design and management itself. A SETs framing illuminates the important role of social and ecological systems alongside technology within all infrastructure life- cycle stages (Fig. 2).

Democratically Setting Goals for Infrastructure Systems

Who articulates the goals of an infrastructure project? At what so- cial and political level are goals set? What policies and regulations frame the market environment determining unit costs? Who owns infrastructure and to what purpose? How do different organizational structures affect infrastructure performance? What cultures, norms, and behaviors of the design and user communities influence design considerations? In response to traditional technocratic planning practices, participatory-based, scenario-based, and charrette based design and planning approaches have sought to open decision-making processes to facilitate co-design of urban environments (Innes and Booher 2010; Wates 2014).

Figure 1. SETS frame as a prism; five interdependent critical considerations can be seen when viewing infrastructure through the multifaceted lens of SETS rather than along usual, component-based disciplinary boundaries

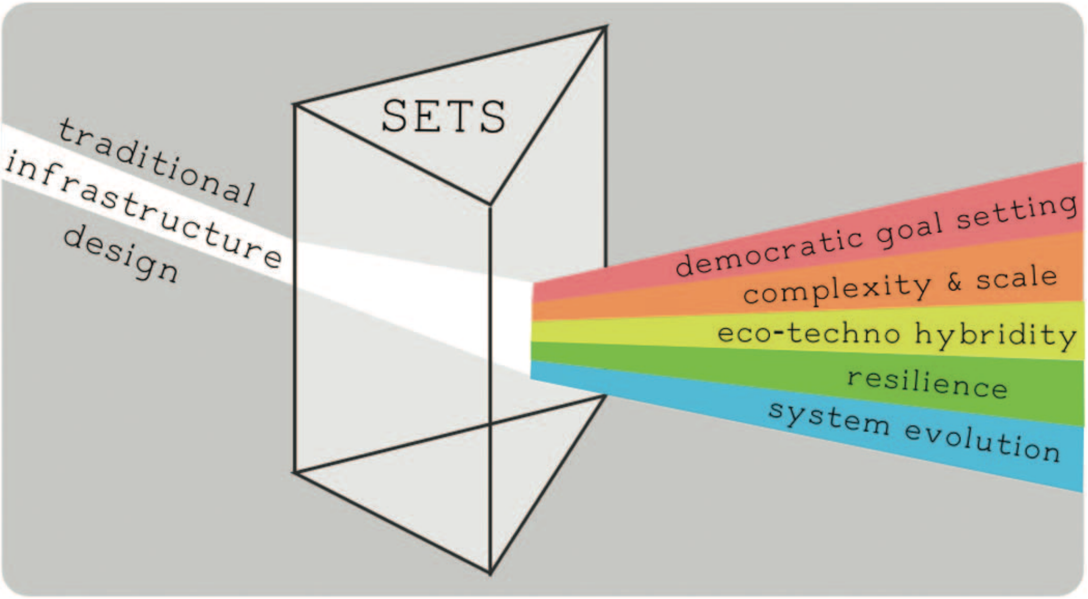
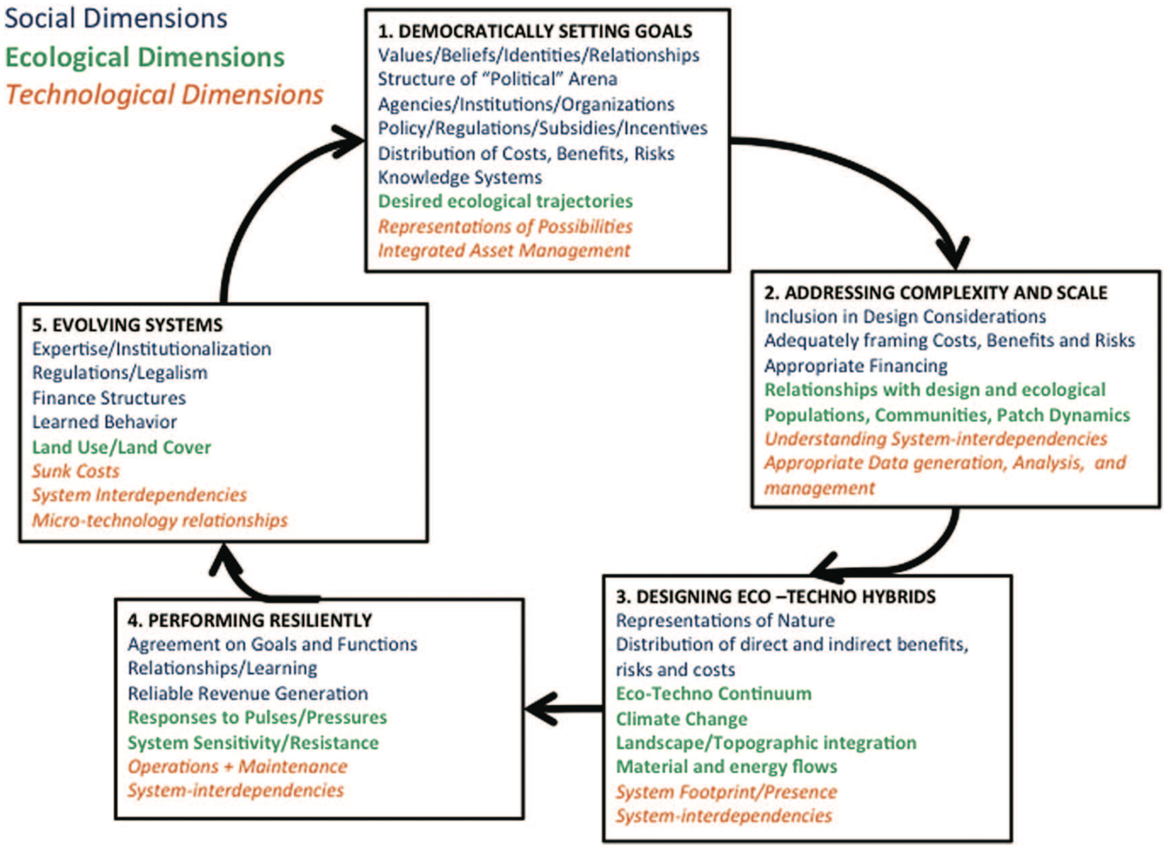


Figure 2. Infrastructure lifecycle through the SETS prism; each consideration has several nested components relating to how infrastructure is designed, operated, and evolved



Goals are defined as an infrastructure system's ultimate purpose, be it the provision of safe, reliable transport; clean drinking water; or dependable electricity. Goals fundamentally constrain the definition of costs, benefits, and financing of a given project and set up the trade-offs to be negotiated. They are a reflection of the values, identities, beliefs, and relationships of those at the goal-setting table. Thus, prior to any technical discussion of the efficiency of providing services, discussions need to focus on the context- specific desirability of services and options for delivering them.

Historically, large infrastructure spending programs reflected both specific political, social, and cultural projects and collective imaginaries that envisioned human progress as embodied in large, centralized technologies (Jasanoff and Kim 2013). The authors posit that a current shift in thinking calls for a new representation of possibilities, including both technical models and media presentations of systems that utilize technological change to preserve ecological security and integrity at local, regional, and planetary scales; it is a call to articulate desired ecological trajectories of clean air and water and resilient, biodiverse, and beautiful ecosystems vital to human well-being.

ASCE has embarked upon a promising approach to meeting these shifting demands through its integrated systems approach. Integrating between infrastructure systems should allow for cost savings in terms of installation and maintenance (although with in- creased costs during design), as in the case of dedicated bundled utility service corridors. Without such physical integration, many municipalities and nations face the challenge of attempting to create integrated asset management systems on top of spatially and administratively fractured systems (Halfawy 2008; Meite 2015; Shahata and Zayed 2010). Although such approaches represent the cutting edge of infrastructure management, their cost savings, risk reductions, and performance improvements would be much higher if the design process were similarly integrative; in both cases integration must bring together the many stakeholders needed to plan and maintain a diverse integrated system (ASCE 2009). Although the more open design process may hold the key to providing a forum for collaboration on infrastructure design, opening the process of decision making further complicates the neatness of designed solutions and requires changes to the current structure of the political arena (including bureaucracies and agencies) surrounding infrastructure design and operation.

Addressing Complexity and Scale

Infrastructure systems operate at different spatial, temporal, and social scales, and their successful implementation requires that they adequately deal with the complexity inherent in crossing scales. Most straightforwardly, crossing scales adds complexity to calculating the distribution of infrastructure effects in terms of service provision, cost recovery/revenue generation, and the apportionment of risks. Unintended consequences may accumulate downstream of infrastructure interventions, as evidenced by increased flood risk downstream of traditional flood defenses such as dikes and hardened banks (Wheater and Evans 2009). Likewise, consequences may accrue differentially over time, and subsequent generations may be harmed or reap the benefits of projects (Stirling 2010).

A SETs perspective makes apparent not only the complexities of how technological systems interact, but also how interdependencies between different processes at different scales can be harnessed to improve system function and lower unit costs. It becomes apparent that broad categorizations of urban form (e.g., residential, commercial, industrial, high/low density) are not particularly useful for characterizing ecological and technological relationships, even though housing types may predict coarse gradients of ecosystem service provision (Tratalos et al. 2007). Additionally, a large body of literature on how cities function as agents in global networks of infrastructure (Tranos and Gertner 2012) requires bridging global political boundaries to local levels while remaining cognizant of over privileging the local (Jun 2013) when conceptualizing infra- structure. To deal with issues of scaling, it becomes critical to first accurately characterize drivers affecting the process at hand (e.g., climatic, landscape, and hydrogeomorphological drivers affecting flooding, stormwater management, drinking water, and/or energy provision in a complex hydraulically engineered landscape) and match the scale of the process to the scale of the intervention. Citywide modeling at superfine scales may be necessary to appropriately integrate ecological and technological systems, at least through current decision-making systems, especially as predetermined topographic/geomorphic boundaries are not necessarily relevant to many ecological processes (Post et al. 2007).

Lastly, different disciplines and sectors have different foci on very different spatial, temporal, and social scales. Acknowledging scale dependency of different analytical frameworks will be required to address those types of scale incompatibilities. The generation of knowledge academically as well as operationally around infrastructure must take scale dependencies into account when generating data, as well as analyzing operations, maintenance, and management.

Designing Ecological-Technological Hybrids

The ecological-technological hybridity of urban infrastructures highlights the interdependency of ecosystems and built infrastructures. All human-built infrastructure is embedded in an ecological system; ecology and earth systems form the background, base parameters, and many of the component pieces of the services provided by infrastructure (Carse 2012; Edwards 2003). During the design process, particular representations of natural processes be- come fixed in design criteria, including metaphysical ideas about how nature works [e.g., resilience, frailty (Gunderson and Holling 2002)] and technically constructed models of biophysical processes, such as climate change projections. Careful attention must be paid to the actual representativeness of these social and technical constructs in order to adequately design systems.

From a purely ecology-based approach to infrastructure, humans simply act as another ecological engineer (Smith 2007), capable of transforming their physical habitat for their benefit in ways that impose, improve, and worsen conditions for other members of the ecological community. Research on urban metabolism (Kennedy et al. 2007; Pincetl et al. 2012; Wolman 1965) and industrial ecology

(Erkman 1997) function to analyze and optimize industrial material, energy, and information flows at the landscape scale. Through the combination of these perspectives, infrastructures act as the multifunctional and redundant systems of a robust hybrid techno-ecosystem designed and operated by multiple ecological actors. As evidenced by emergent urban ecosystem services research (Millennium Ecosystem Assessment 2005; Potschin and Haines-Young 2011), green infrastructure designs intend to produce multiple benefits; however, benefit provision depends on where a facility falls along the ecological-technological continuum [see Royal Society (2014) for a similar treatment]. Explicitly analyzing the connections and interdependencies along an eco- techno continuum between technological and ecological systems transcends existing ways of thinking about the impacts of infra- structure decision-making just based on system footprints.

Such a multibenefit approach is illuminated by a SETs framing in which social and technical successes are inextricably linked to ecological function. For example, many cities already pursue joint strategies of improved stormwater management by increasing conveyance capacity through traditional grey infrastructure and reducing runoff rates to combined sewer systems by using distributed green infrastructure, such as Portland, Oregon, Philadelphia, and New York City. Green and grey facility types require different maintenance regimes (i.e., plants are managed differently than pipes), requiring different kinds of expertise at the local management level (Carlet 2015). However, if integrated wisely, such hybrid graygreen systems can provide functional certainty as well as co- benefits including ameliorating urban heat islands (Emmanuel and Loconsole 2015), improving air quality of indoor environments (Wang et al. 2014), enhancing the visual and recreational quality of development (Nazir et al. 2014), and contributing to urban renewal and city competitiveness (Bennett 2013; Philadelphia Water Department 2011). However, as with all infrastructure interventions, there exist inherent social conflicts over appropriate methods and consequences of urban renewal (Lubitow and Miller 2013).

Debate continues over such soft path versus hard path approaches toward infrastructure planning (e.g., Gleick 2003; Palmer et al. 2015; Muller et al. 2015); acknowledging hybridity in all approaches can resolve this debate by focusing instead on an appropriate degree of hybridity for the task at hand. Significant consensus on the value of ecosystems' infrastructural work has already created substantial policy instruments, such as the Water Resources Reform and Development Act of 2013. Ultimately, infrastructure systems evolve alongside and in relation to their resident ecologies; design should be flexible enough to anticipate change and robust enough to deliver under uncertainty.

Performing Resiliently

Traditional infrastructures are designed to operate reliably to reach the agreed upon goals and functions of the system, often in a fail- safe manner (Ahern 2011), and their resilience is often defined by their ability to continue to operate under surprise shocks (Rogers et al. 2012) or their ability to recover quickly and adapt to changing circumstances through networked architecture reinforcing learning behavior (Woods 2015). However, mounting challenges specifically related to climate change create wicked problems, defined by irreconcilable problem framings (Rittel and Webber 1973), manifest in disagreement over the relative desirability of using infra- structure to adapt to or to mitigate the impacts of climate change. While technical and political blocs argue over solutions, climatic conditions continue to shift with increasing variability exceeding known conditions (Seager et al. 2012), making fail-safe systems increasingly difficult to design and maintain.

With the advent of unpredictable hazards, a growing body of engineering literature attempts to move from the traditional approach of risk management toward an ecological-resilience approach within a systems-engineering framework, explicitly including the value of social learning and knowledge. Such an approach refers to an infrastructure systems' social, ecological, and technological ability to recognize and absorb variation, disturbances, and surprises (Hollnagel et al. 2007), often through adaptive management (Linkov et al. 2013). Systems approaches to resilience engineering embrace system dynamics (Fiksel 2003) and evolve systems through a constant cycle of anticipation, monitoring, and adaptation (Seager et al. 2012; Woods 2015).

These approaches can draw upon strategies developed by Ahern (2011) to integrate ecological interdependencies for enhancing resilience capacity; for example, redundancy—having multiple infrastructure components that could provide the same service in case of failure of one component. Although traditionally this has been seen as inefficient in optimized engineered systems (Park et al. 2013), integrated planning identifies a desirable level of redundancy for a system to continue to function when disturbed (Mitra et al. 2010). The strategy of multi-functionality in resilient infrastructural systems (Ahern 2011) can be leveraged using the notion of ecological-technological hybridity. Thus, multifunctional infrastructure can allow a smaller amount of space and funds to pro- vide the same benefits as multiple single-function infrastructures. For example, in the city of Rotterdam, spaces have been designed to be multifunctional: parks and basketball courts most of the time can serve as water storage facilities in times of flooding (Klinenberg 2013; Shorto 2014).

Alongside this sensitivity and resistance to pulses and pressures of physical systems, a key component of resilience is a system's social infrastructure, or the ways in which operators generate and share knowledge and experience through their networked relation- ships (often in unanticipated ways) to maintain function and minimize damage under extreme stress, as well as recover after extreme events (Aldrich and Meyer 2015) and more generally in day-to-day operations and maintenance (O+M). Previous disasters like the Chicago heat wave of 1995 and Hurricane Sandy in 2013 highlight the importance of social capital and community networks in pre- venting mass casualties. Extending the notion of social infrastructure beyond the confines of a single system, it becomes apparent that overall system resilience also requires sustainable economic connections and financing. Systems recoup costs either through revenue generation or through public expenditures requiring highly politicized financial administration, either of which critically deter- mines design parameters and O+M budgets. System resilience cannot be defined in isolation of how the system lives socially; adaption to change requires intelligent behavior before, during, and after its design phase, as well as a public that experiences its benefits as equitable rather than contributing to economic and social inequalities (Fernández et al. 2016).

An excessive focus on resilience, in all four senses of the word [system rebound, robustness, extensibility, and adaptability (Woods 2015)], neglects the more pressing need facing infrastructure systems—that of evolving the system. Such a consideration goes beyond emerging joint frameworks for analyzing sustainability and resilience, which certainly address numerous considerations articulated within this paper (Bocchini et al. 2014). However, it has become clear that infrastructure systems, and the sociopolitical relations that have produced them, are becoming primary drivers of risk generation to those systems, risks that continue to intensify the more the current system architecture is maintained, enhanced, and defended.

Such a claim will likely make many within the current infrastructure community of practice uncomfortable. However, in an era of intensifying climate change, rising economic and political inequality, and clamoring demand for new services and economic structures, the infrastructure community cannot continue to defend outmoded, increasingly obsolete and maladaptive forms of infra- structure planning, design, and governance. Efforts will be better spent thinking creatively about how to evolve.

Evolving Systems

The last stage in this framework pertains to infrastructure systems' evolution, which critically must overcome constraints on innovation. In theory, it would be quite easy to utilize current calls for infrastructure investment to significantly improve and redesign existing infrastructure systems. However, in the existing planning and policy environment, legal, regulatory, and institutional structures have privileged particular forms of expertise and created both physical and intellectual path dependencies via sunk costs in social and technological infrastructures. Often, political and financial decision makers choose to make incremental fixes to existing systems in the face of knowledge that incremental fixes are inadequate (Hommels 2005). In this sense, a financial path dependency occurs, where obdurate modes of infrastructure spending accumulate costs over time, neglecting spending on preventative measures and locking-in undesirable trajectories (Kong and Frangopol 2003). Obduracy refers to the inability to evolve a system despite recognized need for change and, less dramatically, constrains the directions in which the system can evolve despite recognition of new goals and design considerations. When designing infrastructure systems of the future, planned obsolescence may be a key yet underappreciated component of infrastructural evolution (Lemer 1996). Modular and appropriately scaled systems that meet the demands of shifting demographics (Ansar and Pohlers 2014), overcoming routinized learned behavior (Star 1999), and adapting to changing environments (Infrastructure Climate Change Impacts: Report Card 2015) may prove to be even more effective.

With the advent of regulation of waste disposal practices [a social and economic decision with technological consequences (Melosi 1990)], many cities in the United States were historically forced to confront the challenge of no longer discharging untreated sewage into open water bodies using combined sewer infrastructure. Many opted to channel both storm and sanitary systems to centralized wastewater treatment plants before discharge. However, changes in storm frequencies and continued population growth has overwhelmed the capacity of these combined systems, causing major ongoing water quality and public health issues. Due to the perceived high cost of separating combined sewer systems, most municipalities opt to maintain the existing pipe network (EPA 2004), and increase capacity by increasing the size of central conveyance arteries and treatment plants, as in the case of Portland, Oregon's Big Pipe project, and in the current London Thames Tideway Tunnel Projects. Although often touted as cheaper than separating systems, such centralized projects incur enormous long-term costs associated with financing and miss opportunities to derive additional services from system wide improvements. These systems continue to face large uncertainties in future performance requirements due to changing flooding frequencies around the continental United States (Melillo et al. 2014), exacerbated by in- creased runoff rates from ongoing land use (Grimm et al. 2008), and further complicated in coastal regions by rising sea levels (Hallegatte et al. 2013).

These factors highlight the interplay between the complexity of anticipating multiscalar changes in system parameters and socially negotiating desirable developmental pathways. Broader patterns of land use and urban development affect infrastructure path- ways in more ways than stormwater volume increases; patterns of built environment development fundamentally define infrastructure needs and costs by defining service density and demand. Thus, urban and spatial planning should ideally be utilized to coordinate long-term development trajectories with infrastructure needs as an explicit part of the planning calculus.

Overcoming physical path dependencies and cost barriers, large-scale infrastructure integration and evolution faces the challenge of bringing together managers and agencies across a range of disciplines and overcoming barriers to public engagement. Traditionally, specific agencies with relevant expertise managed particular types of infrastructure at politically determined scales, e.g., municipal, state, or federal levels. Bridging existing silos requires coordination of conflicting perspectives and expertise as well as diverse funding sources and budget allocations. The ASCE has identified interdisciplinary coordination as a key to infrastructure planning and management and has stated that the failure to share knowledge across agencies can compromise the system's ability to properly function under extreme events (ASCE 2009). On the municipal level, New York City provides one example of successful inter-department coordination for infrastructure management: the New York City Department of Parks and Recreation, Department of Environmental Protection (DEP), and Department of Transportation (DOT) have forged a coordinated effort to implement bioretention swales in city sidewalks that will manage stormwater runoff in addition to providing co-benefits like pollinator habitat and shade (NYC DEP 2013). On the federal level, the U.S. Department of Housing and Urban Development (HUD), DOT, and EPA have formed a partnership to coordinate housing and transportation development in pursuit of creating more sustain- able communities (EPA 2014). However, agency coordination without public engagement around qualitatively different goals will not evolve systems.

New Directions for Infrastructure Systems

Achieving sustainable, integrated infrastructural systems requires an interdisciplinary research approach that bridges the silos of different expertise, forms of governance, and social worlds (Lave et al. 2014). The infrastructure community will also need to work across spatial, temporal and organizational scales: microscopic to global, seconds to centuries, species to ecosystems, town halls to Congress and beyond.

Overall, the authors hope to invigorate research and dialogue around infrastructure systems in order to guide investments that wisely integrate into ecosystems, provide for improved social well-being, and utilize the best technical knowledge. The real test for this framing will be its application in live infrastructure planning processes open to public and expert participation. Such a framework lends itself readily to analysis of both opportunities to improve the effective management and investments in existing infrastructure systems, as well as providing a platform for thinking about how to evolve infrastructure systems to meet a wider variety of socially conscious and environmentally friendly goals while providing for human well being. The authors hope a stimulated interdisciplinary discussion will help the infrastructure community collectively en- vision new infrastructure ideal, sustainably utilizing humans' vast transformational capabilities to better the human condition while improving relations with the rest of life on earth.

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References for Chapter 1:

Ahern, J. (2011). "From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world." *Landscape and Urban Planning*, 100(4), 341–343.

Aldrich, D. P., and Meyer, M. A. (2015). "Social Capital and Community Resilience." *American Behavioral Scientist*, 59(2), 254–269.

Alexander, C. (1977). *A pattern language: towns, buildings, construction*. Oxford University Press, New York.

Amati, M., and Taylor, L. (2010). "From Green Belts to Green Infrastructure." *Planning Practice and Research*, 25(2), 143–155.

Ansar, A., and Pohlers, M. (2014). "Fluid populations, immobile assets: Synchronizing infrastructure investments with shifting demography." *International Area Studies Review*, 17(2), 222–248.

ASCE. (2009). *Guiding Principles for the Nation's Infrastructure*. American Society of Civil Engineers (ASCE) Critical Infrastructure Guidance Task Committee.

ASCE. 2013. 2013 Infrastructure Report Card. http://www.infrastructurereportcard.org/making-the-grade/report-card-history/2013-report-card/

ASCE. 2017. 2017 Infrastructure Report Card. http://www.infrastructurereportcard.org/

Barbier, E. (2010). *A global green new deal: rethinking the economic recovery*. Cambridge University Press, Cambridge ; New York.

Basu, S., and Weil, D. N. (1998). "Appropriate Technology and Growth." *The Quarterly Journal of Economics*, 113(4), 1025–1054.

Batty, M., Axhausen, K. W., Giannotti, F., Pozdnoukhov, A., Bazzani, A., Wachowicz, M., Ouzounis, G., and Portugali, Y. (2012). "Smart cities of the future." *The European Physical Journal Special Topics*, 214(1), 481–518.

Bennett, R. (2013). *EcoDISTRICTS Framework Concept for Metro Portland*.

Bocchini, P., Frangopol, D. M., Ummenhofer, T., and Zinke, T. (2014). "Resilience and Sustainability of Civil Infrastructure: Toward a Unified Approach." *Journal of Infrastructure Systems*, 20(2), 4014004.

Carlet, F. (2015). "Understanding attitudes toward adoption of green infrastructure: A case study of US municipal officials." *Environmental Science & Policy*, 51, 65–76.

Carse, A. (2012). "Nature as infrastructure: Making and managing the Panama Canal watershed." *Social Studies of Science*, 42(4), 539–563.

Collins, S. L., Carpenter, S. R., Swinton, S. M., Orenstein, D. E., Childers, D. L., Gragson, T. L., Grimm, N. B., Grove, J. M., Harlan, S. L., Kaye, J. P., Knapp, A. K., Kofinas, G. P., Magnuson, J. J., McDowell, W. H., Melack, J. M., Ogden, L. A., Robertson, G. P., Smith, M. D., and Whitmer, A. C. (2011). "An integrated conceptual framework for long-term social–ecological research." *Frontiers in Ecology and the Environment*, 9(6), 351–357.

Comes, T., & Van de Walle, B. (2014). Measuring disaster resilience: the impact of Hurricane Sandy on critical infrastructure systems. In Proceedings of the eleventh international ISCRAM conference, University Park, Pennsylvania, USA (pp. 195-204). Pdf online at: http://w.iscram.org/legacy/ISCRAM2014/papers/p18.pdf

Crawford, J., and French, W. (2008). "A low-carbon future: Spatial planning's role in enhancing technological innovation in the built environment." *Energy Policy*, 36(12), 4575–4579.

Derrible, S. (2016). "Urban infrastructure is not a tree: Integrating and decentralizing urban infrastructure systems." *Environment and Planning B: Planning and Design*.

Dueñas-Osorio, L., Craig, J. I., Goodno, B. J., and Bostrom, A. (2007). "Interdependent response of networked systems." *Journal of Infrastructure Systems*, 13(3), 185–194.

Edgar, A., and Sedgwick, P. R. (Eds.). (1999). *Key concepts in cultural theory*. Key concepts series, Routledge, London ; New York.

Edwards, P. N. (2003). "Infrastructure and Modernity: Force, Time, and Social Organization in the History of Sociotechnical Systems." *Modernity and Technology*, T. J. Misa, P. Brey, and A. Fennberg, eds., MIT Press, 185–225.

Egyedi, T. M., and Mehos, D. C. (Eds.). (2012). *Inverse infrastructures: disrupting networks from below*. Edward Elgar, Cheltenham, UK ; Northhampton, MA.

Emmanuel, R., and Loconsole, A. (2015). "Green infrastructure as an adaptation approach to tackling urban overheating in the Glasgow Clyde Valley Region, UK." *Landscape and Urban Planning*, 138, 71–86.

EPA. (2004). *Report to Congress on the Impacts and Control of CSOs and SSOs*. Washington, DC.

EPA. (2014). *HUD-DOT-EPA Partnership for Sustainable Communities*.

Fernández, I., Manuel-Navarrete, D., and Torres-Salinas, R. (2016). "Breaking Resilient Patterns of Inequality in Santiago de Chile: Challenges to Navigate towards a More Sustainable City." *Sustainability*, 8(8), 820.

Fiksel, J. (2003). "Designing Resilient, Sustainable Systems." *Environmental Science & Technology*, 37(23), 5330–5339.

Food and Agriculture Organization of the United Nations (Ed.). (2011). *FAO in the 21st Century: Ensuring Food Security in a Changing World*. Food and Agriculture Organization of the United Nations, Rome.

Gabrys, J. (2014). "Programming environments: environmentality and citizen sensing in the smart city." *Environment and Planning D: Society and Space*, 32(1), 30–48.

Gaston, K. J., Ávila-Jiménez, M. L., and Edmondson, J. L. (2013). "REVIEW: Managing urban ecosystems for goods and services." *Journal of Applied Ecology*, (J. Jones, ed.), 50(4), 830–840.

Gleick, P. H. (2003). "Global freshwater resources: soft-path solutions for the 21st century." *Science*, 302(5650), 1524.

Graham, S., and Marvin, S. (2001). *Splintering urbanism: networked infrastructures, technological mobilities and the urban condition*. Routledge, London ; New York.

Greene, D. L., and Wegener, M. (1997). "Sustainable transport." *Journal of Transport Geography*, 5(3), 177–190.

Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J., Bai, X., and Briggs, J. M. (2008). "Global Change and the Ecology of Cities." *Science*, 319(5864), 756–760.

Grimm, N. B., Grove, J. G., Pickett, S. T., and Redman, C. L. (2000). "Integrated Approaches to Long-Term Studies of Urban Ecological Systems Urban ecological systems present multiple challenges to ecologists—pervasive human impact and extreme heterogeneity of cities, and the need to integrate social and ecological approaches, concepts, and theory." *BioScience*, 50(7), 571–584.

Gross, M. (2010). *Ignorance and Surprise: Science, Society, and Ecological Design*. MIT Press.

Gunderson, L. H., and Holling, C. S. (Eds.). (2002). "Chapter 1: In quest of a theory of adaptive change." *Panarchy: understanding transformations in human and natural systems*, Island Press, Washington, DC.

Haimes, Y. Y., and Jiang, P. (2001). "Leontief-based model of risk in complex interconnected infrastructures." *Journal of Infrastructure Systems*, 7(1), 1–12.

Halfawy, M. R. (2008). “Integration of Municipal Infrastructure Asset Management Processes: Challenges and Solutions.” *Journal of Computing in Civil Engineering*, 22(3), 216–229.

Hall, J. W. (Ed.). (2016). *The future of national infrastructure: a system-of-systems approach*. Cambridge University Press, New York.

Hallegatte, S., Green, C., Nicholls, R. J., and Corfee-Morlot, J. (2013). “Future flood losses in major coastal cities.” *Nature Climate Change*, 3(9), 802–806.

Hollnagel, E., Woods, D. D., and Leveson, N. (2007). *Resilience engineering: Concepts and precepts*. Ashgate Publishing, Ltd.

Hommels, A. (2005). *Unbuilding cities: obduracy in urban socio-technical change*. Inside technology, MIT Press, Cambridge, Mass.

“Infrastructure Climate Change Impacts: Report Card 2015.” (2015). Living with Environmental Change.

“Infrastructure Week 2016.” (2015). *Infrastructure Week*, <http://infrastructureweek.org/about/> (Sep. 7, 2016).

Innes, J. E., and Booher, D. E. (2010). *Planning with complexity: an introduction to collaborative rationality for public policy*. Routledge, Milton Park, Abingdon, Oxon ; New York, NY.

Jacobson, M. Z., and Delucchi, M. A. (2009). “A path to sustainable energy by 2030.” *Scientific American*, 301(5), 58–65.

Jasanoff, S., and Kim, S.-H. (2013). “Sociotechnical Imaginaries and National Energy Policies.” *Science as Culture*, 22(2), 189–196.

Jones, P., Lannon, S., and Williams, J. (2001). “Modelling building energy use at urban scale.” 1683–1697.

Jones, V., and Conrad, A. (2008). *The green-collar economy: how one solution can fix our two biggest problems*. HarperOne, New York.

Jovane, F., Yoshikawa, H., Alting, L., Boër, C., Westkamper, E., Williams, D., Tseng, M., Seliger, G., and Paci, A. (2008). “The incoming global technological and industrial revolution towards competitive sustainable manufacturing.” *CIRP Annals-Manufacturing Technology*, 57(2), 641–659.

Jun, K.-N. (2013). “Escaping the Local Trap? The role of community-representing organizations in urban governance.” *Journal of Urban Affairs*, 35(3), 343–363.

Kahn Jr, P. H. (1999). *The human relationship with nature: Development and culture*. The MIT Press.

Karlsson, R. (2014). “Theorizing sustainability in a post-Concorde world.” *Technology in Society*, 39, 1–9.

Kemp, R. (1994). “Technology and the transition to environmental sustainability.” *Futures*, 26(10), 1023–1046.

Kennedy, C., Cuddihy, J., and Engel-Yan, J. (2007). “The changing metabolism of cities.” *Journal of industrial ecology*, 11(2), 43–59.

Klinenberg, E. (2013). “Adaptation.” *New Yorker*.

Kong, J. S., and Frangopol, D. M. (2003). "Evaluation of Expected Life-Cycle Maintenance Cost of Deteriorating Structures." *Journal of Structural Engineering*, 129(5), 682–691.

Lave, R., Wilson, M. W., Barron, E. S., Biermann, C., Carey, M. A., Duvall, C. S., Johnson, L., Lane, K. M., McClintock, N., Munroe, D., Pain, R., Proctor, J., Rhoads, B. L., Robertson, M. M., Rossi, J., Sayre, N. F., Simon, G., Tadaki, M., and Van Dyke, C. (2014). "Intervention: Critical physical geography." *The Canadian Geographer / Le Géographe canadien*, 58(1), 1–10.

Lee, A. C. K., and Maheswaran, R. (2011). "The health benefits of urban green spaces: a review of the evidence." *Journal of Public Health*, 33(2), 212–222.

Lemer, A. (1996). "Infrastructure Obsolescence and Design Service Life." *Journal of Infrastructure Systems*, 153–161.

Linkov, I., Eisenberg, D. A., Bates, M. E., Chang, D., Convertino, M., Allen, J. H., Flynn, S. E., and Seager, T. P. (2013). "Measurable Resilience for Actionable Policy." *Environmental Science & Technology*, 130903081548008.

Lubitow, A., and Miller, T. R. (2013). "Contesting Sustainability: Bikes, Race, and Politics in Portlandia." *Environmental Justice*, 6(4), 121–126.

Manuel-Navarrete, D. (2015). "Double coupling: modeling subjectivity and asymmetric organization in social-ecological systems." *Ecology and Society*, 20(3).

McKinney, M. L. (2006). "Urbanization as a major cause of biotic homogenization." *Biological conservation*, 127(3), 247–260.

Meite, M. (2015). "An integrated approach for municipal infrastructure interventions management." Concordia University.

Melillo, J. M., Richmond, Terese (T. C.), and Yohe, G. W. (2014). "Climate Change Impacts in the United States: The Third National Climate Assessment."

Melosi, M. V. (1990). "Cities, Technical Systems and the Environment." *Environmental History Review*, 14(1/2), 45.

Melosi, M. V. (2008). *The sanitary city: environmental services in urban America from colonial times to the present*. History of the urban environment, the University of Pittsburgh Press, Pittsburgh, Pa.

Millennium Ecosystem Assessment. (2005). *Ecosystems and Human Wellbeing Synthesis*. Synthesis.

Mitra, A., Bennett, T., Henderson, J., McDowell, B., and Wright, R. (2010). *Planning Infrastructure to Sustain America: Next Generation Concepts to Guide the Community, Design, and Infrastructure Professions*. American Society of Civil Engineers (ASCE) Task Committee on Planning for Sustainable Infrastructure.

Monstadt, J. (2009). "Conceptualizing the political ecology of urban infrastructures: insights from technology and urban studies." *Environment and Planning A*, 41(8), 1924–1942.

Muller, M., Biswas, A., Martin-Hurtado, R., and Tortajada, C. (2015). "Built infrastructure is essential." *Science*, 349(6248), 585–586.

Nazir, N. N. M., Othman, N., and Nawawi, A. H. (2014). "Green Infrastructure and its Roles in Enhancing Quality of Life." *Procedia - Social and Behavioral Sciences*, 153, 384–394.

NYC DEP. (2013). *NYC Green Infrastructure: 2012 Annual Report*.

Palmer, M. A., Liu, J., Matthews, J. H., Mumba, M., and D'Odorico, P. (2015). "Manage water in a green way." *Science*, 349(6248), 584–585.

Pandit, A., Minné, E. A., Li, F., Brown, H., Jeong, H., James, J.-A. C., Newell, J. P., Weissburg, M., Chang, M. E., Xu, M., Yang, P., Wang, R., Thomas, V. M., Yu, X., Lu, Z., and Crittenden, J. C. (2015). "Infrastructure Ecology: An Evolving Paradigm for Sustainable Urban Development." *Journal of Cleaner Production*.

Park, J., Seager, T. P., Rao, P. S. C., Convertino, M., and Linkov, I. (2013). "Integrating Risk and Resilience Approaches to Catastrophe Management in Engineering Systems: Perspective." *Risk Analysis*, 33(3), 356–367.

Perrow, C. (1999). *Normal accidents living with high-risk technologies*. Princeton University Press, Princeton, N.J.

Philadelphia Water Department (PWD). (2011). *Green city, clean waters: the City of Philadelphia's program for combined sewer overflow control*.

Pincetl, S., Bunje, P., and Holmes, T. (2012). "An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes." *Landscape and Urban Planning*, 107(3), 193–202.

Post, D. M., Doyle, M. W., Sabo, J. L., and Finlay, J. C. (2007). "The problem of boundaries in defining ecosystems: A potential landmine for uniting geomorphology and ecology." *Geomorphology*, 89(1–2), 111–126.

Potschin, M. B., and Haines-Young, R. H. (2011). "Ecosystem services: Exploring a geographical perspective." *Progress in Physical Geography*, 35(5), 575–594.

Pulselli, R., Simoncini, E., Pulselli, F., and Bastianoni, S. (2007). "Emergy analysis of building manufacturing, maintenance and use: Em-building indices to evaluate housing sustainability." *Energy and buildings*, 39(5), 620–628.

Rinaldi, S., Peerenboom, J., and Kelly, T. (2001). "Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies." *IEEE Control System Magazine*.

Rittel, H. W., and Webber, M. M. (1973). "Dilemmas in a general theory of planning." *Policy sciences*, 4(2), 155–169.

Rogers, C. D. F., Bouch, C. J., Williams, S., Barber, A. R. G., Baker, C. J., Bryson, J. R., Chapman, D. N., Chapman, L., Coaffee, J., Jefferson, I., and Quinn, A. D. (2012). "Resistance and resilience – paradigms for critical local infrastructure." *Proceedings of the Institution of Civil Engineers - Municipal Engineer*, 165(2), 73–83.

Royal Society (Great Britain). (2014). *Resilience to extreme weather*.

Sahely, H. R., Kennedy, C. A., and Adams, B. J. (2005). "Developing sustainability criteria for urban infrastructure systems." *Canadian Journal of Civil Engineering*, 32(1), 72–85.

Seager, T., Selinger, E., and Wiek, A. (2012). "Sustainable Engineering Science for Resolving Wicked Problems." *Journal of Agricultural and Environmental Ethics*, 25(4), 467–484.

Shahata, K., and Zayed, T. (2010). "Integrated decision-support framework for municipal infrastructure asset." *Proceedings of the Pipelines 2010 Conference. Keystone, CO. doi*, 420.

Sharkey, T. C., Nurre, S. G., Nguyen, H., Chow, J. H., Mitchell, J. E., & Wallace, W. A. (2015). Identification and classification of restoration interdependencies in the wake of Hurricane Sandy. Journal of Infrastructure Systems, 22(1), 04015007. DOI: 10.1061/(ASCE)IS.1943-555X.0000262

Shorto, R. (2014). "How to think like the Dutch in a post-Sandy world." *New York Times*.

Smith, B. D. (2007). "The ultimate ecosystem engineers." *SCIENCE-NEW YORK THEN WASHINGTON-*, 315(5820), 1797.

Star, S. L. (1999). "The Ethnography of Infrastructure." *American Behavioral Scientist*, 43(3), 377–391.

Stirling, A. (2010). "Keep it complex." *Nature*, 468(7327), 1029–1031.

Tranos, E., and Gertner, D. (2012). "Smart networked cities?" *Innovation: The European Journal of Social Science Research*, 25(2), 175–190.

Tratalos, J., Fuller, R. A., Warren, P. H., Davies, R. G., and Gaston, K. J. (2007). "Urban form, biodiversity potential and ecosystem services." *Landscape and urban planning*, 83(4), 308–317.

Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kaźmierczak, A., Niemela, J., and James, P. (2007). "Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review." *Landscape and Urban Planning*, 81(3), 167–178.

Wang, Y., Bakker, F., de Groot, R., and Wörtche, H. (2014). "Effect of ecosystem services provided by urban green infrastructure on indoor environment: A literature review." *Building and Environment*, 77, 88–100.

Wates, N. (2014). *The community planning handbook: how people can shape their cities, towns and villages in any part of the world*. Routledge, New York, NY.

Wheater, H., and Evans, E. (2009). "Land use, water management and future flood risk." *Land Use Policy*, 26, S251–S264.

WHO Global Urban Ambient Air Pollution Database. (2016). World Health Organization.

Winkler, J., Dueñas-Osorio, L., Stein, R., and Subramanian, D. (2011). "Interface network models for complex urban infrastructure systems." *Journal of Infrastructure Systems*, 17(4), 138–150.

Wolman, A. (1965). "THE METABOLISM OF CITIES." *Scientific American*, 213, 179–190.

Woods, D. D. (2015). "Four concepts for resilience and the implications for the future of resilience engineering." *Reliability Engineering & System Safety*, 141, 5–9.

Chapter 2: Fracturing dams, fractured data: Empirical trends and characteristics of existing and removed dams in the United States

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Abstract: Dam removals in the United States continue to accelerate in pace and scope, but no national analyses have examined how removed dams compare with existing dam stock. Here, we review and analyse the best available national data on dams from the National Inventory of Dams (NID), dam removals from American Rivers, the U.S. Geological Survey, and the National River Restoration Science Synthesis databases to compare trends and characteristics of removed versus existing dams in the United States. If historical trends continue, by 2050 the United States can expect between 4,000 and 36,000 total removals, including 2,000–10,000 removals of NID dams. Best-fit regression models estimate total costs between $50.5 million and $25.1 billion (mean $10.5 billion, median $416.5 million) for all removals and $29.6 million to $18.9 billion (mean $7.2 billion, median $285 million) for NID removals, a significant cost savings over present stated dam rehabilitation needs. Structural characteristics and ages of documented removals are not representative of existing dams, with privately owned hydroelectric dams subject to public oversight and water supply dams the most disproportionately removed. We conclude that dam removal science would benefit from the creation of an interdisciplinary framework for studying dams as

environmental, social, and technological interventions, facilitated by transparent datasets around dams and removals and reflexive research approaches that combine statistical approaches with place-based analyses.

1 INTRODUCTION

Following the release of the Oroville dam spillway incident report (IFT, 2018), an urgent need remains for systematic assessment of the state of existing dams in the United States to avoid loss of life, property, and critical infrastructure function (Phillips 2017, Nunez 2017, Ho et al. 2017, NEST 2017). At the same time, dam removal has become a mainstream option for dam safety management (Wildman 2002) and restoring river and coastal ecosystems and the human communities that depend on them (Doyle et al. 2008, Pittock and Hartmann 2011, Beck et al. 2012, Lovett 2014, O'Connor et al. 2015, Tullos et al. 2016). In the USA, over 1,300 documented removals (AR, 2016) have attracted international attention due to the potential for large-scale river restoration through improved infrastructure policy (McCulloch 2008, Barraud 2011). Today, documented removals of dams over 6ft (1.8m) tall have outpaced documented dam constructions in the United States (AR 2016, NID 2016). Yet only a few analyses have examined whether removals represent existing dam stock, with two exceptions being Magilligan et al.'s (2016) comparison of heights and basin characteristics for existing and removed dams in New England, and Foley et al.'s (2017) comparison of landscape context and a few dam variables of scientifically evaluated removals and existing dams within the

National Inventory of Dams (NID). No analysis to date has investigated how representative removals are of the existing dam stock in terms of their functions and construction type, limiting our understanding of what processes drive removal as a rehabilitation option. While shifts in the political economy of river and infrastructure management may be driving removals (Lowry 2003, Hawley 2011, McCool 2012), the major considerations of dam safety management - operational, functional, and engineering dimensions of dams as infrastructures - remain largely absent in the dam removal literature. Disciplinary and sectoral differences in the ontology and epistemology of dams and removals have thus fractured dam data, science, and governance. This paper provides an overview of available data on dams and removals in the USA, analyzes trends in dam building and removal, and estimates numbers of removals and associated costs through 2050. Our conclusions point towards promising research avenues for investigating the likelihood of dam removals of different classes. Drawing upon our results, we make three major recommendations for improving dam removal science.

2 DATA AND METHODS

We examined the American Rivers Dam Removal Database (AR DRD - AR, 2016), the United States Geological Survey's database of dam removals associated with peer-reviewed literature (the USGS DRD, from Bellmore et al. 2017), and a database of dam removals with before and after studies (the BAR DRD from Foley et al. 2017), and compared them against the NID (obtained by request from

USACE-NID (2016) (see Tables 1, 2, and 3). The USGS DRD is generally inclusive of the BAR DRD, although the two databases represent two levels of scientific scrutiny.

While there are an estimated 2-2.5 million dams in the USA (NRC, 1992), the ~90,000 dams in the NID are commonly referenced as they are the only national scale inventory of dams. The NID was authorized by Congress in 1972, directing the Army Corps of Engineers to inventory all dams higher than 25ft (7.6m) and/or impounding at least 50 acre ft. (6.2e-5 km^3), excluding those less than 6 ft. (1.8m) or with storage below 15 acre ft. (1.8e-5 km^3), unless deemed by the FEMA Director to be a public safety hazard (ASDSO 2014).

American Rivers annually compiles the AR DRD from projects they were involved in and voluntary reports from partner organizations (Jessie Thomas-Blate, *personal communication*). The BAR and USGS DRDs contain removal dam NID identifiers, though since the AR DRD does not, it was divided into subsets of dams of differing probabilities of inclusion in the NID based on height, those over 25ft (7.6m) (high likelihood), over 6ft (1.8m) (moderate likelihood). We also evaluated shifts in removals over time by creating three subsets of the AR DRD of dams removed prior to 1999 (the mainstreaming of dam removal), during the first decade of major dam removals (2000-2010), and dams removed during the last 5 years of complete data (2011-2015). Additional cost data on dam removals was obtained from the

National River Restoration Science Synthesis (NRRSS) database (Bernhardt et al. 2005).

2.1 Descriptive Statistics and Dam Age

We summarized each database from above in terms of the number (n) of dams in each database, n reporting for each data field, as well as summary statistics and results of Welch's two-sided t-tests (from the base R package stats - R core team 2016) for quantitative variables with n > 15 (Table 1). The distributions of build year, removal year, and age of existing and removed dams were examined for normality using Shapiro-Wilkes (R core team, 2016), and multi-modality using the package 'diptest' (Maechler 2015). Parametric (Welch's), non-parametric (Kendall's) t-tests, and a linear model ('lm' in R base package 'stats' – R core team (2016)), were utilized to examine correlations between dam build and removal years.

2.2 Functions, Types, and Ownership of Removed and Existing Dams

Dam primary type and function (defined by the NID as the first listed and reclassified within the AR DRD to match NID categories) of removed dams from the AR DRD, USGS, and BAR subsets were compared against dams in the NID (Tables 1, 2, 3, and Figure 5). Given that over 75% of dam removals with a documented build year were built prior to 1940 and only 25% of NID dams were built prior 1940, we also performed a separate comparison of removed and existing dams built pre-1940. Motivations for removal were also examined for the USGS and BAR data.

Table 1. Summary statistics for the 2016 AR DRD, subsets over 25ft (7.6m) (AR h>25), 6ft (1.8m) (AR h>6), and the NID. For categorical variables, 'n' refers to the number of dams reporting values for that variable, and '%' refers to reporting. For quantitative variables, 'Mn' refers to mean, 'Md' refers to median, and SD refers to standard deviation. For numerical variables with n > 15, Welch's Two Sample T-test results with $p < 0.05$ indicated by **bold for differences between AR DRD subsets and overall AR DRD (excluding subset from main);** * indicates difference between AR h>6 and AR h>25**,** and *Italic for differences between AR subsets and the NID.*

	AR DRD	**AR DRD > 6ft (1.8m)**	**AR DRD > 25ft (7.6m)**	**NID 2016**	**AR DRD <1999**	**AR DRD 1999-2010**	**AR DRD 2011-2015**
Cat. Variables							
n	1293	705	147	90580	309	522	354
Lat/Long	1107 (85%)	606 (86%)	129 (88%)	NA	203 (66%)	482 (92%)	350 (99%)
Primary Function	520 (40%)	320 (45%)	51 (35%)	84054 (93%)	9 (3%)	218 (42%)	228 (64%)
Primary Material	496 (38%)	320 (45%)	46 (32%)	87116 (96%)	12 (4%)	211 (40%)	264 (75%)
Owner	608 (47%)	358 (51%)	56 (38%)	NA	9 (3%)	287 (55%)	281 (80%)
Quant. Variables							
Dam Height (ft/m)		*	*				
n (%)	***930 (72%)***	***705 (100%)***	***147 (100%)***	*90576 (100%)*	***251 (81%)***	**317 (60%)**	*282 (80%)*
mean	***14.7/4.5***	***18.2/5.5***	***41.0/12.5***	*26.8/8.2*	***20/6.1***	**11.2/3.4**	*12.7/3.9*
median	***10.0/3.0***	***13.0/4.0***	***33.0/10.1***	*23/7.0*	***14/4.3***	**8/2.4**	*8/2.4*
Stdev	***15.8/4.8***	***16.7/5.1***	***24.4/7.4***	*27.9/8.5*	***18.1/5.5***	**9/2.7**	*18.7/5.7*
Dam Length (ft)							
n (%)	**585 (45%)**	**404 (57%)**	**57 (39%)**	NA	**91 (29%)**	**224 (43%)**	259 (73%)
mean	**215.2/65.5**	**264/80.5**	**417/127.1**		**269/82.0**	**180.6/55.1**	224.4/68.4
median	**112/34.1**	**160/48.8**	**300/91.4**		**170/51.8**	**100/30.5**	100/30.5
Stdev	**313.6/95.6**	**358/109.1**	**347/105.7**		**343.8/104.8**	**217.5/66.3**	369.7/112.7
Year Built							
n (%)	*437 (34%)*	*285 (40%)*	*48 (33%)*	*76359 (84%)*	24 (8%)	134 (26%)	130 (37%)
mean	*1915*	*1914*	*1917*	*1960*	1910	1916	1910
median	*1921*	*1920*	*1920*	*1964*	1909	1918	1922
Stdev	*43.4*	*40*	*32.6*	*29.4*	40.2	36.8	49.3
Year Removed		*	*				
n (%)	1185 (92%)	637 (90%)	123 (84%)	NA			
mean	2003	2001	1996				
median	2007	2006	1995				
Stdev	13.6	15.1	15.8				
Rem. Cost (1000s $		*	*				
n (%)	**298 (23%)**	**173 (25%)**	**16 (10%)**	NA	***11 (4%)***	**137 (26%)**	*148 (42%)*
mean	**1076**	**1293**	**8937**		***118.1***	**780.5**	*1832.5*
median	**102**	**160**	**480**		***125***	**83**	*141.7*
Stdev	**6565**	**7128**	**22311**		***81***	**3626.6**	*9142.1*

2.3 Trends, Empirical Removal Probabilities, and Cost Estimates

Time series of AR DRD and the over 6ft (1.8m) tall subset were constructed and examined for trends using linear and exponential forms with R package 'stats' (R Core team 2016), and checked for step changes using the function "breakpoints" in package strucchange in R (Zeileis et al. 2003). Using the 'predict' function (R package 'stats') upper, lower and fitted annual removal totals for different trend lines were estimated (Table 3). Historical empirical probabilities of NID dam removal from 1915 to 2015 were estimated using the following formula (Figure 4.a.):

$$\text{removal\_p}_{\text{year i}} = \text{removals}_{\text{year i}} / (\text{existing\_dams}_{\text{year i}} + \text{removals}_{\text{year i}}) \quad \text{[eq. 1]}$$

where, $\text{removal\_p}_{\text{year i}}$ = the removal probability in year i, $\text{removals}_{\text{year i}}$ = the number of removals over 6ft (1.8m) tall in year i, and $\text{existing\_dams}_{\text{year i}}$ = the number of existing dams in year i derived from cumulative sums of dams in the current NID. We added in removals in the denominator as the NID deletes removed dams from the inventory (USACE, *personal communication*. A second order polynomial (best fit model) using 'lm' (as above) was fit to the time series of removal_p from 1978 to 2015, and the function 'predict' (as above) was used to obtain a 95% prediction confidence envelope of removal probabilities for years from 2017 through 2050 (Figure 4.b.), with regression equation below:

$$removal\_p_i = 8.256e\text{-}04 * YEAR^2 + 2.805e\text{-}04 * YEAR + 2.178e\text{-}04 \text{ [eq. 2] } (R^2 = 0.808) \text{ [eq. 2]}$$

With these annual removal probabilities, total future removals ($f\_removals_{year\ i}$) were estimated using a step function with equations 3 and 4:

$$f\_removals_{year\ i} = f\_removal\_p_{year\ i} * existing\_dams_{year\ i} \text{ [eq. 3]}$$

$$existing\_dams_{year\ i+1} = existing\_dams_{year\ i} - f\_removals_{year\ i} \text{ [eq. 4]}$$

where $f\_removal\_p_{year\ i}$ is the fitted future removal probability. As dam building has decreased steeply in the US, this model includes no new dams being built through 2050; however, if included, removal numbers would increase given model structure.

For the above regressions, all terms are highly significant ($p < 0.001$). The lower 5% from the over 6ft (1.8m) tall AR DRD (as the NRRSS has no height information) and the median, mean, and upper 95% values from the NRRSS were used with estimates of annual total removals to estimate the range of costs in Table 3.

Table 2. (right) Comparison of dam characteristics from the BAR DRD, the USGS DRD, and the AR DRD. Welch's T-test results with p<0.05 indicated by **bold for differences between the BAR DRD and USGS DRD,** *italic for differences between the AR DRD and the BAR DRD,* and * for differences between the USGS DRD and the AR DRD. (left) Comparison of subsets dams with a NID ID in the BAR and USGS DRDs and the NID. Welch's T-test results with p<0.05 indicated by **bold for differences between the BAR_NID and USGS_NID,** *italic for differences between the BAR_NID and NID,* and * for differences between the USGS_NID and the NID**.**

Database	**BAR DRD (n=61)**	**USGS DRD (n=122)**	**AR DRD (n=1293)**	**BAR_NID (n=28)**	**USGS_NID (n=52)**	**NID (n=90580)**
Categorical Variables						
Rem. Motivation	41 (67%)	75 (61%)	NA	21 (75%)	38 (73%)	NA
Dam Function	54 (88%)	88 (72%)	608 (47%)	28 (100%)	52 (100%)	84054 (93%)
Quantitative Variables						
Year Dam Completed					*	*
n (%)	54 (88%)	104 (85%)	437 (34%)	*28 (100%)*	51 (98%)	*76359 (84%)*
mean	1918	1908	1915	*1912*	1909	*1960*
median	1921	1914	1921	*1916*	1914	*1964*
Stdev	36	45	43.4	38	36	29.4
Year Removed		*	*			
n (%)	***55 (90%)***	**122 (100%)**	*1185 (92%)*	*28 (100%)*	52 (100%)	NA
mean	***2004***	**1993**	*2003*	*2004*	*2000*	NA
median	***2006***	**1999**	*2007*	*2006*	*2000*	NA
Stdev	***6***	**21**	*13.6*	6.7	10	NA
Dam Height (ft./m)						
n (%)	56 (92%)	103 (84%)	1293 (100%)	28 (100%)	52 (100%)	90576 (100%)
mean	19.2/5.8	20/6.1	14.7/4.5	25/7.62	25.8/7.9	26.8/8.2
median	13/3.9	13/3.9	10/3	16.7/5.1	14.6/4.5	23/7.0
Stdev	21/6.4	25.8/7.9	15.8/4.8	27.2/8.3	34/10.4	27.9/8.5
Dam Width (ft./m)		*	*			NA
n (%)	48 (79%)	81 (66%)	585 (45%)	*27 (96%)*	50 (96%)	NA
mean	282/86.0	301/91.7	215.2/65.6	*318/96.9*	322/98.1	NA
median	220/67.1	239/72.8	112/34.1	*269/82.0*	254/77.4	NA
Stdev	222/67.7	250/76.2	313.6/95.6	*223/68.0*	244/74.4	NA
Dam Reservoir Vol (af/km^3)					*	*
n (%)	33 (54%)	62 (51%)	NA	*28 (100%)*	52 (100%)	90580 (100%)
mean	4066/5e-3	3188/4e-3	NA	*4771/5e-3*	3430/4e-3	16063/2e-2
median	350/4e-4	197/2e-4	NA	*420/5e-4*	200/2e-4	135/2e-4
Stdev	10334/1e-2	9141/1e-2	NA	*11097/1e-2*	9685/1e-2	963825/1.2

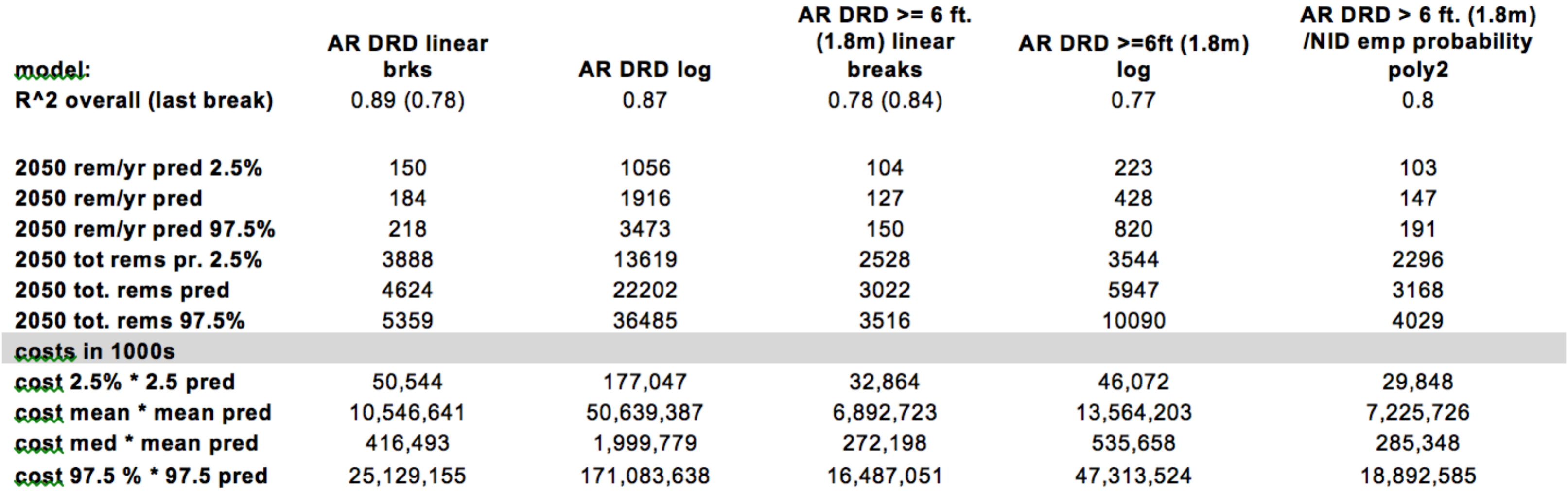
Table 3. Comparisons of functions of removed dams in the BAR, USGS, and AR DRD subsets compared against the NID. NID functions not in the DRDs omitted. N in the first row lists the number of dams in each database reporting a function, and n and % in subsequent rows is a percentage of those reporting. * Other is included as a comparison against mill dams although it likely contains other classes of dams as well.

PRIMARY FUNCTION	**BAR**	**BAR NID**	**USGS**	**USGS NID**	**AR DRD < 1999**	**AR DRD 2000-2010**	**AR DRD 2011-2015**	**AR > 25ft (7.6m)**	**AR > 6ft (1.8m)**	**AR < 6ft (1.8m)**	**NID 2016**
DB n	61	28	122	52	309	522	354	147	705	224	90580
n reporting	34 (83%)	28 (100%)	88 (72%)	52 (100%)	12 (4%)	218 (42%)	228 (64%)	51 (35%)	296 (42%)	98 (44%)	84054 (93%)
flood control	2 (5%)	1 (4%)	2 (2%)	1 (2%)	0	7 (3%)	7 (3%)	0	5 (2%)	5 (5%)	16179 (19%)
fish pond	0	0	0	0	0	10 (5%)	11 (5%)	1 (2%)	13 (4%)	7 (7%)	4930 (6%)
hydrolectric	30 (73%)	21 (75%)	51 (57%)	30 (58%)	4 (33%)	37 (17%)	26 (11%)	16 (31%)	44 (15%)	7 (7%)	2114 (3%)
irrigation	7 (17%)	1 (4%)	12 (14%)	2 (4%)	0	14 (6%)	30 (13%)	8 (16%)	23 (8%)	13 (13%)	7706 (9%)
mill / other *	6 (15%)	0	0	0	5 (42%)	55 (25%)	46 (20%)	2 (4%)	73 (25%)	21 (21%)	8462 (10%)
farm/fire pond	0	0	0	0	0	11 (5%)	5 (2%)	0	7 (2%)	0	10781 (13%)
recreation	6 (15%)	3 (11%)	18 (20%)	16 (31%)	0	24 (11%)	54 (24%)	6 (12%)	58 (12%)	18 (8%)	25394 (30%)
water supply	3 (7%)	2 (7%)	5 (6%)	3 (6%)	3 (25%)	58 (27%)	48 (21%)	18 (35%)	72 (24%)	26 (27%)	5628 (7%)

Table 4. Comparisons of primary type and ownership for the AR DRD subsets and the NID.

	AR DRD < 1999	AR DRD 2000-2010	AR DRD 2011-2015	NID 2016	AR > 25ft (7.6m)	AR > 6ft (1.8m)	AR < 6ft (1.8m)
n	309	522	354	90580	147	705	224
Pr. TYPE	9 (3%)	211 (40%)	264 (75%)	87116 (96%)	46 (31%)	320 (45%)	126 (56%)
concrete buttress	0	1 (0.4%)	0	292 (0%)	1 (2%)	1 (0.3%)	0
concrete	6 (67%)	127 (60%)	141 (53%)	2907 (3%)	13 (28%)	159 (50%)	90 (71%)
rockfill	0	6 (3%)	9 (3%)	1096 (1%)	0	8 (3%)	5 (4%)
masonry	0	1 (0.4%)	4 (2%)	888 (1%)	0	4 (1%)	1 (1%)
other	0	4 (2%)	3 (1%)	906 (1%)	0	2 (1%)	3 (2%)
concrete gravity	0	2 (1%)	2 (1%)	2579 (3%)	0	3 (1%)	1 (1%)
earth fill	2 (22%)	43 (20%)	66 (25%)	78225 (90%)	30 (65%)	102 (32%)	6 (5%)
stone	1 (11%)	14 (7%)	28 (11%)	23 (0%)	0	27 (8%)	13 (10%)
timber crib	0	13 (6%)	10 (4%)	48 (0%)	1 (2%)	13 (4%)	6 (5%)
arch	0	0	1 (0%)	98 (0%)	1 (2%)	1 (0%)	1 (1%)
OWNERSHIP	10 (3%)	177 (34%)	230 (65%)	90088 (99%)	44 (30%)	260 (37%)	98 (43%)
County	0	5 (3%)	24 (10%)	NA	1 (2%)	12 (5%)	16 (16%)
Municipality	1 (11%)	34 (19%)	63 (27%)	NA	9 (20%)	59 (23%)	26 (14%)
Local Govt.*	1 (11%)	39 (22%)	87 (38%)	18091 (20%)	10 (22%)	71 (27%)	42 (42%)
Private	2 (22%)	76 (43%)	91 (40%)	58148 (65%)	20 (45%)	115 (44%)	34 (34%)
Public Utility	3 (33%)	18 (10%)	4 (2%)	3846 (4%)	9 (20%)	17 (7%)	NA
Non-Profit	1 (11%)	14 (8%)	8 (3%)	NA	1 (2%)	10 (4%)	7 (7%)
State Agency	2 (22%)	24 (14%)	31 (13%)	6622 (7%)	3 (7%)	38 (15%)	9 (5%)
Fed. Agency	0	6 (3%)	8 (3%)	3381 (4%)	1 (2%)	8 (3%)	3 (2%)
Tribal	0	0	1 (0%)	NA	0	1 (0%)	0

Table 5. Comparisons of detected linear trends in dam removals, empirical annualized removal probability, and associated cost projections.



model:	**AR DRD linear brks**	**AR DRD log**	**AR DRD >= 6 ft. (1.8m) linear breaks**	**AR DRD >=6ft (1.8m) log**	**AR DRD > 6 ft. (1.8m) /NID emp probability poly2**
R^2 overall (last break)	0.89 (0.78)	0.87	0.78 (0.84)	0.77	0.8
2050 rem/yr pred 2.5%	150	1056	104	223	103
2050 rem/yr pred	184	1916	127	428	147
2050 rem/yr pred 97.5%	218	3473	150	820	191
2050 tot rems pr. 2.5%	3888	13619	2528	3544	2296
2050 tot. rems pred	4624	22202	3022	5947	3168
2050 tot. rems 97.5%	5359	36485	3516	10090	4029
costs in 1000s					
cost 2.5% * 2.5 pred	50,544	177,047	32,864	46,072	29,848
cost mean * mean pred	10,546,641	50,639,387	6,892,723	13,564,203	7,225,726
cost med * mean pred	416,493	1,999,779	272,198	535,658	285,348
cost 97.5 % * 97.5 pred	25,129,155	171,083,638	16,487,051	47,313,524	18,892,585

3 RESULTS AND DISCUSSION

3.1 Existing and Removed Dam Ages and characteristics

It is clear that the 'golden age' of dam building was from 1950 to 1980, when three to six dams in the NID were completed per day (Graf 1999, Babbit, 2002, Doyle et al. 2003), after 1980 dam building plateaued, declining steeply in 2006 to be currently outpaced by removals over 6ft (1.8m) tall (Figure 1.a. and b). Removed dams are on average 39 years older than existing dams (Figure 1.b and 2.a); by 2055, when the mean age of NID dams equals those in the AR DRD (95 years), over 51,000 dams will have ages within the 1st and 3rd quartiles of removed dams. To put these numbers in perspective, the Federal Emergency Management Administration (FEMA) estimates that the operational life span of approximately 76,990 dams (85% of the NID) ends in 2020 (Doyle et al. 2003).

There is no significant correlation between dam built and removal year for removed dams with both documented (n = 418 of 1293 in the AR DRD), explained by large differences in ranges years of their removal (mean(SD): 2003(13.6)) and building (mean(SD): 1915 (43.4), Figure 2), a finding which holds across all dam primary purpose and type classes. These results are not surprising, as no other analysis to date has found a statistically significant relationship between dam age and removal probability (Pohl 2002, Ashley, 2004, though see Lowry 2003), as dam maintenance and construction quality outweigh age in determining dam conditions (Jansen 2012, Wildman 2013). Empirical analyses of dam failures provide some insight, as 50% of dam failures occur within 5 years of operation (Regan 2009).

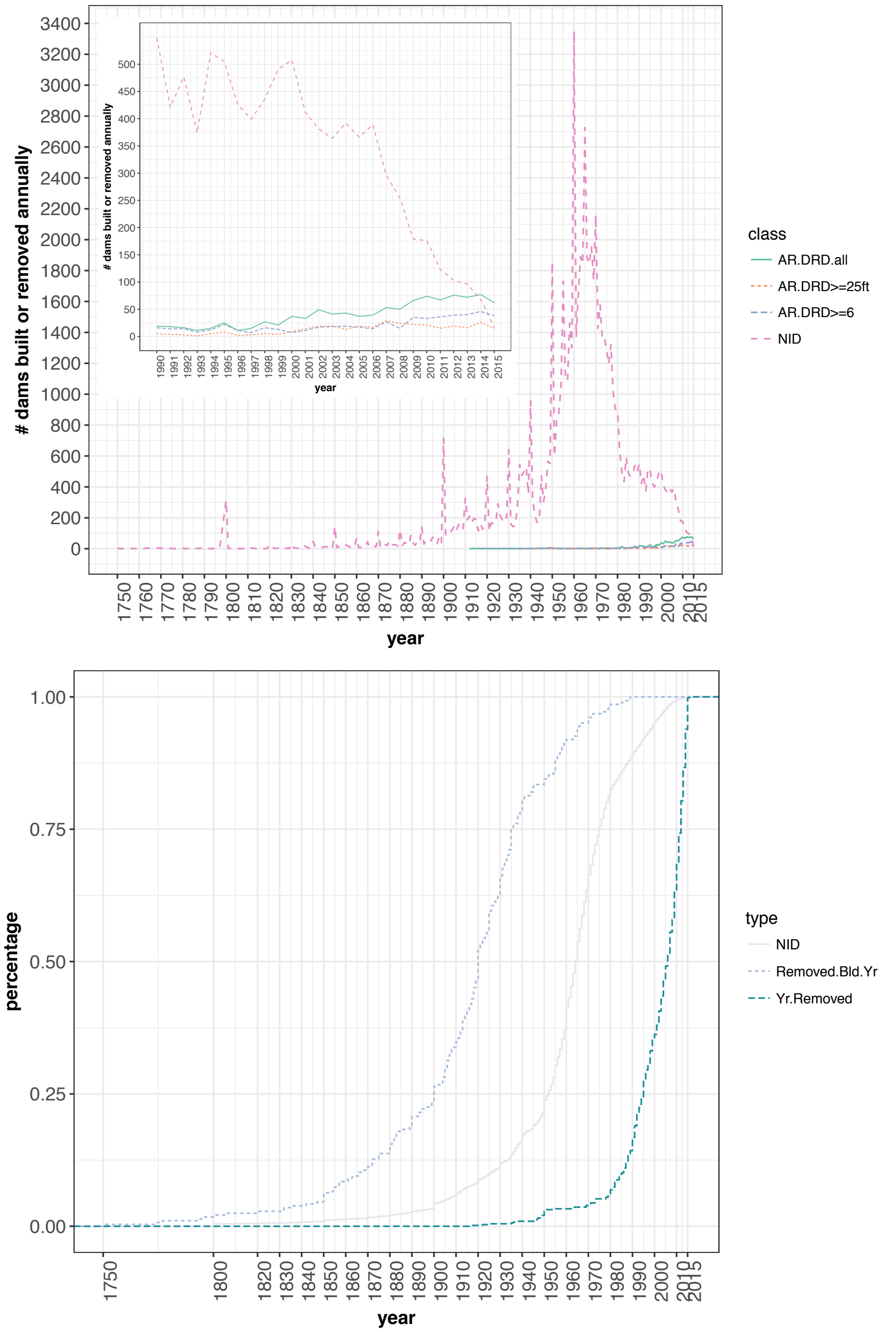


Figure 1. a) (top) All dam building and removals over time in the USA and since 1990 (inset), number of NID dams built (dashed line), all American River's documented removals (AR DRD, solid green line), over 6ft/1.8m tall (AR DRD >=6, dashed blue line), and over 25ft/7.6m tall (AR DRD >= 25ft, dotted red line). b) (bottom) Cumulative density of build years for removed dams (left dotted line), NID dams built (center purple line), and dams removed (right dashed line).

Otherwise, statistically significant differences exist between removed and existing dam heights, construction years, and reservoir volumes, although analyses are limited by a lack of comparable data fields (Tables 1 and 2). Interestingly, subsets of the USGS and BAR removals with NID identification numbers do not differ structurally from NID dams except for the characteristic of reservoir volume; removed dams have significantly smaller reservoirs (Table 2).

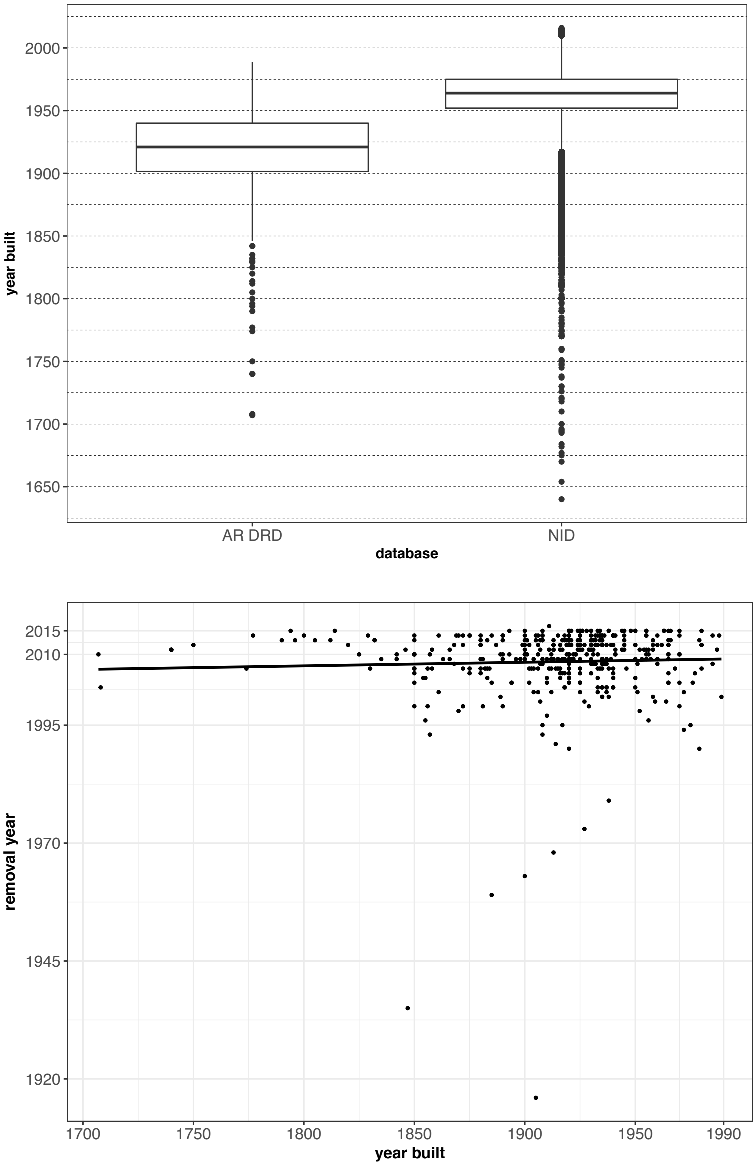


Figure 2. a) (top) Side by side box and whisker plots (center line = median, box = 1 and 3rd quartiles, whiskers = 1.5 * Inter Quartile Range, all points outlying) of build years for removed dams in the American Rivers Dam Removal Database (AR DRD n = 437 out of 1,293) and existing dams in the National Inventory of Dams (NID, n = 76,359 out of 90,580), and b) (bottom) scatterplot with regression line of build year vs removal year for all removed dams (n = 419).

3.2 Representativeness of Removed Dam Types, Functions, and Ownership

Information on dam types, function, and ownership has increased over time (Tables 3 and 4). However, removed dams do not represent primary dam functions of existing NID dams for any AR DRD subset (Figure 5). Examining differences based on size, function and time period, recreation and irrigation removals appear to be more prevalent in recent years, and there are some notable functional differences between size classes. Hydroelectric dams have been extremely disproportionately removed for all databases. Hydroelectric dam removals may be driven by periodic hydro-electric relicensing, a public hearing type process demanding regulatory compliance with a host of social and environmental regulations (Manahan and Verville 2004), lending further empirical support to the importance of democratic governance for river restoration (Lowry 2003). While hydroelectric dams are, as a class, older than other dam types in the NID (mean completion year of 1928 vs. 1961, Welch's $p < 0.001$), no significant correlation exists between hydro-dam completion year and removal year. Smaller 'other' (mostly old mill) dams and large irrigation dams are also over-represented, with flood control, fishponds, farm and fire ponds and recreation dams are all under-represented (Figure 5.a., Table 3). The majority of dams classified as 'Other' in the AR DRD are obsolete milldams, and historical preservation considerations may explain the under-representation of larger 'Other' dams. The over-representation of water supply dam removals contrasts with other studies (Hoenke et al. 2015), possibly due to 'water supply' not being differentiated into potable, industrial, or power generation uses, the replaceability of water supply, or ongoing surface water quality deterioration. While 78.6% of NID are single function, over 95% of removals are single function, not surprisingly since the majority of removed dams were dams built prior to the era of large multi-purpose dam building. Notably, removals with NID identification numbers also over represent hydroelectric dams, although major differences disappear for other primary functions.

Removals also do not represent NID dams with regards to dam type (Table 4, Figure 5.b.) particularly for concrete dams (extremely overrepresented) and earthfill dams (underrepresented), a counterintuitive finding. Earth fill dams do however make up over 60% of removals >25ft (7.6m) tall, likely because large earthfill dams are more susceptible to settling, overtopping, seepage, and other types of deformation (Jansen 2012). Interestingly, while single purpose dams are overrepresented in the AR DRD (indicating a relative lack of multi-functional dam removals), single type dams are underrepresented, indicating that composite dams may be more prone to deterioration and complex rehabilitation issues.

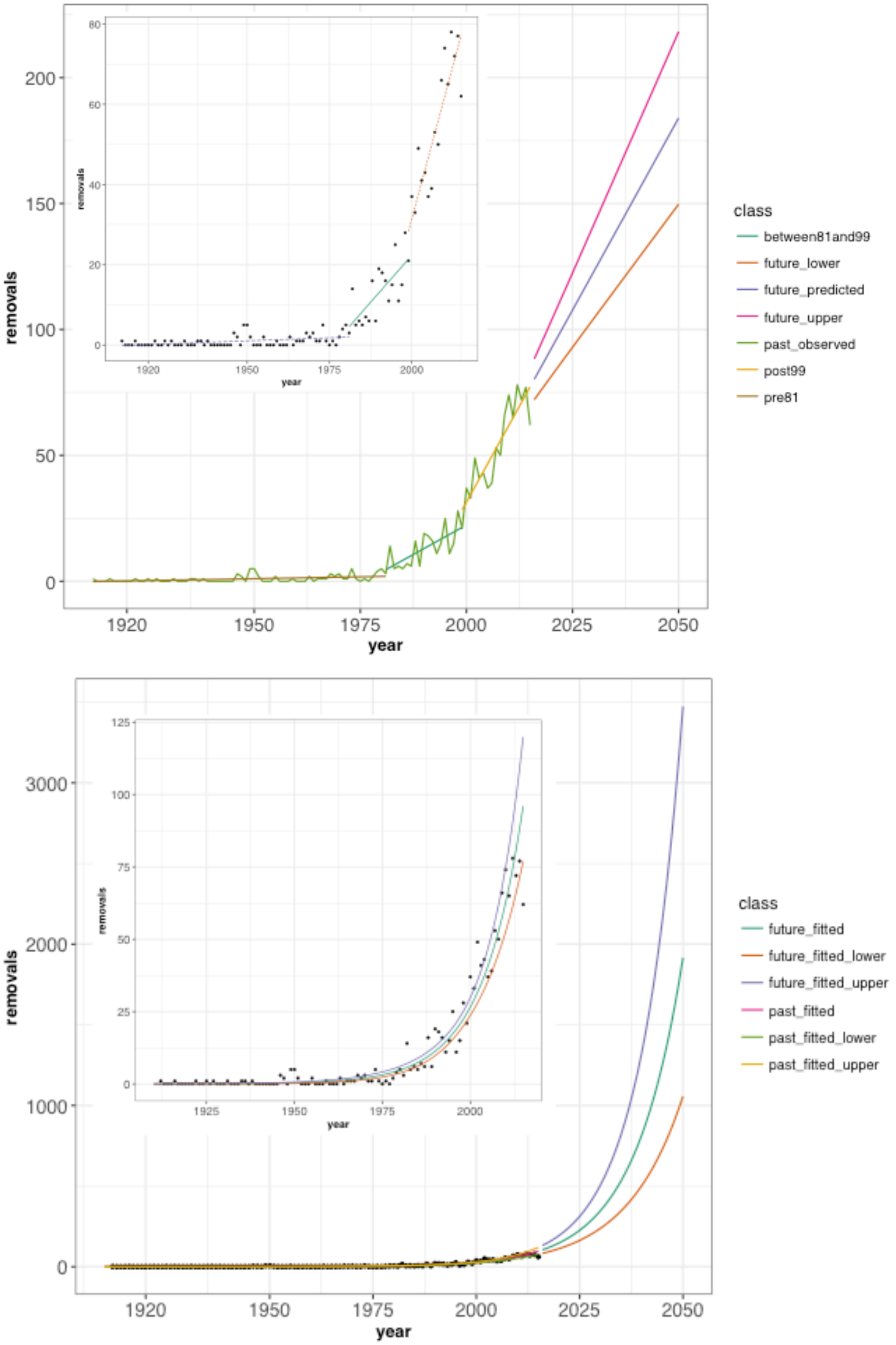


Figure 3. Time series of all removals with regression lines and 95% confidence intervals (inset) and with numbers of removals predicted until 2050 trend analysis a) (top) linear regression with two breakpoints (1981 and 1999) discovered using function breakpoints in R package strucchange (multiple R^2 = 0.89), and b) (bottom) using a logarithmic trend line using function glm post 1981 (multiple R^2 = 0.87).

3.3 Trends in dam building, dam removal, and associated costs

Annual removals have increased dramatically over time, appearing to increase exponentially since 1981 (Figure 3.b.). However, a linear regression with two trend breaks outperforms an exponential model (Figure 3a, Table 5), with one breakpoint in 1981, potentially indicating a lag between policy implementation and improved dam safety management (the first NID was created in 1976, ASDSO, 2014), and another breakpoint of 1999 coinciding with the creation of the American Rivers DRD, indicating potential reporting bias. The 1990s also saw the rise of the 'modern' period of dam removal with the development of major federal and state restoration programs (Lowry 2003, McCool 2012).

Removal probabilities fluctuate dramatically until the late 1970s, at which point they climb steadily due to slowdowns in dam building and increases in annual removal rates (Figure 4.a). If trends continue, we can expect between 4,000 and 36,000 total dam removals, including 2000 - 10,000 removals of NID dams by 2050. The lower 2.5%, median, and upper 97.5% of per removal costs from the > 6ft (1.8m) AR DRD (n = 184) are \$13,000, \$132,500, and \$2,955,000. The cost distribution has two outliers, the \$84 million and \$62 million dollar removals of the San Clemente and Great Works dams. The NRRSS (Bernhardt et al. 2005) has a cost distribution for dam removals with 2.5%, median, mean, and upper 97.5% of

$5,000, $90,072, $2,280,848, and $4,689,150 per removal. Large differences between models indicate an urgent need for improved class based cost

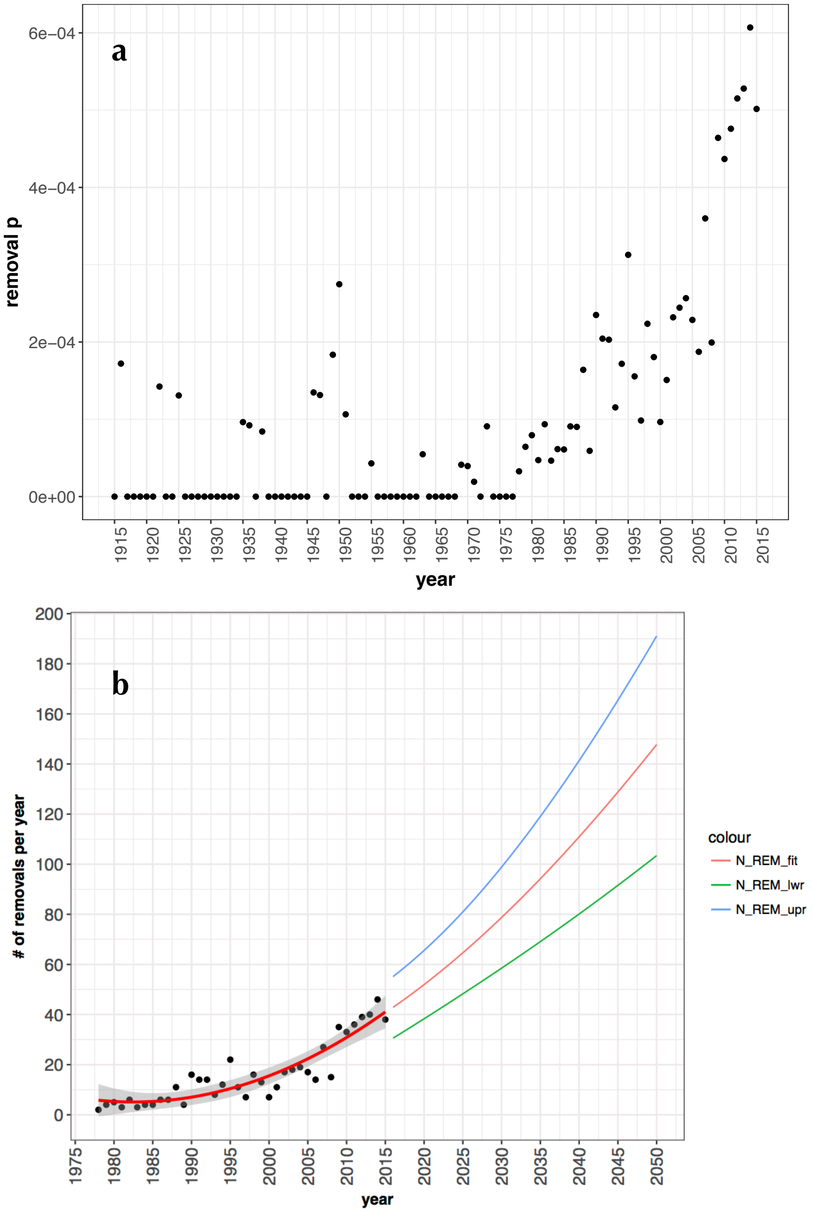


Figure 4. a) (top) Dam removal probabilities given national scale data for removals over 6 feet tall from the American Rivers Dam Removal Database (608 removals) and dams in existence from the National Inventory of Dams. b) (Bottom) b) Annual dam removals with fitted annual predictions based on empirical removal probability from historical values using eq. 2 removal_p_i = 8.256e-04 * YEAR^2 + 2.805e-04 * YEAR + 2.178e-04, all terms significant at $p < 0.001$, adjusted R^2 0.80, with upper and lower prediction intervals, and c) the number of dam removals observed (red) and predicted until 2050; upper 2.5 % confidence interval (purple), fitted (green), and lower 2.5% confidence interval (blue) using eq. from 4.b.

categorization and future removal likelihood estimates; using current data best fit models for all removals estimate cumulative 2050 costs between \$50.5 million and \$25.1 billion (mean \$10.5 billion, median \$416.5 million), and between \$29.6 million and \$18.9 billion (mean \$7.2 billion, median \$285 million) for all NID removals.

To frame these numbers, the ASCE (2017) estimates a need for over \$45 billion to repair and upgrade an estimated 2,170 structurally deficient high hazard dams (an average rehabilitation cost of \$20.7 million/dam), which includes an estimated \$25 billion needed to address deficiencies for the 709 USACE owned dams (\$35.2 million/dam); and the Association of State Dam Safety Officials (ASDSO, 2016) estimates a *present* need of \$64 billion to rehabilitate all US dam infrastructure (\$706,557/NID dam). These estimates of need will only increase over time, as federal funding for dam rehabilitation is currently not appropriated (ASCE 2017). Given these very large ranges likely due to regional and project level factors (Whitelaw and Macmullen 2002, Tonitto and Riha 2016), our goal with these estimates is not to provide absolute certainty in rates and costs of future removal, but to highlight the magnitude of trends, their economic relevance given other estimates of dam safety need, and make a case for more systematic data collection to refine our understanding and future projections.

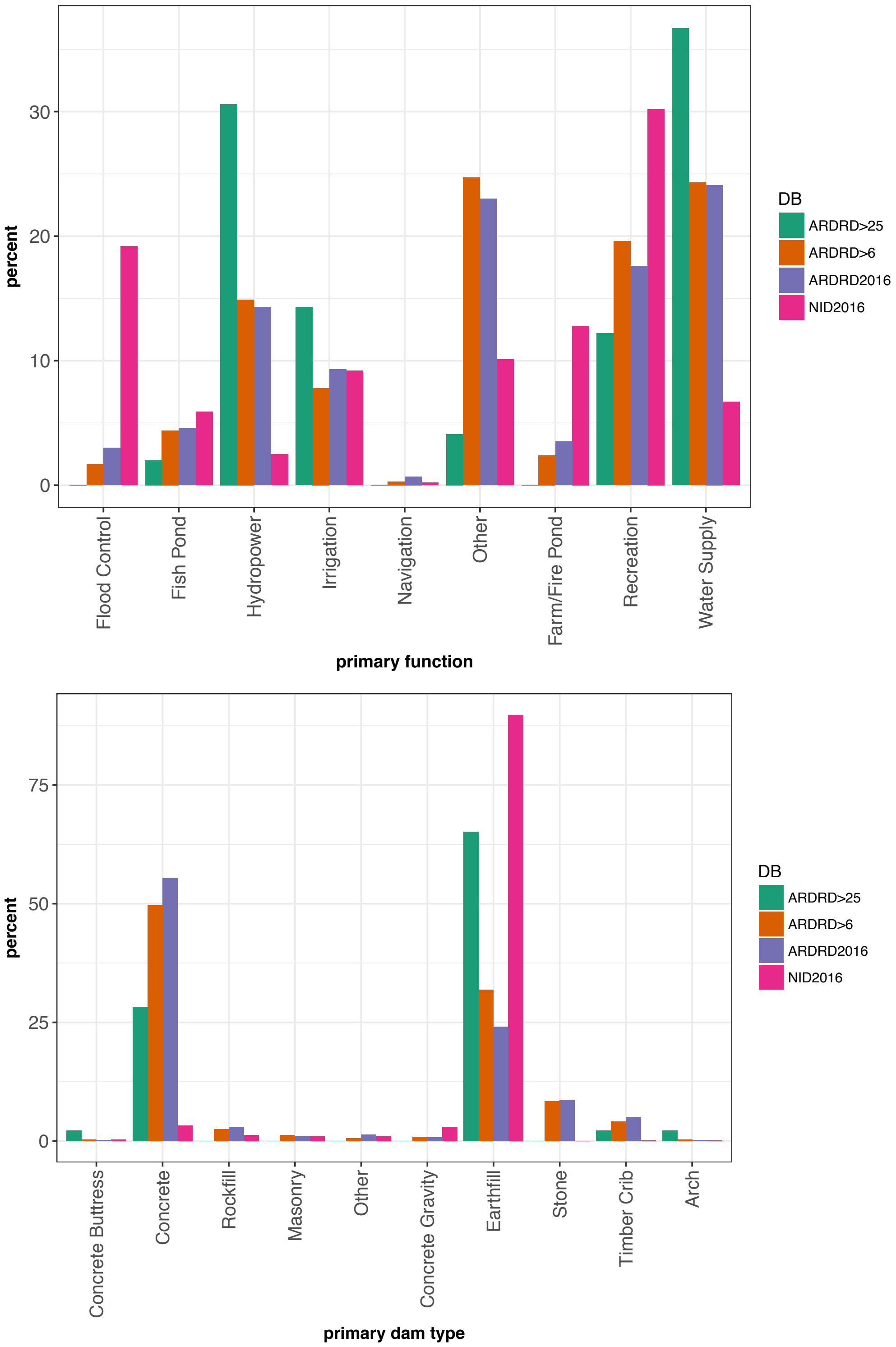


Figure 5. Comparisons of function and type of dams in the National Inventory of Dams (NID) and American Rivers Dam Removal Database (AR DRD) subsets, green = AR DRD > 25ft/7.6m, orange = AR DRD > 6ft / 1.8m, purple = all removals in AR DRD, pink = all dams in NID. A) (top) Primary function b) (bottom) primary type.

4 OPPORTUNITIES FOR IMPROVING DAM REMOVAL SCIENCE

Our analyses point to large expected increases in dam removal in the United States, although highlight unevenness in the functions and types of removed dams as compared against existing dam stock. Existing data points to the cost-effectiveness of dam removal as a rehabilitation option, however, findings indicate that the incidence and costs of dam removal has particular social and technological contingencies, meriting further analysis. Below, we lay out three key considerations for improving work examining the likelihood and rate of future removals and their associated costs.

4.1. Developing Interdisciplinary Frameworks

The lack of relationship between built and removal years may simply be a function of incomplete data sets, but is more likely a function of the influence of significant rehabilitation and maintenance operations. Thus, ongoing work on the engineering dimensions of dam management (Wildman 2013) should be integrated with analyses of their resident landscapes and ecosystems (Foley et al. 2017, Magilligan et al. 2016) and constellations of conflicting social interests (Magilligan et al. 2017). Despite this rich literature, dam removal science remains fragmented between largely biophysical evaluations of dam removal impacts, and the legal, policy, and social dimensions of removal decision making, both of which are largely disconnected from the dam rehabilitation literature. Such fragmentation mirrors that of general problems in the field of ecological restoration, which continues to struggle with framing multi-scalar drivers of river conditions when analyzing and planning river restoration programs (Bernhardt et al. 2005). One recently proposed framework of dams and removals as Political, Financial, Environmental, Social, and Technological Systems (PFESTS), has recently been proposed (Grabowski et al. 2017a). While that framework is preliminary, it may serve as a heuristic for stimulating discussion around how best to address the systemic complexity of dam removal decisions, including the influence of policies, social-environmental contexts, and socio-economics. In order for dam policy and analysis to be truly comprehensive, policy and research communities should combine knowledge and approaches from dam safety engineering, ecological restoration, social studies of science and technology, and the communities affected by dams and removals. Building a shared language and reflexive analytical framework for these disciplines to meaningfully engage diverse social actors remains a top priority.

4.2. Improve comparability and utility of dam and removal databases

A key component of building a shared language and approach for dam removal science will be improving and standardizing dam removal and dam databases for evaluating dam decision-making at the national, state, and local level. Most dam studies currently do not utilize strictly comparable data sets of existing dams and removals without qualifying their lack of comparability.

Ongoing regional analyses, such as the New England Sustainability Consortium's "Future of Dams" project (NEST, 2017), indicate large discrepancies between state dam inventories and the NID (Magilligan et al. 2016), including differences in defining dams and removals. Given differences in state level policy requirements for inventorying dams, combining state databases must be done with caution to ensure representativeness of data. Removal databases that do not attempt to qualify inclusion in comparable dam inventories can only be reliably compared against the nation's estimated two million un-documented dams (NRC 1992), currently an analytical impossibility. Removals are also inconsistently defined and reported, including inconsistencies in defining dam failures vs. removals, with some small reporting errors to the AR DRD known but not currently quantified. In the case of Wisconsin, where the state has identified over 900 removals and dam failures since the 19th century (WI DNR 2017) in contrast to the AR DRD's 127 WI documented removals since 1950 (AR DRD 2016). Thus, data sets on dams and dam removals must be transparent in their definitions of dams and removals, and will likely require further ground-truthing.

With comparable data sets in hand, the research community can continue to make headway on linking dam and removal data to a wide variety of relevant existing datasets. Similar to Foley et al.'s (2017) utilization of the National Anthropogenic Barrier Data Set (NABDS) and National Hydrography Dataset, these efforts can expand pre-existing databases such as the AR and USGS DRDs, although the

NABDS needs to be updated to include the 40,000+ dams added to the NID since 2009. Likewise, Foley et al.'s (2017) BAR DRD linkage to the National Fish Habitat Partnership (NFHP) database represents a promising approach for understanding the impacts and rationales of removals, though the NFHP should also be linked to datasets of existing dams (which would also provide controls for BAR studies). Additionally, data on dam operations currently contained with the NID could be improved on and linked to removals to improve the analysis of dam removal impacts. For example, Foley et al.'s (2017) analysis of BAR studies on impacts on stream thermal regimes show mixed responses to dam removal, but do not have information on the pre-removal dam operational regime which would either create an elevated (e.g., top spill or bypass reach), decreased (e.g., consistent bottom release), or mixed (intermittent bottom release) thermal pre-removal baseline. Similarly, in addition to the land use and land cover characteristics of existing and removed dams serving as proxies for anthropogenic stressors influencing river ecosystems (Foley et al. 2017), researchers could also include analyses of off-channel dams (Mantel et al. 2017), other barriers to fish passage (Januchowski-Hartley et al. 2013), and relevant socio-economic and demographic variables available from the US Census and American Community Survey that may indicate declines in dam utility. AR's recent decision to make its updated DRD publically available represents a step forward in dam removal science, and, if updated in its data fields, can facilitate analysis of dam removal likelihood, costs, and socio-ecological impacts.

4.3. Investigate contextual and systemic complexity of dams and removals

While the creation of interdisciplinary frameworks and robust comparative datasets will accelerate understanding and application of dam removal and restoration research, it is clear that contextual variables also drive dam removals. National and state dam policies must always interact with local contexts in removal decision-making (Chaffin and Gosnell 2017), although examining exactly how they do so requires building relationships with affected stakeholders in the course of place-based research.

In the context of the Americas, the resurgent practices of self-determination by indigenous communities, many of whom have been culturally and materially harmed by dam building (Fisher 2010), will continue to be a critical factor in driving dam removals. The centrality of practices have been documented in the case of numerous dam removals led by the Grand Traverse Band of Ottawa and Chippewa Indians (Fox et al. 2017), and the pivotal role of the Lower Elwha Klallam tribe in the largest dam removal in the world to date from the Elwha river (Guarino 2013). However, continued neo-colonial practices of dam building on Indigenous territories, such as the Site C dam's pivotal role within the "Industrialization of the North," (Lavoie 2015), also highlight the contingency and contestation of Tribal influence on the political economy of regional and national infrastructure development. We must therefore remain cognizant of how treaty rights and contestations influence broader infrastructural trajectories and dam futures and their intersections with national and state agricultural, trade, environmental, and energy policies (Hawley 2011). Without addressing this systemic and contextual complexity, dam removal may stall as a policy option, and at the project level contested removals can vastly increase project costs and undermine budgets available for follow up restoration activities (Becker 2006). Thus, identifying how local and systemic contexts influence project costs requires parsing for deconstruction, restoration, project management, administration, legal, and planning costs (Bonham 2008). At present, authorized federal funds for dam safety programs have yet to be appropriated (S 216 (2016), S 2735 (2006)), and the NID currently does not allow for public scrutiny of dam condition assessments, meaning owner level cost considerations and state dam safety programs will increasingly determine dam futures. Thus, researchers can be useful for improving dam decision-making by combining state and federal level economic analyses (Whitelaw and Macmullen 2002), with research on owner level considerations and experiences of dam removal and rehabilitation. Given the large interest in streamlining hydropower licensing processes and adding significant non-federally owned hydro-electric capacity in the USA (Bracmort *et al.* 2015), combined with the infrastructural turn of re-developing large water infrastructure systems in the United States in the face of climate change (Perry and Praskievicz, 2017), the evolution of the function of dams within complex infrastructure systems remains a pressing research need (Grabowski et al. 2017b).

5 CONCLUSION

Dam removal is established as a mainstream policy option to improve dam safety and restore socio-ecological systems. Yet, data on dams and removals remains fractured in disciplinary and administrative siloes, requiring the elaboration of frameworks and data sets for interdisciplinary analysis. Such a joint research and practice agenda represents an exciting opportunity to overcome historical antagonisms between infrastructure and ecosystem management. Failure to do so will increase administrative costs of removals, further entrenching inefficient systems with large bureaucratic overhead, primarily benefiting law firms (Lind 2015) and consultants (Becker, 2006), instead of deficient infrastructures, human communities, and damaged ecosystems. In an era of increasing political polarization on issues of economic security, regulatory certainty, labor justice, and the environment, the conservation and restoration community must continue to frame river restoration agenda around the alignment of those seemingly diverse interests (Jones 2009). Thus dam removal represents an inherently political practice, where decisions about appropriate human-river relations, including the role of aesthetics, history, identities, what is natural, and what is desirable all come to a head. Collaborations between communities, academics, policy makers, river dependent industries, and non-governmental organizations will provide the democratic basis for sound dam decision making within a broader arc of socio-technological evolution and environmental justice.

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References for Chapter 2:

American Rivers Dam Removal Database (2016a). Received from J. Thomas-Blate.

American Rivers (2016b). A Nation of Rivers: A River Conservation Agenda for the New Administration. Online at: https://www.americanrivers.org/conservation-resource/conservation-agenda-new-admin/ last accessed June 19, 2017

ASCE. (2017). 2017 Infrastructure Report Card. http://www.infrastructurereportcard.org/

ASDSO. (2014). Dam Safety History and National Dam Safety Act of 2006. http://www.damsafety.org/media/Documents/Legislative%20Handouts/2014/National%20Dam%20Safety%20Program%20Background-2014.pdf accessed April 26, 2017.

ASDSO. (2016). State Level Dam Safety Statistics. Online at: http://www.damsafety.org/media/Documents/STATE_INFO/STATISTICS/2015_StateStats%20w-HHP%20per%20FTE.pdf Accessed April 28, 2017.

Ashley, S. (2004). The Influence of Aging Dams and Geography on the Distribution of Dam Removals in the United States. Oregon State University, MS Thesis.

Online at: https://ir.library.oregonstate.edu/downloads/sf2685781 Accessed April 6, 2018.

Barraud, R. (2011). Rivières du futur, wild rivers? *Vertigo-la revue électronique en sciences de l'environnement*, (Hors-série 10).

Babbitt, B. (2002). What Goes Up, May Come Down: Learning from our experiences with dam construction in the past can guide and improve dam removal in the future. *BioScience*, *52*(8), 656-658.

Beck, M. W., Claassen, A. H., & Hundt, P. J. (2012). Environmental and livelihood impacts of dams: common lessons across development gradients that challenge sustainability. *International journal of river basin management*, *10*(1), 73-92.

Becker, D.H. (2006). The challenges of dam removal: The history and lessons of the Condit Dam and potential threats from the 2005 Federal Power Act amendments. *Environmental Law* 36(3): 811-868.

Bellmore, J.R., Duda, J.J., Craig, L.S., Greene, S.L., Torgersen, C.E., Collins, M.J., and Vittum, K. (2017). *Status and trends of dam removal research in the United States*. *Wiley Interdisciplinary Reviews: Water*, 4(2), e1164.

Bernhardt, E. S., Palmer, M. A., Allan, J. D., Alexander, G., Barnas, K., Brooks, S., ... & Galat, D. (2005). Synthesizing US river restoration efforts. *Science*, *308*(5722), 636-637.

Bonham, C.H. (2008). A recipe from the field for dam removal agreements. American Bar Association, Section of Environment, Energy, and Resources. 26th Annual Water Law Conference, San Diego, CA, February 21-22.

Born, S.M., Genskow, K.D., Filbert, T.L.; Hernandez-Mora, N.; Keeper, M.L. and White, K.A. (1998). Socioeconomic and institutional dimensions of dam removals: The Wisconsin experience. *Environmental Management* 22(3): 359–370, https://doi.org/10.1007/s002679900111.

Chaffin, B.C. and Gosnell, H. 2017. Beyond mandatory fishways: Federal hydropower relicensing as a window of opportunity for dam removal and adaptive governance of riverine landscapes in the United States.Water Alternatives 10(3): 819-839

Bracmort, K., Vann, A. Stern, C.V. 2015. Hydropower: Federal and Nonfederal Investment. *Congressional Research Service*, Washington D.C. online at: https://fas.org/sgp/crs/misc/R42579.pdf, last accessed March 15, 2018.

Doyle, M. W., Stanley, E. H., Harbor, J. M., & Grant, G. S. (2003). Dam removal in the United States: emerging needs for science and policy. *Eos*, *84*(4), 29-36.

Doyle, M. W., Stanley, E. H., Havlick, D. G., Kaiser, M. J., Steinbach, G., Graf, W. L., ... & Riggsbee, J. A. (2008). Aging infrastructure and ecosystem restoration. *Science*, *319*(5861), 286-287.

Fisher, A.H. 2010. Shadow tribe: The making of Columbia River Indian identity. Seattle, WA: University of Washington Press.

Foley, M. M., Magilligan, F. J., Torgersen, C. E., Major, J. J., Anderson, C. W., Connolly, P. J., ... & Craig, L. S. (2017a). Landscape context and the biophysical response of rivers to dam removal in the United States. *PLoS One*, *12*(7), e0180107.

Fox, C.A.; Magilligan, F.J. and Sneddon, C.S. (2016). "You kill the dam, you are killing a part of me": Dam removal and the environmental politics of river restoration. *Geoforum* 70: 93-104.

Fox, C. A., Reo, N. J., Turner, D. A., Cook, J., Dituri, F., Fessell, B., ... & Turner, A. (2017). "The river is us; the river is in our veins": re-defining river restoration in three Indigenous communities. *Sustainability Science*, *12*(4), 521-533.

Guarino, J. (2013). Tribal advocacy and the art of dam removal: The Lower Elwha Klallam and the Elwha Dams. *American Indian Law Journal* 2(1): 114-145

Grabowski, Z. J., Denton, A., Rozance, M. A., Matsler, M., & Kidd, S. (2017a). Removing Dams, Constructing Science: Coproduction of Undammed Riverscapes by Politics, Finance, Environment, Society and Technology. *Water Alternatives*, *3*(3), 769.

Grabowski, Z.J., Matsler, A.M., Thiel, C., McPhillips, L., Hum, R., Bradshaw, A., Miller, T., Redman, C. (2017b). Infrastructures as Socio-Eco-Technical Systems: five considerations for interdisciplinary dialogue. *Journal of Infrastructure* Systems 23(4), 02517002.

Graf, W. L. (1999). Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water resources research 35*(4), 1305-1311.

Hawley, S. (2011). *Recovering a lost river: Removing dams, rewilding salmon, revitalizing communities*. Beacon Press.

Hirsch, R. M., & Archfield, S. A. (2015). Flood trends: not higher but more often. *Nature Climate Change*, *5*(3), 198-199.

Ho, M., Lall, U., Allaire, M., Devineni, N., Kwon, H. H., Pal, I., ... & Wegner, D. (2017). The future role of dams in the United States of America. *Water Resources Research*.

Hoenke, K. M., Kumar, M., & Batt, L. (2014). A GIS based approach for prioritizing dams for potential removal. *Ecological Engineering*, *64*, 27-36.

Januchowski -Hartley, S. R., McIntyre, P. B., Diebel, M., Doran, P. J., Infante, D. M., Joseph, C., & Allan, J. D. (2013). Restoring aquatic ecosystem connectivity requires expanding inventories of both dams and road crossings. *Frontiers in Ecology and the Environment*, *11*(4), 211-217.

Jansen, R. B. (2012). *Advanced dam engineering for design, construction, and rehabilitation*. Springer Science & Business Media.

Jones, V. (2009). *The green collar economy: How one solution can fix our two biggest problems*. Harper Collins.

Lavoie, J. (2015). 'Industrialization of the Wilderness': Wade Davis on the Northwest Transmission Line. *Desmog Canada*, Aug 5th.

Lind, M. (2015). Raiding Progress. *Breakthrough Journal*. Summer. https://thebreakthrough.org/index.php/journal/past-issues/issue-5/raiding-progress

Lovett, R. A. (2014). Rivers on the run. *Nature*, *511*(7511), 521.

Lowry, W. R. (2003). *Dam politics: restoring America's rivers*. Georgetown University Press.

Maechler, M. (2015). diptest: Hartigan's Dip Test Statistic for Unimodality - Corrected. R package version 0.75-7.

Magilligan, F. J., Graber, B. E., Nislow, K. H., Chipman, J. W., Sneddon, C. S., & Fox, C. A. (2016). River restoration by dam removal: Enhancing connectivity at watershed scales. *Elementa*, *4*.

Magilligan, F.J., Sneddon, C., Fox, C.A. (2017). The social, historical, and institutional contingencies of dam removal. *Environmental Management*, 59(6), 982-994.

Manahan, M. D., & Verville, S. A. (2004). FERC and dam decommissioning. *Nat. Resources & Env't.*, *19*, 45.

Mantel, S. K., Rivers-Moore, N., & Ramulifho, P. (2017). Small dams need consideration in riverscape conservation assessments. *Aquatic Conservation: Marine and Freshwater Ecosystems*.

McCool, D. (2012). *River Republic: The Fall and Rise of America's Rivers*. Columbia University Press.

McCulloch, C. S. (2008). Decommissioning, discontinuation and abandonment of dams: is there a case for a national strategy? *Ensuring reservoir safety into the future*. Thomas Telford, London.

NEST (2017) New England Sustainability Consortium: The Future of Dams. http://www.newenglandsustainabilityconsortium.org/dams

Nunez, C. (2017). The Oroville Dam Crisis Could Happen Elsewhere. *National Geographic*. http://news.nationalgeographic.com/2017/02/oroville-dam-crisis-infrastructure-safety/, last accessed June 19, 2017

NRC (1985) Safety of Dams: Flood and Earthquake Criteria.

NRC (1992) Dam and Levee Safety and Community Resilience: A Vision for Future Practice.

O'Connor, J. E., Duda, J. J., & Grant, G. E. (2015). 1000 dams down and counting. *Science*, *348*(6234), 496-497.

Perry, M.D. and Praskievicz, S.J. 2017. A new era of big infrastructure? (Re)developing water storage in the U.S. West in thecontext of climate change and environmental regulation.Water Alternatives 10(2): 437-454

Phillips, K. (2017). The government was warned that the Oroville Dam emergency spillway was unsafe. It didn’t listen. *Washington Post*: February 14th.

Pittock, J., & Hartmann, J. (2011). Taking a second look: climate change, periodic relicensing and improved management of dams. *Marine and Freshwater Research*, *62*(3), 312-320.

Poff, N. L., & Hart, D. D. (2002). How dams vary and why it matters for the emerging science of dam removal. *BioScience*, *52*(8), 659-668.

Pohl, M. M. (2002). Bringing down our dams: trends in American dam removal rationales. *JAWRA Journal of the American Water Resources Association*, *38*(6), 1511-1519.

R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org/.

Regan, P. J. (2010). Dams as systems - a holistic approach to dam safety. In *30th Annual USSD Conference Sacramento, California* (pp. 554-563).

Regan, P.J. (2009) An Examination Of Dam Failures Vs. Age Of Dams. U.S. Society on Dams 29th Annual Conference Proceedings. Online at: https://www.researchgate.net/publication/286384117_An_Examination_of_Dam_Failures_vs_Age Accessed April 26, 2017.

S. 216: Water Infrastructure Improvements for the Nation Act. (2016). https://www.congress.gov/bill/114th-congress/senate-bill/612/text, last accessed Jun 19, 2017.

S. 2735: Dam Safety Act. (2006). https://www.govtrack.us/congress/bills/109/s2735 last accessed Jun 19, 2017.

Tonitto, C. and Riha, S.J. 2016. Planning and implementing small dam removals: Lessons learned from dam removals across the eastern United States. Sustainable Water Resources Management 2(4): 489-507.

Tullos, D. D., Collins, M. J., Bellmore, J. R., Bountry, J. A., Connolly, P. J., Shafroth, P. B., & Wilcox, A. C. (2016). Synthesis of common management concerns associated with dam removal. *JAWRA Journal of the American Water Resources Association*, *52*(5), 1179-1206.

US Army Corps of Engineers (2016) *National Inventory of Dams*. Obtained by request from Rebecca Ragnon.

USGS (2016) Dam Removal Database online at https://www.sciencebase.gov/catalog/item/55071bf9e4b02e76d757c076). Accessed November 11, 2016.

Whitelaw, E., & MacMullan, E. (2002). A Framework for Estimating the Costs and Benefits of Dam Removal. *BioScience*, *52*(8), 724-730.

Wildman, L. 2013. Dam Removal: A history of decision points. In DeGraff, J. V., & Evans, J. E. (Eds.). (2013). *The Challenges of Dam Removal and River Restoration* (Vol. 21). Geological Society of America.

Zeileis, Achim, Christian Kleiber, Walter Kraemer and Kurt Hornik (2003). Testing and Dating of Structural Changes in Practice. Computational Statistics & Data Analysis, 44, 109-123.

Chapter 3: 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.

1 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).

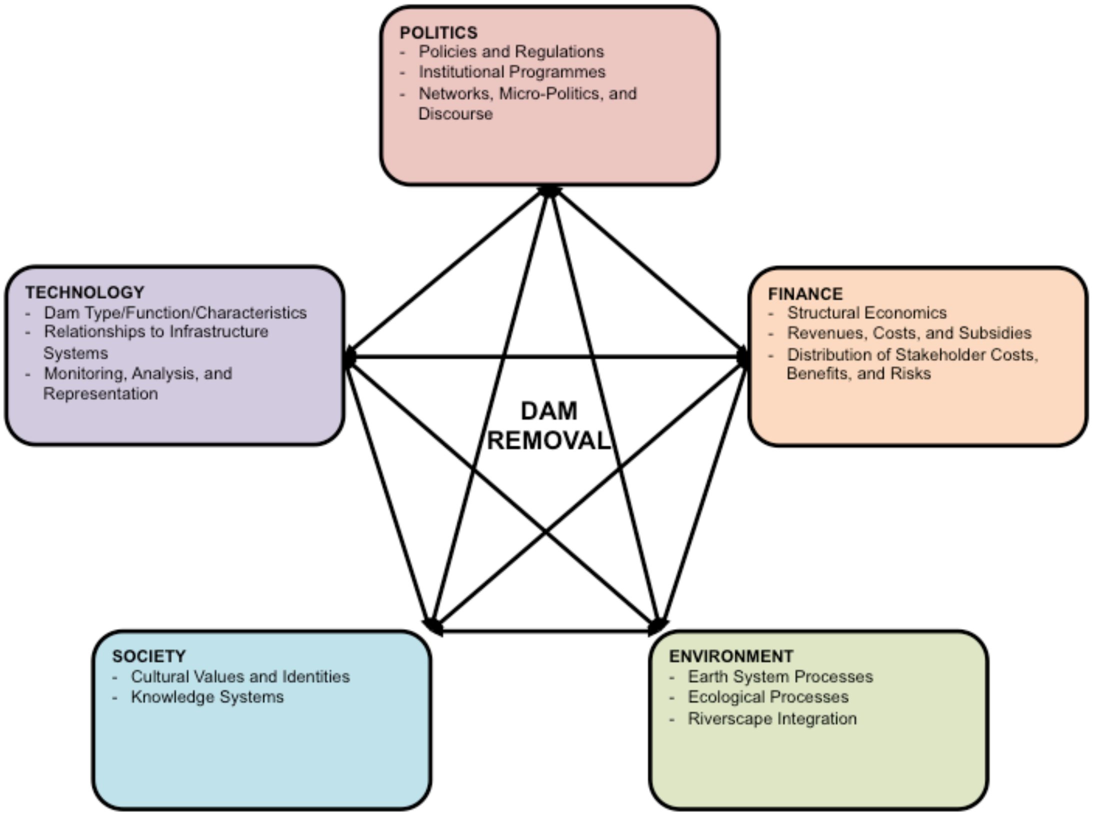
In this paper, we engage in three major tasks. First, drawing upon existing literature, we propose a conceptual framework for integrating existing knowledge around dam removal through a Political-Financial-Environmental-Social-Technological Systems (PFESTS) lens. With PFESTS, we also seek to provide 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.

2 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. 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.

3 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.

4 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.

5 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.

6 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.

7 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.

8 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 license 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 license 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 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 – variable temperatures 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 Widely acknowledged demographic change Tribal fishery in upper river – recreational fishery throughout	6000 kW concrete roller gate dam built in 1923 Flood damaged flow line and power plant
Institutional actions	***Revenues, costs, subsidies***	***Ecological processes***	***Knowledge systems***	***Infrastructure connections***
CTWS Fisheries co-management with OR. Dept. o Fish and Wildlife Extensive funds available from BPA for CTWS restoration budgets Columbia River Basin Fish Accord 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 and SWCD provides education and training Recognised need by federal agencies for improved data analysis and dissemination Tribal acceptance of technical approaches	Electricity replaced with coal Thick irrigation infrastructure Numerous other small FERC licensed hydropower facilities Railroad continues to own and operate tracks in conservation easement

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 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 BLM accepts land transfer CRB Fish Accord context	Significant O&M costs Upgrades for fish passages inadequate Marginal returns prior to FERC relicensing Funding available for feasibility studies from city	Downstream fish diverted into flowline/holding pond (100% mortality) Historical loss of off channel habitat Lack of LWD Fish hatchery	Non-overlapping data sets of federal, state, city, NGOs of stream temps and conditions Coordination by SRBP No collaborative group for forest management Limited/No tribal input E. Multnomah Soil and Water Conservation District provides training and technical assistance for landowners	Major tributary downstream of Bonneville Dam Holding pond provided water to local wells – PGE not found 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***
pending Lake home owners pressed county governments to intervene pre and post settlement Strong Yakima Nation presence Ongoing retrocession and co-management	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	pipe overhauled at river crossing river crossing) and domestic well issues (needed re-drilling) Power replaced by coal Original power sold to paper mill in lower Columbia

issues CRB Fish Accord context Loss of Cons Dist. director			District provides education and training for land / river stewardship	Local PUD purchased old transmission lines
Networks and micropolitics	***Stakeholder distribution***	***Riverscape integration***		***Technologies of representation***
No current coordination body (failure of WRIA 29b process) – informal efforts ongoing conflicts in public meetings Annual Riverfest festival brings together river community	Cabin owners leasing land from PacifiCorp – a few cabins condemned due to soil instability post removal Commercial rafting industry booming Direct costs 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 monitoring 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.

9 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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References for Chapter 3:

Abbey, E. 1975. *Monkey wrench gang*. Philadelphia, PA: Lippincott Williams & Wilkins.

Agrawal, A. 2005. *Environmentality: Technologies of government and the making of subjects*. Durham, NC: Duke University Press.

Alfred, T. and Corntassel, J. 2005. Being indigenous: Resurgences against contemporary colonialism. *Government and Opposition* 40(4): 597-614.

Alfred, T. 1999. *Peace, power, righteousness: An Indigenous Manifesto*. Ontario, Canada: Oxford University Press.

Allan, J.D. 2004. Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution, and Systematics* 35(1): 257-284.

American Rivers. 2016. Dam removal database, obtained by request from Dr. Laura Craig and Jessie Thomas-Blate.

American Rivers; Friends of Earth and Trout Unlimited. 1999. *Dam removal success stories: Restoring rivers through selective removal of dams that don't make sense*. December. www.michigan.gov/documents/dnr/damsuccess_513764_7.pdf

ASDSO (Association of State Dam Safety Officials). 2014. *Dam safety history.* www.damsafety.org/media/Documents/Legislative%20Handouts/2014/National%20Dam%20Safety%20Program%20Background-2014.pdf (accessed April 26, 2017)

Ashley, S. 2004. *The influence of aging dams and geography on the distribution of dam removals in the United States*. Oregon: Oregon State University.

Babbitt, B. 2002. What goes up, may come down: Learning from our experiences with dam construction in the past can guide and improve dam removal in the future. *BioScience* 52(8): 656-658.

Baker, S.; Eckerberg, K. and Zachrisson, A. 2013. Political science and ecological restoration. *Environmental Politics* 23(3): 509-524.

Becker, D.H. 2006. The challenges of dam removal: The history and lessons of the Condit Dam and potential threats from the 2005 Federal Power Act amendments. *Environmental Law* 36(3): 811-868.

Becker, H.S. 1982. *Art worlds*. California: University of California Press.

Bednarek, A.T. 2001. Undamming rivers: A review of the ecological impacts of dam removal. *Environmental Management* 27(6): 803-814.

Bellmore, J.R.; Duda, J.J.; Craig, L.S.; Greene, S.L.; Torgersen, C.E.; Collins, M.J. and Vittum, K. 2016. Status and trends of dam removal research in the United States. *Wiley Interdisciplinary Reviews: Water* 4: e1164.

Bennett, S.; Pess, G.; Bouwes, N.; Roni, P.; Bilby, R.E.; Gallagher, S.; Ruzycki, J.; Buehrens, T.; Krueger, K.; Ehinger, W.; Anderson, J.; Jordan, C.; Bowersox, B. and Greene, C. 2016. Progress and challenges of testing the effectiveness of stream restoration in the Pacific Northwest using intensively monitored watersheds. *Fisheries* 41(2): 92-103.

Blackstock, M.D. 2005. Blue ecology: A cross-cultural approach to reconciling forest-related conflicts. *Journal of Ecosystems and Management* 6(2): 38-54.

Bonham, C.H. 2008. A recipe from the field for dam removal agreements. American Bar Association, Section of Environment, Energy, and Resources. 26th Annual Water Law Conference, San Diego, CA, February 21-22.

Born, S.M.; Genskow, K.D.; Filbert, T.L.; Hernández-Mora, N.; Keeper, M.L. and White, K.A. 1998. Socioeconomic and institutional dimensions of dam removals: The Wisconsin experience. *Environmental Management* 22(3): 359-370.

Bowker, G.C. and Star, S.L. 2000. *Sorting things out: Classification and its consequences*. Cambridge, Mass.: MIT press.

Bowman, M.B. 2002. Legal perspectives on dam removal. *BioScience* 52(8): 739-747.

Carse, A. 2012. Nature as infrastructure: Making and managing the Panama Canal watershed. *Social Studies of Science* 42(4): 539-563.

Cartwright, N. 1999. *The dappled world*. Cambridge, MA: Cambridge University Press.

Charlwood, R. 2009. Predicting the long term behavior and service life of concrete dams. In *Conference on Long Term Behavior of Dams,* pp. 1-11, 2009.

Collins, S.L.; Carpenter, S.R.; Swinton, S.M.; Orenstein, D.E.; Childers, D.L.; Gragson, T.L.; Grimm, N.B.; Morgan, G.J.; Harlan, S.L.; Kaye, J.P.; Knapp, A.K.; Kofinas, G.P.; Magnuson, J.J.; McDowell, W.H.; Melack, J.M.; Ogden, L.A.; Philip, R.G.; Smith, M.D. and Whitmer, A.C. 2011. An integrated conceptual framework for long-term social-ecological research. *Frontiers in Ecology and the Environment* 9(6): 351-357.

Cronon, W. 1996. The trouble with wilderness: Or, getting back to the wrong nature. *Environmental History* 1(1): 7-28.

DamNation. 2015. http://damnationfilm.com/

Deloria, V. Jr., 2003. *God is red: A native view of religion*. Golden, CO: Fulcrum Publishing.

Escobar, A. 1998. Whose knowledge, whose nature? Biodiversity, conservation, and the political ecology of social movements. *Journal of Political Ecology* 5(1): 53-82.

Eakin, H.; Bojórquez-Tapia, L.A.; Janssen, M.A.; Georgescu, M.; Manuel-Navarrete, D.; Vivoni, E.R.; Escalante, A.E.; Baeza-Castro, A.; Mazari-Hiriart, M. and Lerner, A.M. 2017. *Opinion: Urban resilience efforts must consider social and political forces*. *Proceedings of the National Academy of Sciences* 114(2): 186-189.

Fausch, K.D.; Torgerson, C.E.; Baxter, C. V. and Li, H.W. 2002. Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes. *BioScience* 52(6): 483.

Fisher, A.H. 2010. *Shadow tribe: The making of Columbia River Indian identity*. Seattle, WA: University of Washington Press.

Fox, C.A.; Magilligan, F.J. and Sneddon, C.S. 2016. "You kill the dam, you are killing a part of me": Dam removal and the environmental politics of river restoration. *Geoforum* 70: 93-104.

Gende, S.M.; Edwards, R.T.; Willson, M.F. and Wipfli, M.S. 2002. PacficSamon Pacific Salmon in aquatic and terrestrial ecosystems 52(10): 917-928.

Giddens, A. 1984. *The constitution of society: Outline of the theory of structuration*. California: University of California Press.

Grabowski, Z.J.; Chang, H. and Granek, E. *Fracturing dams, fractured knowledge: Challenges to empirical analysis of dam removals in the United States. In preparation*.

Grabowski, Z.J.; Matsler, A.M.; Thiel, C.; McPhillips, L.; Hum, R.; Bradshaw, A.; Miller, T. and Redman, C. 2017. Infrastructures as socio-eco-technical systems: Five considerations for interdisciplinary dialogue. *Journal of Infrastructure Systems* 23(4): 02517002.

Grabowski, Z.J.; Matsler, M.; Kidd, S.; Denton, A. and Rozance, M.A. 2016. Restoration (P)FESTS – A new framework for practice and research. *Cascadia restoration and management news: The Newsletter of the Society for Ecological Restoration Northwest, August 2016.*

http://us3.campaign-archive1.com/?u=94e33c864c7f1d49aa03d7119&id=046bf0850e&e=e06fbcd934

Guarino, J. 2013. Tribal advocacy and the art of dam removal: The Lower Elwha Klallam and the Elwha Dams. *American Indian Law Journal* 2(1): 114-145.

Graf, W.L. 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology* 79(3-4): 336-360.

Graf, W.L. (Ed). 2003. *Dam removal research: Status and prospects*. Washington, DC: The Heinz Center.

Hadorn, G.H.; Biber-Klemm, S.; Grossenbacher-Mansuy, W.; Hoffmann-Riem, H.; Joye, D.; Pohl, C. and Zemp, E. 2008. The emergence of transdisciplinarity as a form of research. In *Handbook of transdisciplinary research,* pp. 19-39. Netherlands: Springer.

Handleman, C. 2014. When a dam comes down: A recent history of restoration in Oregon's Sandy River. *The Osprey* 78(May): 6-8.

Hartmann, F. 1998. *Political ecology global and local*. New York, NY: Routledge.

Hawley, S. 2011. *Recovering a lost river: Removing dams, rewilding salmon, revitalizing communities*. Boston, MA: Beacon Press.

Ho, M.; Lall, U.; Allaire, M.; Devineni, N.; Kwon, H.H.; Pal, I. and Wegner, D. 2017. The future role of dams in the United States of America. *Water Resources Research* 53(2): 982-998.

HR News. 2017. Public access planned at Powerdale Corridor. June 13. www.hoodrivernews.com/news/2017/jun/14/public-access-planned-powerdale-corridor/

Hull, R.B. and Robertson, D.P. 2000. The language of nature matters: We need a more public ecology. In Gobster, P.H. and Hull, R.B. (Eds), *Restoring nature: Perspective from the social sciences and humanities*, pp. 97-118. Washington, DC: Island Press.

Hydropower Reform Coalition. 2016. Laws governing hydropower relicensing. www.hydroreform.org/resources/laws

Janetski, D.J.; Chaloner, D.T.; Tiegs, S.D. and Lamberti, G.A. 2009. Pacific salmon effects on stream ecosystems: A quantitative synthesis. *Oecologia* 159(3): 583-595.

Jasanoff, S. 2004. *States of knowledge: The co-production of science and the social order*. New Brunswick, NJ: Routledge.

Jezorek, I.G. and Hardiman, J.M. 2017. Juvenile Salmonid Monitoring in the White Salmon River, Washington, Post-Condit Dam Removal, 2016. https://pubs.usgs.gov/of/2017/1070/ofr20171070.pdf

Johnson, S.E. and Graber, B.E. 2002. Enlisting the social sciences in decisions about dam removal. *BioScience* 52(8): 731.

Jørgensen, D. and Renöfält, B. 2013. Damned if you do, dammed if you don't: Debates on dam removal in the Swedish media. *Ecology and Society* 18(1): 18-26.

Keller, T.M. 2009. Dam decommissioning: Removing Marmot Dam. *Hydro Review*. www.hydroworld.com/articles/hr/print/volume-28/issue-6/featured-articles/articles/dam-decommissioning.html.

Knorr-Cetina, K. 1999. *Epistemic cultures: How the sciences make knowledge*. Cambridge, Mass: Harvard University Press.

Kruse, S. A. and Scholz, A. J. 2006. *Preliminary economic assessment of dam removal: The Klamath River*. Portland, Oregon: Ecotrust.

Larkin, B. 2013. The politics and poetics of infrastructure. *Annual Review of Anthropology* 42(1): 327-343.

Latour, B. 1999. Circulating reference: Sampling the soil in the Amazon forest. In *Pandora's hope: Essays on the reality of science studies,* pp. 24-79. Cambridge, MA: Harvard University Press.

Latour, B. 2010. An attempt at a "Compositionist Manifesto". *New Literary History* 41(3): 471-490.

Lave, R.; Doyle, M. and Robertson, M. 2010. Privatizing stream restoration in the US. *Social Studies of Science* 40(5): 677-703.

Lee, K.N. 1994. *Compass and gyroscope: Integrating science and politics for the environment.* Washington, DC: Island Press.

Lowry, W.R. 2003. *Dam politics: Restoring America's rivers*. Washington, DC, USA: Georgetown University Press.

Magilligan, F.J.; Sneddon, C.S. and Fox, C.A. 2017. The social, historical, and institutional contingencies of dam removal. *Environmental Management* 59(6): 982-994.

Magilligan, F.J.; Graber, B.E.; Nislow, K.H.; Chipman, J.W.; Sneddon, C.S. and Fox, C.A. 2016. River restoration by dam removal: Enhancing connectivity at watershed scales. *Elementa: Science of the Anthropocene* 4: 108.

Marx, K. 2008. *Das Kapital*. New York, NY: John Wiley & Sons, Inc.

McCool, D. 2012. *River republic: The fall and rise of America's rivers*. NY, NY: Columbia University Press.

Mckernan, D.L.; Johnson, D.R. and Hodges, J.I. 1950. *Some factors influencing the trends of salmon populations in Oregon*. Portland, OR: Oregon Fish Commission.

Miller, C.A.; Munoz-Erickson, T. and Monfreda, C. 2010. Knowledge systems analysis: A report for the advancing conservation in a social context project. http://cspo.org/legacy/library/1210260959F83311826SI_lib_KnowledgeSystems.pdf

Mogren, E.T. 2014. Agency in networks: Implications for theory and practice in New Public Governance. In Morgan, D. and Cook, B. (Eds), *New public governance: A regime-centered perspective,* pp. 223-238. Armonk, NY: ME Sharpe.

NID (National Inventory of Dams). 2016. Partial data, obtained by request from Rebecca Ragon, US Army Corps of Engineers.

NPS (National Park Service). 2016. Elwha River restoration. www.nps.gov/olym/learn/nature/elwha-ecosystem-restoration.htm

NRC (National Research Council). 1996. *Upstream: Salmon and society in the Pacific Northwest.* Washington, DC: National Academy Press.

Nielsen-Pincus, M. and Moseley, C. 2013. The economic and employment impacts of forest and watershed restoration. *Restoration Ecology* 21(2): 207-214.

ORS (Oregon Revised Statue). 2015. Reauthorizing and decommissioning hydroelectric projects.
www.oregonlegislature.gov/bills_laws/ors/ors543a.html

Ozawa, C. 1991. *Recasting science: Consensual procedures in public policy*. Boulder, CO: Westview Press.

Palmer, M.A.; Filoso, S. and Fanelli, R.M. 2014. From ecosystems to ecosystem services: Stream restoration as ecological engineering. *Ecological Engineering* 65(April): 62-70.

Pesanti, D. 2016. Condit Dam: Life after the breach. *The Columbian*. October 23.
www.columbian.com/news/2016/oct/23/condit-dam-life-five-years-after-breach-white-salmon-river/

Poff, N.L. and Hart, D.D. 2002. How dams vary and why it matters for the emerging science of dam removal. *BioScience* 52(8): 659-668.

Pollock, M.M.; Pess, G.R.; Beechie, T.J. and Montgomery, D.R. 2004. The importance of beaver ponds to coho salmon production in the Stillaguamish River Basin, Washington, USA. *North American Journal of Fisheries Management* 24(October 2015): 749-760.

Powell Center Working Group. 2016. Dam removal: Synthesis of ecological and physical responses.
https://powellcenter.usgs.gov/view-project/526ae54ae4b0be4db9fbf979

Pritchard, S.B. 2011. *Confluence. The nature of technology and the remaking of the Rhône*. Cambridge, MA: Harvard University Press.

Raabe, J.K. 2012. Factors influencing distribution and survival of migratory fishes following multiple low-head dam removals on a North Carolina river. Raleigh, North Carolina: North Carolina State University.

Rancière, J. 2015. *The politics of aesthetics*. London, UK: Continuum.

Rayner, S. and Heyward, C. 2013. The inevitability of nature as a rhetorical resource. In Hastrup, K. (Ed), *Anthropology and Nature*, pp. 125-146, Chapter 8. New York, NY: Routledge.

Richardson, J.S.; Zhang, Y. and Marczak, L.B. 2010. Resource subsidies across the land – Freshwater interface and responses in recipient communities. *River Research and Applications* 26(1): 55-66.

Regan, P.J. 2009. Managing our water retention systems. In *USSD Annual Meeting and Conference*, pp. 35-58. Nashville, TN, 2009.

Regan, P.J. 2010. Dams as systems-a holistic approach to dam safety. In *30th Annual USSD Conference,* pp. 554-563. *Sacramento, California*, April 2010.

Roemer, G.W.; Gompper, M.E. and van Valkenburgh, B. 2009. The ecological role of the mammalian Mesocarnivore. *BioScience* 59(2): 165-173.

Rogers, J.D. 2012. Dams and disasters: A brief overview of dam building triumphs and tragedies in California's past.

http://web.mst.edu/~rogersda/dams_of_ca/Dams-of-California-Presentation-2012.pdf

Rosenfeld, J.; Porter, M. and Parkinson, E. 2000. Habitat factors affecting the abundance and distribution of juvenile cutthroat trout (Oncorhynchus clarki) and coho salmon (Oncorhynchus kisutch). *Canadian Journal of Fisheries and Aquatic Sciences* 57(February): 766-774.

Rozance, M.A.; Denham, D. and Kidd, S. *in preparation*. Political landscapes: A case study of tidal wetland restoration in Youngs Bay, Oregon. *Plan to submit to Geoforum*.

Rye, M.E. 2000. Dam removals - A discussion of issues and impacts. In *Building Partnerships,* pp. 1-10. In *Joint Conference on Water Resource Engineering and Water Resources Planning and Management 2000, Minneapolis Minnesota,* July 30-Aug 2, 2000.

Scott, J.C. 1998. *Seeing like a state: How certain schemes to improve the human condition have failed*. New Haven, CT: Yale University Press.

Stanley, E.H. and Doyle, M.W. 2003. Trading off: The ecological effects of dam removal. *Frontiers in Ecology and the Environment* 1(1): 15-22.

Swyngedouw, E. 2010. Impossible sustainability and the post-political condition. In Cerreta, M.; Concilio, G. and Monno, V. (Eds), *Making strategies in spatial planning,* pp. 185-205. Dordrecht, Netherlands: Springer.

Syvitski, J.P.; Vörösmarty, C.J.; Kettner, A.J. and Green, P. 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science* 308(5720): 376-380.

Tonitto, C. and Riha, S.J. 2016. Planning and implementing small dam removals: Lessons learned from dam removals across the eastern United States. *Sustainable Water Resources Management* 2(4): 489-507.

Tullos, D.D.; Collins, M.J.; Bellmore, J.R.; Bountry, J.A.; Connolly, P.J.; Shafroth, P.B. and Wilcox, A.C. 2016. Synthesis of common management concerns associated with dam removal. *Journal of the American Water Resources Association* 52(5): 1179-1206.

Ulrich, R. 1999. *Empty nets: Indians, dams, and the Columbia River*. Corvallis, OR: Oregon State University Press.

Van Hyning, J.M. 1968. *Factors affecting the abundance of fall chinook salmon in the Columbia River*. Oregon: Oregon State University.

van Riper, C.J.; Landon, A.C.; Kidd, S.; Bitterman, P.; Fitzgerald, L.A.; Granek, E.F.; Ibarra, S.; Iwaniec, D.; Raymond, C.M. and Toledo, D. 2017. Incorporating sociocultural phenomena into ecosystem-service valuation: The importance of critical pluralism. *BioScience* 67(3): pp. 233-244.

Vogel, E. 2012. Parcelling out the watershed: The recurring consequences of organising Columbia River management within a basin-based territory. *Water Alternatives* 5(1): 161-190.

Weber, M. 1946. Bureaucracy. *From Max Weber: Essays in Sociology* 196: 232-235.

Wildman, L. 2013. Dam removal: A history of decision points. In DeGraff, J.V. and Evans, J.E. (Eds), *The challenges of dam removal and river restoration* (Vol. 21), pp. 1-10. Geological Society of America.

Worster, D. 1985. *Rivers of empire: Water, aridity, and the growth of the American West*. Oxford, UK: Oxford University Press.

Whitelaw, E.D. and Macmullan, E.D. 2002. *A framework for estimating the costs and benefits of dam removal*. *Bioscience* 52(8): 724-730.

Zent, S. 2012. A genealogy of scientific representations of indigenous knowledge. In Heckler, S. (Ed), *Landscape, process and power: Reevaluating traditional environmental knowledge,* pp. 19-67. Oxford, UK: Berghahn Books.

Chapter 4: A tale of three dam removals: Historical and contemporary co-production of science and watershed governance in the mid-Columbia river region

Abstract:

Dam removals and collaborative watershed governance have emerged as leading river restoration strategies, requiring new methods for understanding the interdependency of social, environmental, and technological dimensions of watershed conditions. Here, we provide a synthetic framework and methodology to study three dam removals in the Hood, Sandy, and White Salmon Rivers in the Mid-Columbia River Region, USA. Utilizing social science (participant observation, surveys with 52 participants in watershed groups), and interviews with 18 highly engaged individuals), biophysical (stream temperature and fish return data), and synthetic (land use change) data, we provide a descriptive analysis of the impacts of three dam removals on watershed ecological integrity in their governance contexts. While we find a high degree of alignment in the values, worldviews, and problem-solution framings of participants in watershed governance programs, the impacts of dam removal remain dependent on multi-scalar political arenas and the representation of rivers by their resident knowledge systems. While removals provide rapid ecological and social benefits, they also have negative impacts on different sets of socio-nature relations, potentially undermining watershed restoration efforts even in the context of robust collaborative governance. While strong institutional leadership can provide overarching guidance to restoration

programs, it may paradoxically occur due to the crossing of regulatory ecological thresholds (e.g. Endangered Species Act listing). In contrast to reactive US state and federal regulations, treaty rights and responsibilities provide an overarching and pre-emptive framing of human rights and obligation. Watershed restoration, as form of environmental governance, is not limited by information, but by social power.

Introduction

Dam removal as a river restoration practice has emerged during the same period as widespread adoption of collaborative watershed governance approaches. While the academic and policy literature situates dam removal as a biophysical intervention within a complex array of interests, institutions, and social processes attached to dams (Stephenson 2000; Bonham 2008; Sneddon et al. 2017a), few analyses have situated removals within the overarching restoration concerns addressed by collaborative watershed governance bodies (but see: Lowry 2003; Gosnell and Kelly 2010). Of particular interest is the role that dam removals play in affecting the longer-term concerns and strategies of these bodies, and the relationship between the scientifically evaluated and perceived impacts of dam removals (Sneddon et al. 2017b). We define collaborative watershed governance bodies as multi-partner organizations (Agrawal and Lemos 2007), coalescing around a particular hydro-geomorphologically defined watershed (Sabatier et al. 2005), representing an active political arena as much as a biophysical scale (Molle, 2009).

In the Mid-Columbia River, debates over dam removal continue to evolve as the region struggles to overcome its colonial legacy and manage the Federal Columbia River Power System (FCRPS) in accordance with treaty obligations and contemporary environmental laws (Cosens et al. 2014, 2018). Over the last 30 years, in response to numerous crises of fish population declines (White 2011), tributary restoration has become a major focus for federal entities in the region, and has interacted with tribal, local, state, regional, and national institutions and organizations in reshaping regional rivers (Hawley 2011). Drawing upon mixed social and biophysical methods, we examined the relationship among dam removal, watershed conditions, and the political economy of river restoration in the Sandy, Hood, and White Salmon river basins. We synthesized our results using a conceptual model for co-productive socio-enviro-technological systems (SETS) to identify the ultimate impacts of dam removal on watershed ecological integrity.

2. Dam Removal through a grounded Socio-Enviro-Technological Systems (SETS) Lens

Methods to study dam removals and river restoration have proliferated in recent years, expanding on biophysical surveys and assays to extensive participant observation, surveys, interviews (Wallace 2014; Fox et al. 2016, 2017), and examinations of the policy literature (Lowry, 2003; McCool, 2012). While few have answered Graf's (2005) call to produce more synergistic and relevant research for dam removal science, the quest for sufficiently interdisciplinary frameworks continues (see Sneddon et al. 2017a). While we have published an integrative framework for understanding the causes and impacts of dam removal elsewhere (Grabowski et al. 2017a), here we place dam removal within its broader watershed governance context in order to understand its ultimate impacts on the ecological integrity of rivers. Our first major methodological and theoretical step is to seek to understand the causal factors affecting the ecological integrity of a watershed through a socio-enviro-technological systems (SETS) framework (Redman and Miller 2016; Grabowski et al. 2017b), in order to frame the systemic interactions of dam removals.

To aid this causal analysis, we draw upon work in event ecology arguing for the importance of multi-scalar and historical processes affecting present socio-ecological conditions (Walters and Vayda, 2005). In this sense, the 'event' of dam removal reverberates through the SETS, ultimately affecting ecological integrity through its direct (e.g., removed fish passage barriers, and restored sediment flux, instream flows in the bypass reach and riparian vegetation in the former reservoir area – see Tullos et al. 2017), and indirect impacts (e.g., social agreements on instream flows, political conflicts over appropriate plans and enforcement). In this sense, scientific information informs a broader social narrative of dams and rivers, illuminating the political economy of river restoration, and laying the experiential ground out of which notions of 'what is to be done' grow and become shaped by cognition, affinity, expertise, and power. Conflicts and negotiations over dam removal thus reflect and magnify ongoing social dynamics of governing resident watersheds; as well as the efforts of actors not rooted in the same geographic spaces and affinities as ‘local’ or ‘watershed’ residents. In all cases, the social narratives at work provide the basis for a common or differentiated understanding of the ‘baseline’ forces affecting watershed conditions, which in turn guide landscape management and restoration programs.

Collaborative governance organizations have become central actors in restoring and managing watersheds, providing novel arenas for adjudicating power inequalities in collaborative settings (Molle 2009; Brisbois et al. 2018). Debate continues over the ecological effectiveness of collaborative watershed governance (Sabatier 2005; Wortley et al. 2013), with evaluative research often focusing on self reported and ad hoc metrics of effectiveness, such as easier to measure habitat characteristic data over fish return and outmigration data, or the achievement of programmatic goals (Palmer et al. 2005; Roni et al. 2008). Collaborative governance programs also rely on knowledge systems, or formal bodies of knowledge through which complex systems become known. Formal knowledge largely consists of the production and analysis of data via disciplinary means, making the watershed scientifically and politically ‘legible’ (Latour, 1999), thus enabling the managerial activities of governing institutions (Scott 1998). How knowledge becomes enacted in affecting and modifying the riverscape SETS, however, depends on the institutional and organizational practices of managing land and rivers, building infrastructure, as well as the human activities outside of institutional control and steering. Because collaborative governance bodies in the

PNW often feel limited by financial and organizational stability (Chaffin et al. 2015), they must balance the interests of multi-scalar stakeholder groups, and they cannot adopt approaches threatening their financial well-being or political capital (Lubell 2004). Collaborative watershed governance and dam removal thus both occur within the broader neo-liberal turn in environmental governance of decentralizing state authority to more local sets of stakeholders who must negotiate a multi-scalar socio-economic terrain in order to govern the environment (Agrawal and Lemos, 2007). In this context, both framing and enacting watershed restoration is continuously re-negotiated by actors of varying influence and capabilities (Hull and Robertson, 2000; Lave et al. 2010; Violin et al. 2011). Which human activities can be effectively governed by these novel structures seeking improved institutional 'fit' with the watershed (Folke et al. 2004), and which are inherently ungovernable, remains a key question for human-nature scholars.

Our interrogation of the power-knowledge dynamics of watershed governance however is not content with a simple critique of the inevitable power knowledge relationships, rather we draw upon the notion of 'matters of concern' (Latour 2004), in a broader attempt to understand the underlying processes of making the 'environment' known. In this sense, the ecological integrity of rivers as a matter of social concern indicated both by fish exhibiting their own agency in inhabiting certain types of habitats and rivers (Schiemer 2000; Druschke et al. 2017) and as a social construct and boundary object (Moog and Chovanec 2000) motivating the engagement and knowledge production of a diverse set of social actors. In order to understand ecological integrity, we must therefore simultaneously understand the biophysical causality of integrity as well as the inherently political processes of framing, filtering, and adjudicating between definitions of integrity. To do so we draw upon Foucault's notions of genealogy and the episteme (Foucault 2002), where 'knowledge' depends on deeply held a-priori beliefs about causality in nature and society (Ross, 1994 in Jacoby 2014, 6; Hull and Robertson 2000; Raynor and Hayward 2010) underpinning specific disciplinary and methodological, or technical, practices (Kuhn 1976; Latour 1999). These technical practices in turn, are situated within specific institutions of varying social power, which often hinges upon their claims of representativeness of 'real world' phenomenon (Wynne, 1992). Knowledge from this point of view is not a collection of facts, but currency within a social system of generating, analyzing, communicating, and defending claims of what has happened and what is to be done (Munoz-Erickson 2014). Two important sub-domains of this overarching area of concern are the notion of 'wickedness' (Rittel and Weber 1978), and the notions of cultural theories of nature (Holling et al. 2001).

The 'wickedness' of many water issues refers to inseparability of problem framing and resultant sets of proposed solutions, and the inevitable contestations of problem framing that arise from different experiences of the phenomena characterized as problematic (Lach et al. 2005). The cultural theory of nature hypothesizes that all people possess a mental model of causality in nature, and thus fundamentally impacts how they frame problems of human nature relations. The five models thought to be in circulation in questions of natural resource management include 'nature as chaotic – necessitating trial and error, nature as fragile – necessitating precautionary management, nature as resilient – management as promoting stable states, nature as balanced – requiring minimal management, and nature as evolving – requiring adaptive management (Holling et al. 2001). In addition to these five models, we add the idea of nature as kin, or a relational model of nature requiring non-anthropocentric management (Klain et al. 2017).

In our work here we test the cultural theories of nature in affecting problem-solution framings, although we also draw upon Jennifer Mason's notion of "affect as aperture" and affinity as a charged and living relationship to examine the role of particular experiences in shaping human-watershed relations (Mason 2018). Affect and affinity form a vital part of placed-based research, as they engender empathetic understanding for other research participants, and allow for explicit examination of the agency of the researcher, participants, and non-humans (Kohn 2013), all co-inhabiting a more-than-human world (Whatmore, 2017). Utilizing our own senses as apertures also allows us to draw upon inspiration from our own living relationships with landscapes, peoples, and rivers, all of which affect the scope and purpose of our research. Such a practice embraces and emphasizes co-presence (Chuah 2015) complementing collaborative and participatory research methods utilizing research return and the translation of results for contextual application, creating opportunities for co-learning (Baba 2002, Spoon 2014).

By emphasizing affinity as resulting from *living* relationships making the world discernable through our sensory faculties, we expose the 'sense making' processes at work in delineating study objects, as well as desirable vs. undesirable courses of action. Such a turn towards the senses and the ways in which affinities are experienced through them, allows us to investigate the ways in which senses and affinities between people and the land can simultaneously span multiple time periods, including the distant past and the possible future. Affinity also allows us to unpack what is considered 'sensible' in the practice of dam removal (i.e., in reference to American Rivers' slogan, "Removing Dams that Don't Make Sense"), which often forms the center of contestation in removal decisions (Fox et al. 2016, Sherren et al. 2017). Human relations with landscapes undergird specific restoration practices, and the charged energies of affinity motivate individuals to become involved in collaborative governance bodies (Powers, 2000; Cronin and Ostergren, 2007; CRITFC, 2013).

3. Case Study Region

The Columbia River, or the 'big river' *Nch'I Wana* in the native Sahaptin language, continues to be re-worked by a constellation of networked international, tribal, national, regional, state, and local authorities and organizations (Mogren et al. 2014). Similar to other rivers around the world (Pritchard 2011), these networked institutions draw upon technical practices to manage the river as an 'organic machine' (White 2011). The river has the fifth largest average annual discharge

(7500 cms) in the United States, draining 670,810 sq km and flowing over 2,000 km. The geologically young landscape averages a gradient of 0.38 m/km as it crosses the Cascade Mt. Range through the bedrock canyons of the Columbia River Gorge carved by a series of glacial floods (the Missoula floods; NW Council, 2018). Highly climatically variable, the region contains parts of the arid Columbia Plateau, where annual precipitation averages 18 to 38 cm/yr, through the highly variable precipitation belt of the Eastern Cascades (56 to 234 cm/yr), to the wet slopes of the Western Cascades where precipitation averages 152 to 254 cm/yr, WRCC 2017). Each of our case study rivers has its source at the top of one of the twin peaks of the region – Wy'East / Mt. Hood (elev. 11,250' or 3429 m) for the Sandy and Hood Rivers South of the big river, and Pah'to / Klickitat / Mt. Adams (elev.12,280' or 3743 m) for the White Salmon River to the north (Figure 3a and b).

Prior to the era of dam building, widespread beaver extirpation, wetland filling, >90% deforestation, and fisheries exploitation (White 2011), the river was one of the largest salmon fisheries in the world (CRITFC 2018). While these changes continue to profoundly disrupt not only the river, but tribal life throughout the region (Ulrich 2007; Barber 2011), recent scholarship re-centers the agency of tribal peoples in self determination and cultural resurgence (Fisher 2010; Jacob 2013). These ongoing acts of resistance (Scott 1990) continue to evade easy categorization with typical declensionist and progressive tropes in the Americas (Cronon 1991). Institutionally, these dynamics manifest as ongoing contestation and litigation over the interpretation and enforcement of the scope of treaty rights and obligations to recognized Tribes, and dealing with compensation for ongoing losses incurred by dam building by River Indians (Ulrich 2007; Barber 2011), who themselves have complex relationships with past and present processes of federal tribal recognition (Fisher, 2011). In addition to fundamental governance questions over sovereignty, jurisdiction, and the legality of settler uses of the landscape, significant contestation exists over the enforcement and interpretation of US State and Federal Laws including the Endangered Species and Clean Water Acts (Hawley 2011).

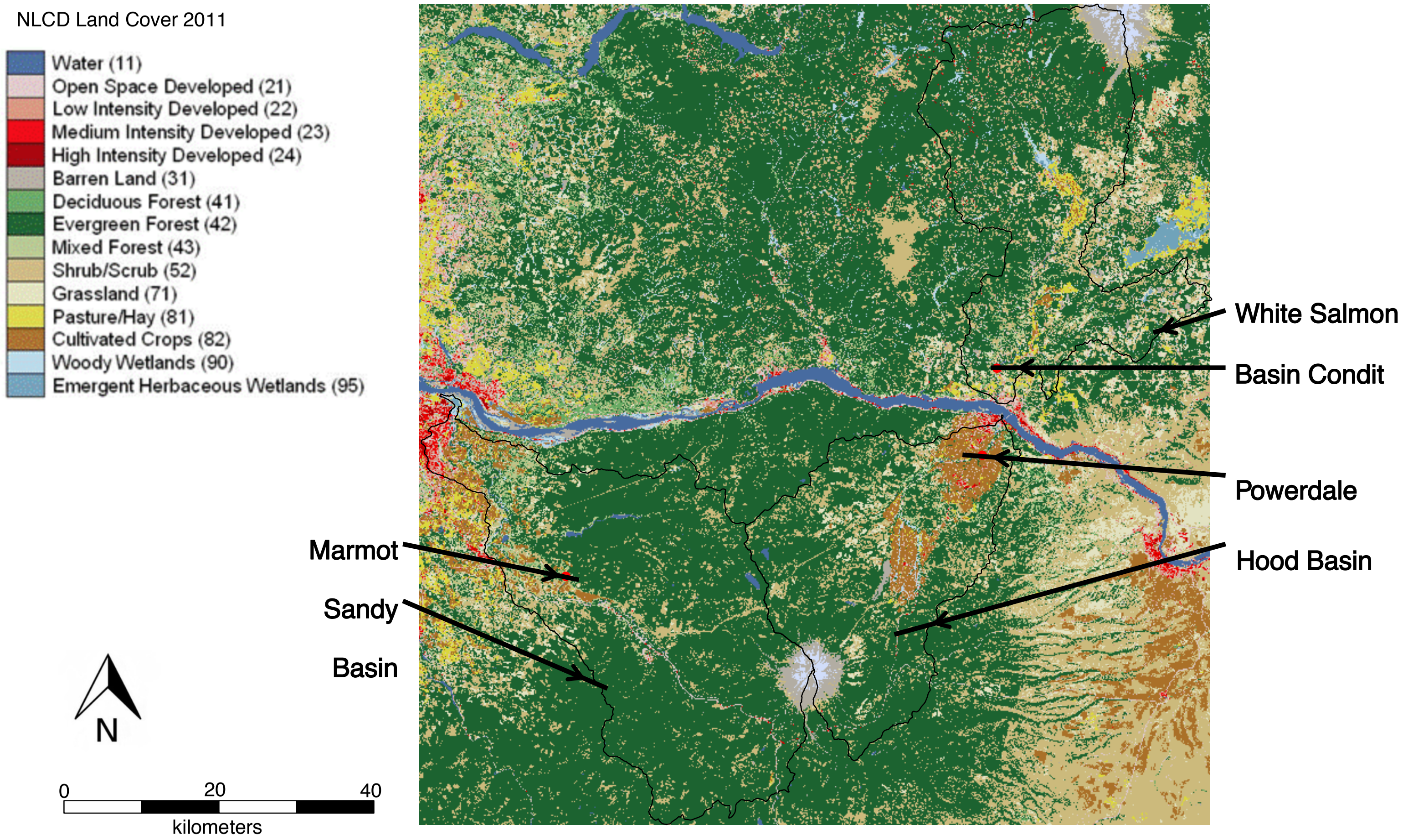
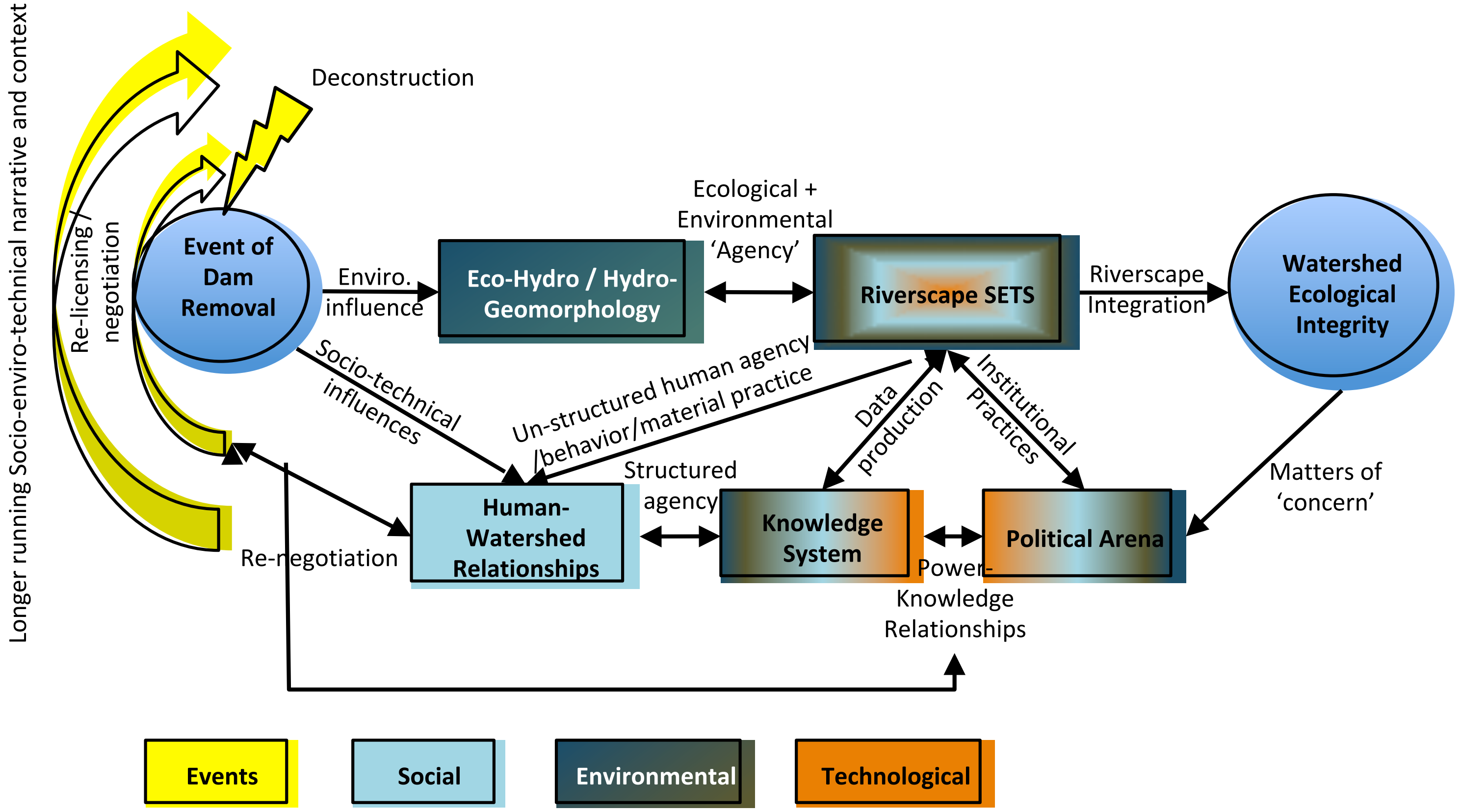


Figure 1. Case Study Region of in the Mid-Columbia River. Watershed boundaries in black overlain on top of NLCD 2011 Land Cover Data. Red dots indicate former dam sites.

4. Methods and Data

Conceptual Framework

River restoration scholarship has embraced socio-ecological systems thinking (Drouineau et al. 2018; Fernández-Manjarrés et al. 2018), the watershed scale (NRCC 1999; Nguyen et al. 2016), and addressing issues of inter-sectoral governance (Song et al. 2018). To address these interdependent concerns we sought to operationalize an empirical framework for evaluating both how watershed level restoration practitioners conceptualized the dominant issues facing their watersheds post dam removal, as well as what data could be used to evaluate the effectiveness of different governance regimes. Similar to Song et al.'s (2018) four discursive mechanisms of inland fisheries governance: characterizing the system, valuation, power relations, and vertical policy integration, we hoped to create a conceptual framework to understand how institutional arrangements (power relations), values, and world views of human-nature relations (Holling et al. 2001; Klain et al. 2017) themselves influence system characterization. Such an approach builds off of parallel developments in socio-eco-technical systems (SETS) work attempting to understand the social forces shaping different models or representations to be studied and managed (Manuel-Navarette 2015), as well as the relationship of physical infrastructures in shaping social and ecological possibilities of restoration (Grabowski et al. 2017). To this end, we iteratively constructed a SETS conceptual framework to guide data collection and analysis (Figure 3). However, the irreducible complexity of coupled human and natural systems quickly became apparent, and overwhelming for empirical evaluation. We therefore chose a subset of key factors to examine using empirical variables (Table 1) from the framework.



A dynamic coupled human and natural systems framework for understanding the impacts of hydro-electric dam removal

Figure 2. Overall Conceptual Framework for understanding impacts and feedbacks between dam removal and watershed ecological integrity through the major factors influencing the riverscape Socio-Enviro-Technological System (SETS), variables examined in this study in table 1.

Table 1. Hypothesized relevant factors for understanding the impacts of dam removal on watershed ecological integrity. Empirically examined factors for the three case study watersheds italicized

Social Narrative	**Dam removal**	**Eco-Hydrology/Ecology**	**Riverscape SETS**	**Watershed Ecological Integrity**
Identities	*Perceived Impacts*	Precipitation-Flow Regime	*Land Use Land Cover*	*Land cover change*
Meaning	Operations	Geology - Soils - sediment	Ecological community dynamics	*Water quality*
Context	Dam + reservoir characteristics	Topography	Demographic change	in-stream habitat
Relationships	Removal method Infrastructural connections	Retained Sediments	Infrastructure economic / industrial development	*Fish return /* productivity

Watershed Restoration Planning	**Human Watershed Relationships**	**Knowledge System**	**Political Arena**
Framing / mandate	[Co]presence	Disciplinary / Traditional Practices	*Organization and Institution Types*
Goals	*Values*	Data composition	*Interests*
Activities / Recommendations	*World Views*	Spatial Temporal Resolution	*Scales*
	Affinities	*Delineation of Expertise*	Avenues of influence
	Activities / Behaviors	*Problem-Solution Framings*	

Social Narrative

To provide the necessary context for current restoration and governance challenges in the basin we drew upon historical narratives centering Indigenous Peoples, restoration, and infrastructure development (Hunn and Selam 1991; Lichatowicz 2001; Jetté 2007; Ulrich 2007; Barber 2011; Fisher 2010; Hawley 2011; Jacob 2013; Deloria et al. 2016; CRITFC 2018) to construct an overall narrative that minimized the silencing of 'inconvenient narratives' (Trouillot in Jetté, 2007). Such an approach purposefully disrupts the extant hegemonic and imperialist narratives which frame the history of the region largely in terms of Euro-American achievement against the forces of nature (BPA [1941] 2016), a framing obscuring the conditional and contextual developments of human-nature relationships. The end result of our historical analysis is a timeline of key social, environmental, and technological changes in the study region (Appendix A).

Planning Documents

For each watershed, we selected the most recent post-dam removal watershed level planning documents in each basin for comparative analysis. We used discourse analysis (Schensul and Lecompte 2012) facilitated by keyword searches for 'goals,' 'recommendations,' 'actions,' 'activities,' 'treaties,' 'tribal,' 'rights,' and 'responsibilities,' and text extraction to tables to examine the overall framings of restoration need, restoration goals, and their specific recommendations, activities, acknowledgment of treaty rights, and a distillation of these results along Social, Environmental, and Technological dimension (results in Table 3).

Focused Ethnography and Participant Observation

Document analysis occurred concurrently with over three years of mixed methods focused ethnographic work (Schensul and Lecompte, 2012) on individuals engaged in collaborative watershed governance initiatives and groups. Focused ethnography provides a relatively rapid assessment of the social dynamics affecting a particular issue of concern (in this case the relationship of dam removal to watershed governance), and aims for strategic research participation of both core and peripheral stakeholders in order to bound major issues and themes (Schensul and Lecompte 2012). A major component of focused ethnographic work involved identifying individuals who could provide insights into the hidden transcripts (Scott 1990) of dam removal and watershed restoration not available from the official planning documents. To this aim we attended over 15 watershed group meetings and related events in 2013-2015, and used initial observations and impressions to design preliminary survey instruments and tested them using focus groups in each of our watersheds. While tribal perspectives in literature and planning documents were heavily considered, there is very little direct tribal involvement in the watershed groups under consideration, and thus we focused largely on tribal staff.

Survey

We constructed a survey instrument (Appendix B) with seven sections of 2-10 items each: relative ranking watersheds values, how issues affecting watershed health were framed, potential solutions to those issues, how dam removal appeared to affect watershed conditions, organizational affiliations, world-views, and demographic variables. After the research project was introduced in open meetings, surveys were distributed through email list-serves of collaborative watershed groups, yielding 52 complete individual responses, out of 300 potential respondents (response rate ~15%). Ordinal ranked variables of values and world views were examined for statistical differences between basins using Student's t-test. Categorical variables of problem-solution framings, and the scales, interests, and types of organizational and institutional affiliations were examined for between basin differences using Pearson's Chi-sq tests (see Appendix C).

Semi Structured-Interviews

From this pool of respondents, 18 willing individuals of varying degrees of centrality to collaborative governance efforts (defined by the duration of their involvement in the watershed and degree of involvement across watersheds) were contacted for semi-structured interviews. Selection criteria (n = 2 per criteria per basin) were based on a combination of reputational and snow-ball sampling (Schensul and Lecompte 2012), as well as purposefully selecting individuals born and raised in each watershed, long term transplants (having resided for over 10 years in the basin but not being born there, recent immigrants having moved within the last 10 years). Interviews intended to explicate relationships between surveyed factors and construct more detailed narrative histories of watershed change pre-and post dam removal as experienced by individuals of varying life histories and affinities with other participants and the land itself.

Interviews provided deeper insight into the affective factors driving different levels of engagement in governance activities, including relationships with other watershed stakeholders, the landscape, and extra-humans, revealing some of the hidden transcripts (Scott 1990) and lessons learned from dam removals from different organizational perspectives. We were also particularly interested in identifying 'blind spots' in watershed management and restoration programs in terms of how specific problems and solutions were framed by some stakeholders but were not taken up in wider discourse or formal action plans or management activities, and what opportunities existed to address these under-acknowledged limiting factors. Interviews were selectively transcribed to clarify points where notes were insufficient, and content was thematically coded to identify the relative importance of factors in our overall causal model.

Stream Temperature and Fish Returns

In consultation with biophysical science professionals, researchers, and agency representatives working on watershed issues in each study basin, we identified a sampling scheme for stream temperatures that would be representative of the river network and allow us to estimate sub-basin level factors affecting this critical biophysical parameter (Peterson et al. 2013). Stream temperature remains a concern in all of the study basins, with formal thermal Total Maximum Daily Loads (TMDLs) having been established in both the Sandy and Hood River basins. In all three basins, stream temperature had been a consideration of dam operational management during re-licensing, and remains a mater of concern tied to mainstem and tributary low flow conditions resulting from human water abstraction (see below in results of document analysis for more detail). At each major stream junction we utilized a network sampling strategy to measure above and below stream junction temperatures using standard Hobo water temperature loggers (Onset corp. .2 C accuracy) logging on a 5 or 15 minute interval (some loggers had a maximum resolution of 15 minutes) in order to provide high temporal resolution of stream temperature fluctuations. Our temperature data were combined with data from the US Geological Survey National Water Information System (USGS 2018), the Underwood Conservation District (Carly Lemon, *personal communication*), ongoing USGS studies of fish habitat in the White Salmon (Ian Jezorek *personal communication*), and US Forest Service monitoring of temperatures in the Sandy Basin (Todd Parker *personal communication*). Data were checked for consistency and accuracy, reformatted and collated for summary analysis in R for the period of June 15th to September 9th 2016, the peak temperature season of the region. Daily summary statistics were calculated for these sites during the seasonal period above for the regulatory metric of the maximum 7 Day Average of the Daily Maximum

Temperatures (WAC 2018), the average daily flashiness, the flashiness of daily means (see Grabowski et al. 2016), seasonal mean, mean daily range, maximum daily range, standard deviation of daily mean temperatures, percent of samples and number of days with minimum above 12, 17, and 20C, respectively, the total hourly degree accumulation, and the number of continuous measurements at each site. (Appendix 4). Lastly, we compiled and synthesized reports and published data on fish returns (Hardiman and Allen 2015; Jezorek and Hardiman 2017; French et al. 2017; SRBWC 2017; Fish Passage Center 2018) post dam removal to evaluate the impacts of dam removal on habitat availability and fish populations.

Land Use and Land Use Change

For each basin we examined land use change from 2001 to 2011 using data from the National Land Cover Dataset (NLCD) for 2001 (Homer et al. 2007), and 2011 (Homer et al. 2015), as well as the 2001 to 2011 land cover change index. We examined land cover change for all NLCD classes at the basin scale as well as within the 60 m (180ft) stream buffers roughly coinciding with the 200 ft buffer zone for streams with annual average flows greater than 20 cfs in the State of Washington (WA DEC 2018), and encompassing the 60-80 ft buffers for Salmon, Steelhead, and Bull Trout bearing streams mandated by 2017 updates to the Oregon Forest Management Act for small and medium streams (ORDF, 2018). We also examined land cover and land cover change within the Wild and Scenic River

(WSR) designated portions of each basin, which also mandates that no vegetative disturbance shall occur within 200ft of the designated watercourse regardless of its classification as a wild, scenic, or recreational river, although enforcement is subject to negotiation and interpretation of the respective role of voluntary, federal, state, and county level institutions (see Appendix 3)

5. Results

5.1. Plan Comparison the Sandy, Hood, and White Salmon River Basins.

In the context of the large scale infrastructural development, land use change, and governance regime change (described in detail in Appendix 1), the Sandy, Hood, and White Salmon rivers have all been re-conceptualized as cohesive planning units for improving watershed conditions. Within these watersheds complex drivers of ecosystem change are represented in formal planning processes with designated lead entities and collaborative partnerships of varying organizational scope and richness undertaking restoration efforts of varying complexity and scope. A comparative analysis of planning documents in each basin yields several notable differences. First, plans vary with regards to the comprehensiveness in addressing different drivers of watershed integrity loss in social, environmental, and technological domains (Table 2), as well as in their motivations for addressing environmental concerns, which are broadly split between compliance with state and federal regulations, maintaining the legality of economically beneficial land uses, and a concern for treaty obligations.

In the Sandy River basin, there is no mention of treaty obligations in the Bull Run Habitat Conservation Plan (which pertains to the entire basin), although the recent 'State of the Sandy' (SRBWC 2017) does mention that the basin contains ceded lands of both the Confederated Tribes of the Grande Ronde and Warm Springs. In contrast, both the White Salmon and Hood River Basin plans reference the role of contemporary tribal governments, as well as traditional Tribal use and relationships with those sub-basins. However, these references are largely to voluntary efforts to engage Tribal managers (and funds) in basin projects and strategies. Omissions of treaty rights and the treaty obligations of settlers, federal, and state agencies within planning documents are made even more striking by the centrality of treaty concerns and rights as outlined in the overarching Mid-Columbia River restoration strategy put forth by CRITFC (2014), whereby:

> "The treaty promises of the United States to protect the aboriginal right of our tribes to take fish at all of our usual and accustomed fishing places precedes all other laws affecting the Columbia Basin and were not diminished by those laws."

Table 2. Plan comparisons using a SETS lens

Plan	Social	Environmental	Technological
CRITFC: Wy-kan-ush-mi Wa-kish-wit (Spirit of the Salmon) (2014)	Honor Treaties, build new institutions, modify existing, restore relations	Pre-colonization runs in Gravel-to-Gravel management	Comprehensive system evolution, new information infrastructure
Hood River Action Plan (2014)	Education and outreach, promotion of stewardship	Long and short term process restoration in sub-basin	Voluntary efforts to address Irrigation, culverts, diversions, contaminants
Klickitat County Shoreline Draft (2018)	Adopt existing larger scale planning goals	Improve shoreline above existing	NA
Northwest Power and Conservation Council 2004 White Salmon Sub-basin Plan	Tribal and non-tribal harvest and cultural values	Protect and enhance structural attributes, diversity, towards historical distributions	Address fragmentation
Sandy River Basin Aquatic Habitat Restoration Strategy 2007	NA	Restore connectivity and watershed function, riparian and in-stream habitat	Fragmentation, roads, water quality
Bull Run Habitat Conservation Plan	Clarify ESA and CWA obligations to calculate costs and liability for city and customers	Compensate for direct impacts, improve habitat and populations throughout basin	Manage WS system in compliance with ESA and CWA

In line with this position, CRITFC and tribal leaders view the treaty obligations of settlers residing and working on treaty lands as akin to a conditional 'lien' on their title and use of the land, which is spelled out in plain language in the Chinook Trilogy (CRITFC 2014). Otherwise, sub-basin planning processes frame biophysical concerns around habitat needs, and rely on technical expertise to prioritize projects and frame matters of concern.

5.2 Survey and Interview Results

Survey and interview results indicate key differences between basins in terms of the values, problem-solution framings, perceived impacts of dam removal, and institutional types, interests, and scales at work on restoration in each basin. Overall, however, respondents displayed a high degree of alignment around relational and both anthropocentric and eco-centric value systems in collaborative governance participants. These results indicate the importance of contextualizing values within local drivers of watershed conditions, which remain largely subject to control by county, state, and federal government authority as well as the un-mediated human behaviors beyond regulatory control.

Survey Respondent Values

Overall, survey results indicate mixed alignment and significant differences on the values of watersheds, although all respondents had high values for recreation, connection, and drinking water.

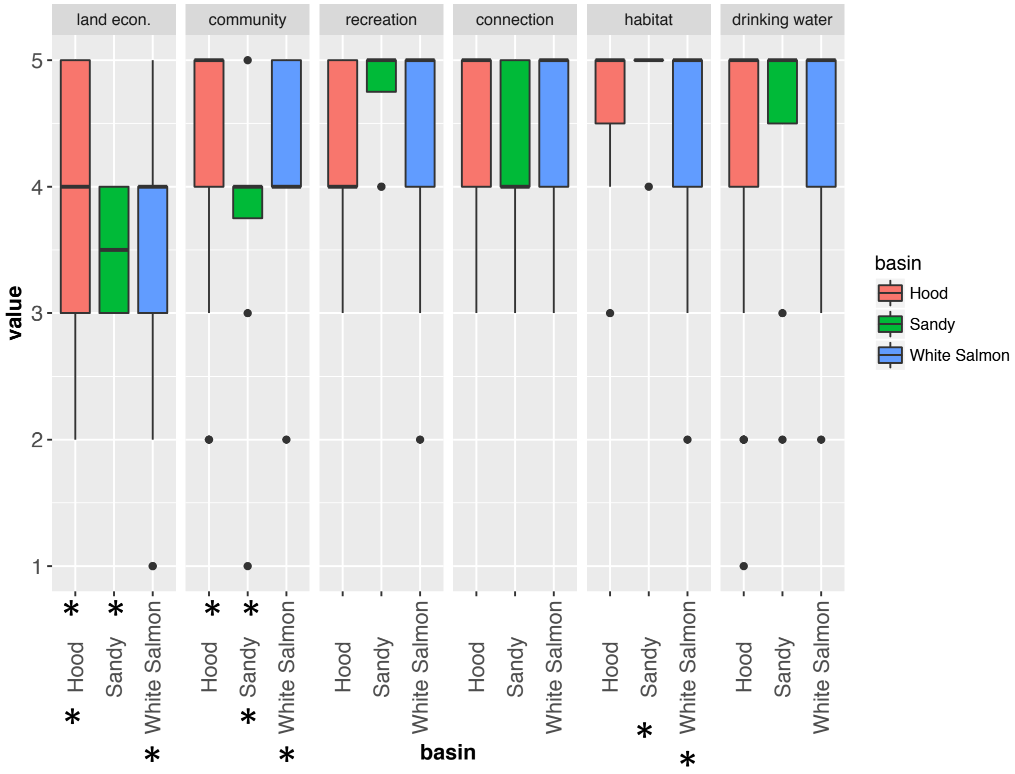


Figure 3. Distributions of value rankings in the Hood, White Salmon, and Sandy River watersheds for survey respondents. * indicates significant difference of Student's T-Tests, between basins at p<0.1.

Problem-Solution Framings

Given this mixed agreement and disagreement on the values of watersheds, there was a surprising amount of agreement on the overall problem-solution framings of restoration needs in the three basins, indicating that the motivations of those involved in collaborative governance efforts may be somewhat generalizable despite their contextualized activities. Overall, there was a strong preference for habitat restoration to address diverse drivers of habitat loss and degradation, with demographic and economic pressures dominating issues of concern. In the Sandy river, where survey response rates were much lower than the other two basins, climate change and extreme weather made the top three (with increasing use and land use in the top five). In the Hood river, where collaboration was reported as strong, financial incentives were seen as more important for changing land owner behavior than in the other two basins, indicating an entrenched neo-liberal turn of governance. In the heavily agricultural Hood River basin, where there are extensive programs in place to mitigate the impacts of irrigation infrastructure, technological innovation was seen as more important, and water availability was seen as much more of a concern than in the other basins. Additionally, in the White Salmon and Sandy basins, respondents ranked the solution of more collaboration 2nd to addressing the constellation of watershed issues, compared to Hood river respondents who ranked it 5th.

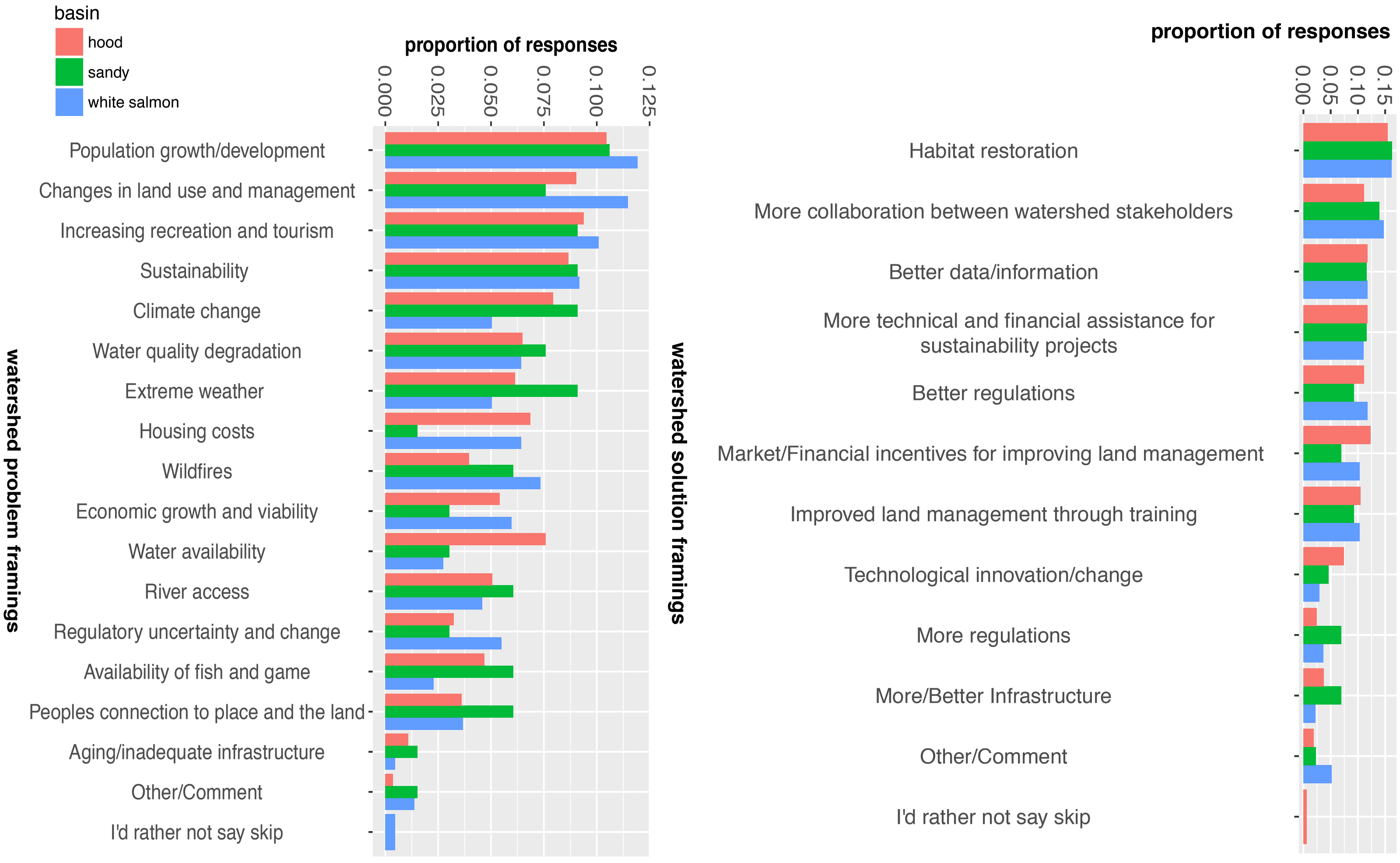


Figure 4. Problem – Solution framings for the three watersheds, y-axis corresponds to factor identified as a problem or solution, and x-axis corresponds to proportion of overall responses for that factor.

Organizational and Institutional Scale, Type, and Interests

Significant differences exist (Pearson's Chi-squared test $p << 0.01$) in the constellation of organizational scales, types, and interest across the three basins. These results indicate that the types of organizations, as well as their interests and scales of operation may have significant implications for the perceived efficacy of collaborative governance efforts. It is also worth noting that many respondents were active in several organizations, indicating that collaborative watershed groups provide additional cross linkages between individuals who themselves link across organizations.

In the Hood River, the HRWG truly does appear to serve a coordinating function between a large number of other voluntary and statutory organizations, including advocacy groups, irrigation districts, and county government. However, respondents tended to be involved in either natural resource, agricultural groups, or non-river recreation interests, and no respondents identified affiliation with the Chamber of Commerce, terrestrial recreation organizations, or volunteer fire departments. In the Sandy River Basin, there was very little cross over between survey respondents and official planning and municipal government bodies, although a high degree of overlap between the Sandy River Basin Watershed Council and the Sandy River Basin Partners, as well as some representation from a number of national and regional river-based organizations. In the White Salmon there was no distinct organizational hub that respondents coalesced around as in the Sandy and Hood Rivers, rather several non-profit and advocacy organizations served as clusters, and respondents were also less involved in county level political processes as compared to Hood River. While others have noted the importance of federal and state agency relationships in driving collaborative governance success in the PNW (Chaffin et al. 2015), these results indicate that we should also pay attention to the cross institutional and organizational affiliations of participants in watershed groups (Figure 6). Interview results indicated that there was much more engagement in county level political processes in the Sandy and Hood river basins than in the White Salmon, which was corroborated by their respective relatively larger affiliations of survey respondents with public bodies. Overall results indicate that participants in watershed restoration efforts felt more successful when they participated in established community-based organizations and structured political processes than when pursuing purely voluntary efforts.

Impacts of Dam Removal

Dam removal affected the majority of respondents in each basin; overall results indicate that while dam removals certainly have large biophysical impacts on their resident SETS, their social and infrastructural impacts may either jeopardize or enervate collaborative restoration programs at the watershed scale. The most commonly stated impacts of dam removal included both upstream and downstream fish passage improvements, and in dam removal's capacity to 'stimulate a conversation about the rivers future'. Dam removals were also thought to increase within river flows, and create new recreational opportunities (Figure 9).

Some notable differences included that dam removal on the Hood and White Salmon rivers increased conflict over water resources, while decreasing conflict on the Sandy. Interestingly, removing dams with fish passage facilities like the Powerdale (Hood) and Marmot (Sandy), did increase uncertainty in fish population statuses, as the dams had previously acted similarly to main-stem Columbia dams in providing standardized fish ladder counts. While many respondents from the White Salmon and Hood basins perceived new recreation opportunities resulting from dam removal, there were also those who felt that recreation and river access had been lost post dam removal; highlighting the perceived tradeoffs of dam removal.

World Views

Underlying world views of respondents corroborated with a dominant narrative of human population growth as being inherently opposed to watershed health. The vast majority of respondents felt that nature is fragile, although comments on the question revealed strong emotive responses that nature is also resilient, and how nature was particularly vulnerable to human influence, as well as strong responses to the contrary, indicating a significant minority opinion on the resilience of nature captured by this one comment:

> “Individuals in nature, and individual species, and individual bits of ecosystems (a wetland, for example) are fragile, but "nature" is not

> fragile. Nature has been here for millions of years. Nature changes, but it's not fragile." (Euro-American Female, Farmer)

Respondents also felt very strongly about nature being balanced without human influence, although multiple respondents indicating contingency and directionality of human influence being important qualifiers, with several respondents indicating that nature now *needed* human involvement to be balanced. The idea of nature being chaotic was perhaps the most ambivalently responded to, although there was also profound disagreement with the statement that humans should strive to control natural systems. Even more agreement was found with the idea that nature is evolving, and that human management must proceed on an adaptive cycle. In contrast, the vast majority of respondents strongly agreed (58%) that 'Humans, plants, and animals are all related as kin.' In line with this idea, most respondents felt that human management of ecosystems should take into account the perspective of non-humans, despite one respondent indicating that "this type of language is not very effective in a rural town" (Euro-American female, college student). Taken together these results indicate that respondents generally were highly sympathetic to both relational, kinship, and non-anthropocentric approaches towards managing ecosystems. Although, the majority of respondents felt that they did indeed rely on ecosystem for their well being (over 95%), so it seems that relational and non-anthropocentric values and utilitarian values are non-exclusive.

When asked about the relationship of Native peoples and the land, responses were positive but the content of comments was striking. Several statements are worth reproducing in full:

> "Not anymore, they can barely manage their own reservations!" (50-60yr old Euro-American male, Bachelors Degree)
>
> "The mastadons were wiped out within 100 years of humans arriving in this continent. We've learned from Mesa Verde that whenever there are too many humans, they exhaust natural resources of an area. " (70-80 year old Eureo-American female, Masters degree)
>
> "Although I am disappointed that they keep gill-netting the salmon in the Columbia River. This is inconsistent with their traditional values in my opinion, and harmful to the salmon which they so highly value. " (60-70 year old Euro-American Female, Doctorate).

These comments indicate racist tropes, and treating traditional ecological practices as necessarily static (or essentialized policing - Gómez-Baggethun et al. 2013), are still issues in recognizing tribal relations with land in co-management programs (Deloria 1992). Thus overall, while there is consistency in values, and to some extent, world-views, in respondents from collaborative governance groups, the ways in which those values translate into institutional structures and land management practices is highly contingent upon the relationships between individuals in institutions. How this social terrain maps onto the biophysical terrain of the river SETS is what we turn to now.

6.3. Biophysical Indicators of Watershed Condition

Stream Temperatures

All three rivers have thermally flashy glacially fed headwater streams exhibiting considerable variation in their 24 hour temperature cycles, as well as significant thermal impairment (Appendix 2). Overall, the White Salmon has the lowest stream temperatures through the summer season, although 14 % of monitored sites (all tributaries) have seven day average of daily maximum thresholds (7DADMax) above the regulatory and migratory threshold of 18 C (EPA 2001). The Hood in contrast has 18% of its sites above the 18 C 7DADMax threshold (mainstem and tributaries), and the Sandy has over 40% of monitored sites above that threshold (mainstem and tributaries). Examining thermographs for the main-stem Columbia for summer 2016, all three Columbia sites exceed 18 °C for the entire study period of early July through early September, and display a stunning lack of variability (~3°C for all sites). High mainstem temperatures on the Hood and Sandy rivers provide mixed support for prior claims that large tributaries provide thermal refugia when Columbia temperatures exceed the lethal threshold of 20 °C (Goniea et al. 2006) as lethal temperatures of 20C 7DADMax were experienced in all rivers studied (9, 19, and 14 % of the Hood, Sandy, and White Salmon logger sites respectively). Some of these sites were affected by either irrigated agriculture (Trout and Rattlesnake creeks in the White Salmon) or extensive urbanization (Beaver Creek and the lower Sandy River in the Sandy Basin), although many of them, especially in the Sandy, are dispersed throughout mixed public and private land. In all of the basins, there were slight temperature increases from above former reservoir sites to below them, although these temperature increases were below <1 °C except on the hottest of days.

Land Use Change

Land use change analysis identifies several notable differences among basins in specific land use transition dynamics (Figure 9), indicating the importance of forestry practices in influencing basin scale, riparian (60m stream buffers), and Wild and Scenic River designated areas land cover, despite the fact that development pressure was seen as the dominant concern by most survey respondents (Figure 10). The Hood River basin experienced two significant forest fires during this period (the Blue and Gnarl Ridge fires), so it is not clear what amount of forest to grassland or bare earth transition is due to inherently dynamic and non-equilibrium ecological processes (Botkin 1990), which nevertheless remain heavily influenced by historical and ongoing management decisions (Langston 2005). In the White Salmon basin, these changes can largely be attributed to forest management on public lands. In all basins, development pressure is definitely present and increasing, especially for 'open space,' and all basins have notable increases in high and medium intensity development –

indicating that the stated concerns of survey respondents are founded, but perhaps biased by the relative visibility of development land use transitions, as well as their potentially irreversible ecological impacts. Even the restrictive governance regimes of designated Wild and Scenic Rivers (WSR) are highly variable (NWSRS 2018), and almost all those studied here have had significant land use conversions from forest to grassland/herbaceous and/or shrub/scrub (Figure 11). Although it does appear that the combination of WSR and Wilderness designation may constrain land use change, as indicated by the Sandy sub-basins WSRs of the Zig Zag and Salmon Rivers (Appendix 3.

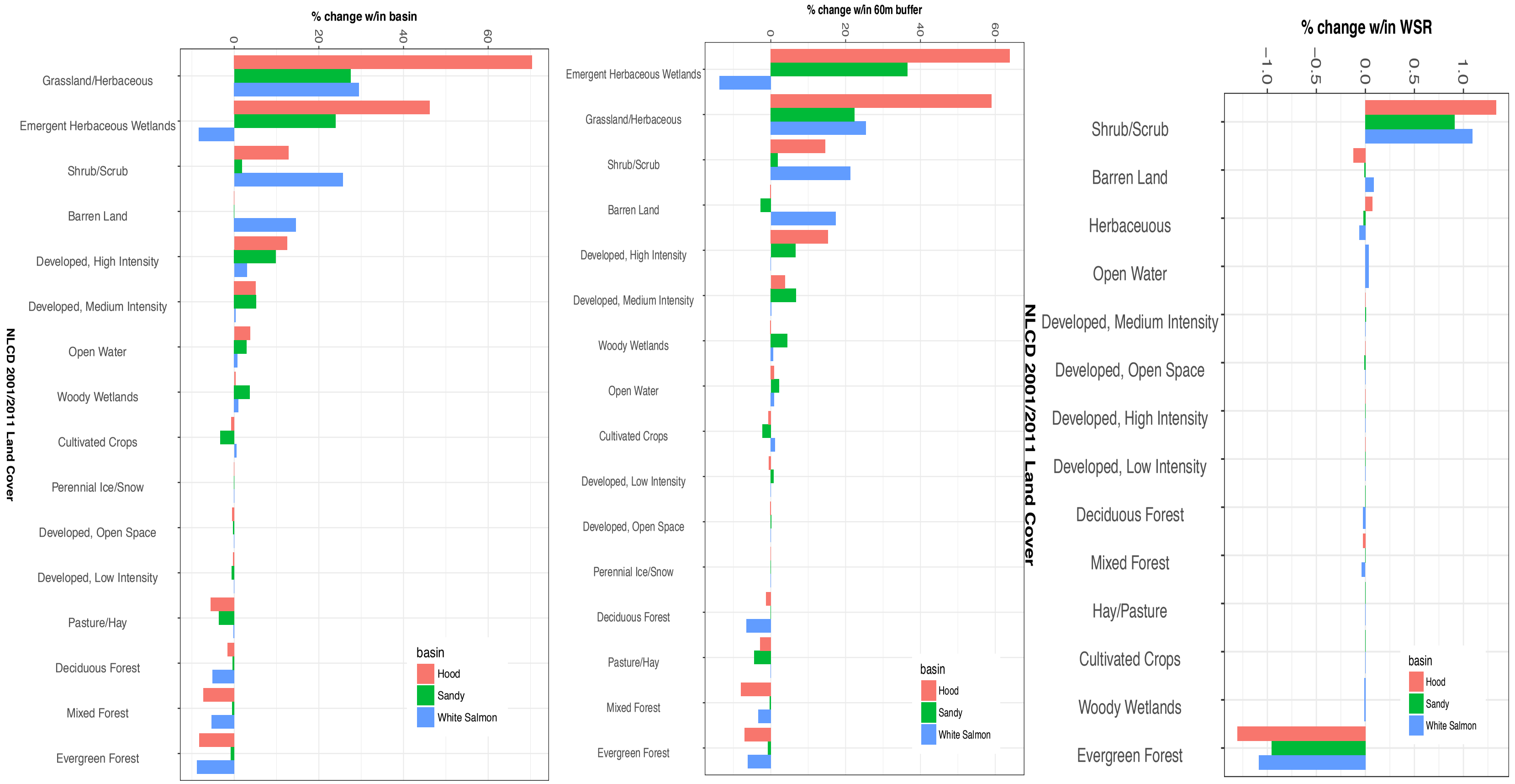


Figure 5. Percent change per NLCD land use category between 2001 and 2011 in the Hood, Sandy, and White Salmon Basins (far left), and within the 60m streamside buffer of the NHD+ hydrography stream network (middle), and within the Wild and Scenic River Act Boundaries (far right).

Fish Returns

While most fish populations of concern appear to be increasing in these three basins, they remain intensively managed by hatchery operations and detailed information as to their statuses remain dependent upon ongoing and complex scientific efforts pursued by Tribal, State, and Federal agencies as well as volunteer efforts. In the Sandy basin, Fall Chinook populations remain depressed, but other historical runs appear to have large increases in documented spawning redds, juveniles, and returning adults (SRBWC 2017). In the Hood river, which has long served as a laboratory for genetic management of hatchery fish, similar efforts are underway, and overall fish populations appear to be increasing despite increased uncertainties in their estimates (French et al. 2017). In the White Salmon, where Condit dam served as a complete fish passage barrier for up-migrating fishes, reaches upstream of the former dam site have been rapidly re-occupied by spawning Spring Chinook, Fall Chinook, Tule Chinook, bright fall Chinook, Coho, and Steelhead (Hardiman and Allen, 2015). Of these fish, only Steelhead were found above the dam prior to its removal, and those resident rainbow trout may be re-anadromizing, corroborated by limited pit tag data pre-dam removal of out-migrating rainbow trout.

While not explicitly mentioned in most interviews and survey comments, recovering fish populations must deal with the subtle deleterious effects of emerging (primarily pharmaceuticals and personal care products and flame retardants) and legacy contaminants (e.g. extensive pesticides in the Hood River

Basin) associated with forestry, agriculture, and residential land use (Nilsen et al. 2007; Temple and Johnson 2011). Isolating the relevant dominant uncertainties affecting fish population status cannot be separated from the knowledge system or political arena of managing the SETS. Perhaps most importantly, fish in these sub-basins must also be considered as sub-populations subject to the population fluctuations of the Columbia river / Nch'I Wana. In the big river, salmonids appear to be recovering despite population explosions of the introduced anadromous shad (*Alosa sapidissima)*, although Coho and Chum remain in a perilous state (CRITFC 2014; Figure 12).

7. Discussion and Conclusion: living SETS, and an affinity for justice

Our survey and interview results indicate that while scientific information is actively sought to frame restoration needs, goals, and project priorities, motivations for restoration are split between compensating for ongoing harms of economically desirable land uses, deep historical injustices, and a sense of relational affinity with non-humans and the broader landscape. Our analysis of stream temperatures, land use, and fish populations are all inherently analyses of SETS, and yet, the realities they attempt to adequately represent are of life and death significance for the species of concern. Given our results, we must confront the paradox that strong settler institutions managing the environment, either as highly centralized entities, or as dispersed collaborative bodies, may only come into being in response to ecological degradation or crisis, and that the infrastructural transformations of the landscape may preclude any return to ‘pre-disturbance’ conditions. However, drawing upon affinity and notions of grounded ecological governance, we can reframe governance challenges around the need for incremental and iterative learning through a sense of responsibility and interdependence (Turner and Berkes 2006). And while conservation has historically focused on “‘natural’ areas management”, the relatively small footprint of developed areas in each basin indicates that a much-needed focus on improving infrastructures (Doyle and Havlick 2009). A treaty perspective addresses all of these concerns through an affinity and relational based experience of the land as living kin that has already confronted dispersed and centralized infrastructures in its plans (CRITFC 2014). Treaty considerations also continue to guide legal interventions on infrastructure such as the denial of expanded railway capacity in the Columbia Gorge (CRGC 2017), culverts throughout all of Washington state (Eligon 2018), and dam removals elsewhere (Guarino 2013; Fox et al. 2017). Ultimately infrastructures ignore their environmental relationships at their own peril, with the cracking of Wannapum (Hunter et al. 2016) and Priest Rapids dams (Wang 2018), highlighting the transience of all built structures in a dynamic landscape constantly reconstituted by social negotiations.

Overall, this mixed methods study highlights long standing issues in restoration ecology, and offers a new framework for understanding the complex feedbacks between large infrastructure interventions and the complex factors affecting river conditions. The issue of shifting baselines (Balaguer et al. 2014) has run head onto the more ontologically complex notion of 're-wilding' landscapes and ecosystems (Corlett 2016), best exemplified by the return of wild fish to the White Salmon River. In the PNW, these ideas are further complicated by an infrastructurally thick landscape; extensive hatchery infrastructures now seek to maintain 'wild type' genomes in an effort to control the consequences of their biological manipulations; extensive wind power development in the region must be occasionally paid to shut down electricity production to avoid generating toxic levels of dissolved gasses to avoid paying to put power on the grid (BPA 2011; Flatt 2017); and urban dwellers in Portland must pay for habitat restoration to maintain the legality of their drinking water supply. The riverscape of salmon conservation and restoration is thoroughly and irreducibly social, ecological, and technological.

What does this mean for the science and study of dam removal? It is clear that we have much to learn about the intricate ecological connections between terrestrial, riverine, and marine ecosystems when restoring ecological connectivity (Cooke et al. 2014). Removing significant physical and thermal barriers to fish passage can have rapid cross-system ecological benefits (Ishiyama et al. 2018; McCaffery et al. 2018), yet in landscapes full of humans, infrastructures, and competing land uses, the realization of these benefits will continue to depend on *how* these complex systems are governed, by whom, using what types of information, and what types of actions (Song et al. 2018). Recent literature in fishery restoration and management indicates a growing awareness of the need for strategies of public outreach, engagement, and education in an effort to change hearts and minds (Nguyen et al. 2016; Arlinghaus et al. 2017; Drouineau et al. 2018; Fernández-Manjarrés et al. 2018), indicating a potential substantive shift in the overall socio-ecological 'imaginary' of ecosystem management (Hull and Robertson 2000; Cooke et al. 2013). While it is tempting to see a more robust system characterization as the discursive terrain within which different value constructs, power relations, and policy interactions can be understood (Song et al. 2018), characterizing these complex systems is itself an inherently political act pursued by researchers whose impacts will always be translated by their own social and political positionality and community (Chuah 2015). Our results indicate that even though engaged individuals have a set of shared values and even problem-solution framings of watershed issues, their concerns and strategies are generally practical and constrained by their political economy rather than any stable cultural narrative of how nature and society work.

Furthermore, it is difficult to find a clear signal in the efficacy of different governance regimens and the ecological conditions or recent changes in the watersheds we study here. Given the complexity of these systems, it is therefore not surprising that in response to the cognitive stress of adequately characterizing complex systems (Stirling 2010), individuals resort to familiar narratives of neo-Malthusian population control and the panacea of sustainable development. These tropes may limit political organizing by many individuals within their resident socio-ecological systems, as there successful movements rally around desirable futures rather than those of inevitable decline and loss.

What may such a positive vision be? It is clear we must ask the critical questions of what types of economic and social conflicts are inevitable if we are to reverse the declines of ecosystems and fisheries world wide (Limburg et al. 2011). Our finding treaty rights and responsibilities provide a cohesive organizing principle for broader sets of human-nature relations is reinforced by ongoing work in the Nch'I Wana basin (Cosens et al. 2018). However, these efforts must deal with long standing issues of what constitutes proper relations between a settler-colonial society that has imposed new forms of governance on the landscape inimical to self-determination, all of which have a contested relationship with the possibilities of 'reconciliation' and the politics of recognition (Coulthard 2014; Alfred 1999). Given the history of unequal power relations that have typified the social and technological infrastructures of the settler colonial apparatus (Barber 2011; Fisher 2010), which persist at the local level in the watershed contexts under study – the long running concerns over the possibilities and language of 'sustainable development' (Escobar 1996; Banerjee 2005) cannot be dismissed away. Real institutional, technological, and ecological transformations are in order, and in fact inevitable.

While these transformations will continue to be subject to the strengths and limitations of democratic decision making systems with regards to framing human-environment relations (Norton and Taylor 2002), egalitarian, deliberative, and consensus based decision-making has already emerged within Hood River Watershed Group. Recent work shows that social conventions may have tipping points provided a critical mass of change agents (Centola et al. 2018). While the ecosystems of the PNW remain under threat from dispersed social, environmental, and technological processes, democratic (Purcell 2013) and tribal (Fisher 2011) resurgence provides a potential disruptive impetus to initiate the necessary SETS transformations for sustained improvements to human and environmental well-being while delivering environmental and social justice.

References for Chapter 4:

Alfred, G. R. (2009). *Peace, power, righteousness: An indigenous manifesto*. Oxford University Press, USA.

Agrawal, A., & Lemos, M. C. (2007). A greener revolution in the making? Environmental governance in the 21st century. *Environment: Science and Policy for Sustainable Development*, *49*(5), 36-45.

Arlinghaus, R., Alós, J., Beardmore, B., Daedlow, K., Dorow, M., Fujitani, M., ... & Johnston, F. (2017). Understanding and managing freshwater recreational fisheries as complex adaptive social-ecological systems. *Reviews in Fisheries Science & Aquaculture*, *25*(1), 1-41.

Balaguer, L., Escudero, A., Martin-Duque, J. F., Mola, I., & Aronson, J. (2014). The historical reference in restoration ecology: re-defining a cornerstone concept. *Biological Conservation*, *176*, 12-20.

Barber, K. (2011). *Death of Celilo Falls*. University of Washington Press. Seattle, WA.

Bonham, C. H. (2008). A recipe from the field for dam removal agreements. American Bar Association, Section of Environment, Energy, and Resources. In *26th Annual Water Law Conference, San Diego, CA, February* (pp. 21-22).

Botkin, D. B. (1990). *Discordant harmonies: a new ecology for the twenty-first century* (p. 13). New York: Oxford University Press.

BPA. [1941] 2016. BPA Celebrates 75th Anniversary of Woody Guthrie's Columbia River Songs.

BPA. (2011). BPA Prepares for Too Much Power. February Newsletter.

Brisbois, M. C., Morris, M., & de Loë, R. (2018). Augmenting the IAD framework to reveal power in collaborative governance–An illustrative application to resource industry dominated processes. *World Development*.

Centola, D., Becker, J., Brackbill, D., & Baronchelli, A. (2018). Experimental evidence for tipping points in social convention. *Science*, *360*(6393), 1116-1119.

Chaffin, B. C., Mahler, R. L., Wulfhorst, J. D., & Shafii, B. (2012). Collaborative Watershed Groups in Three Pacific Northwest States: A Regional Evaluation of Group Metrics and Perceived Success 1. *JAWRA Journal of the American Water Resources Association*, *48*(1), 113-122.

Chaffin, B. C., Gosnell, H., Cosens, B. A. (2014). A decade of adaptive governance scholarship: synthesis and future directions. Ecology and Society, 19 (3), 56. doi:10.5751/ES-06824-190356

Chaffin, B. C., Mahler, R. L., Wulfhorst, J. D., & Shafii, B. (2015). The role of agency partnerships in collaborative watershed groups: Lessons from the Pacific Northwest experience. *Environmental management*, *55*(1), 56-68.

Chua, L. (2015). Troubled landscapes, troubling anthropology: co-presence, necessity, and the making of ethnographic knowledge. *Journal of the Royal Anthropological Institute*, *21*(3), 641-659.

Columbia River Gorge Commission (CRGC). (2017). Final Opinion and Order CRGC NO. COA-16-02.

Columbia River Inter-Tribal Fish Commission (CRITFC). (2014). Wy-kan-ush-mi Wa-kish-wit: the Spirit of the Salmon Plan. 2014 update.

Columbia River Inter-Tribal Fish Commission (CRITFC). (2018) Indian Fisheries Timeline. http://www.critfc.org/about-us/fisheries-timeline/

Cooke, S. J., Lapointe, N. W. R., Martins, E. G., Thiem, J. D., Raby, G. D., Taylor, M. K., ... & Cowx, I. G. (2013). Failure to engage the public in issues related to inland fishes and fisheries: strategies for building public and political will to promote meaningful conservation. *Journal of fish biology*, *83*(4), 997-1018.

Cooke, S. J., Arlinghaus, R., Bartley, D. M., Beard, T. D., Cowx, I. G., Essington, T. E., ... & Watson, R. (2014). Where the waters meet: sharing ideas and experiences between inland and marine realms to promote sustainable fisheries management. *Canadian Journal of Fisheries and Aquatic Sciences*, *71*(10), 1593-1601.

Corlett, R. T. (2016). Restoration, reintroduction, and rewilding in a changing world. *Trends in ecology & evolution*, *31*(6), 453-462.

Cosens, B., Gunderson, L., & Chaffin, B. (2014). The Adaptive Water Governance Project: Assessing Law, Resiliance and Governance in Regional Socio-Ecological Water Systems Facing a Changing Climate. *Idaho L. Rev.*, *51*, 1.

Cosens, B., McKinney, M., Paisley, R. et al. Reg. Environ Change (2018). https://doi.org/10.1007/s10113-018-1355-1

Coulthard, G. (2014). Red Skin, White Masks: Rejecting the Politics of Colonial Recognition.

Cronon, W. (1992). A place for stories: Nature, history, and narrative. *The journal of American history*, *78*(4), 1347-1376.

Deloria, V. (1992). Spiritual management: Prospects for restoration on tribal lands. *Restoration & Management Notes*, *10*(1), 48-50.

Deloria Jr, V., Frank, B., & Pavlik, S. (2016). *Indians of the Pacific Northwest: From the coming of the white man to the present day*. Fulcrum Publishing.

Doyle, M. W., & Havlick, D. G. (2009). Infrastructure and the environment. *Annual Review of Environment and Resources*, *34*, 349-373.

Drouineau, H., Carter, C., Rambonilaza, M., Beaufaron, G., Bouleau, G., Gassiat, A., ... & de Oliveira, E. (2018). River Continuity Restoration and Diadromous Fishes: Much More than an Ecological Issue. *Environmental management*, *61*(4), 671-686.

Druschke, C. G., Lundberg, E., Drapier, L., & Hychka, K. C. (2017). Centring Fish Agency in Coastal Dam Removal and River Restoration. *Water Alternatives*, *10*(3).

Eligon, J. 2018. 'This Ruling Gives Us Hope': Supreme Court Sides With Tribe in Salmon Case. *New York Times* June 11.

Fish Passage Center (2018). Annual Totals at Bonneville Dam. http://www.fpc.org/web/apps/adultsalmon/Q_adultcounts_annualtotalsquery.php

Escobar, A. (1996). Construction nature: Elements for a post-structuralist political ecology. *Futures*, *28*(4), 325-343.

EPA. (2001). Technical Synthesis Scientific Issues Relating to Temperature Criteria for Salmon, Trout, and Char Native to the Pacific Northwest online at: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1004J0T.TXT, last accessed Jul 11, 2018

Fernández-Manjarrés, J. F., Roturier, S., & Bilhaut, A. G. (2018). The emergence of the social-ecological restoration concept. *Restoration Ecology*, *26*(3), 404-410.

Fisher, A. H. (2010). *Shadow Tribe: The Making of Columbia River Indian Identity*. University of Washington Press.

Flatt, C. (2017) BPA stops Wind Power Generation for the First time in 4 years. Oregon Public Broadcasting, April 7th. Online at: https://www.opb.org/news/article/bpa-stops-wind-power-generation-for-the-first-time-in-4-years/ accessed June 11, 2018

Foucault, M. (2002). *The order of things: An archaeology of the human sciences*. Psychology Press.

Fox, C. A., Magilligan, F. J., & Sneddon, C. S. (2016). "You kill the dam, you are killing a part of me": Dam removal and the environmental politics of river restoration. *Geoforum*, *70*, 93-104.

Fox, C. A., Reo, N. J., Turner, D. A., Cook, J., Dituri, F., Fessell, B., ... & Turner, A. (2017). "The river is us; the river is in our veins": re-defining river restoration in three Indigenous communities. *Sustainability Science*, *12*(4), 521-533.

French, R., Patterson, S., Brun, C (2017) Hatchery and Genetic Management Plan. Hood River Production Program. Online at https://www.dfw.state.or.us/fish/HGMP/docs/2017/Hood%20River%20Winter%20Steelhead%20HGMP%205-5-17%20to%20NMFS.pdf last accessed June 15, 2018.

Goniea, T. M., Keefer, M. L., Bjornn, T. C., Peery, C. A., Bennett, D. H., & Stuehrenberg, L. C. (2006). Behavioral thermoregulation and slowed migration by adult fall Chinook salmon in response to high Columbia River water temperatures. *Transactions of the American Fisheries Society*, *135*(2), 408-419.

Gómez-Baggethun, E., Corbera, E., & Reyes-García, V. (2013). Traditional ecological knowledge and global environmental change: research findings and policy implications. *Ecology and society: a journal of integrative science for resilience and sustainability*, *18*(4).

Gosnell, H., & Kelly, E. C. (2010). Peace on the river? Social-ecological restoration and large dam removal in the Klamath basin, USA. *Water Alternatives*, *3*(2), 362.

Grabowski, Z. J., Watson, E., & Chang, H. (2016). Using spatially explicit indicators to investigate watershed characteristics and stream temperature relationships. *Science of the Total Environment*, *551*, 376-386.

Grabowski, Z. J., Denton, A., Rozance, M. A., Matsler, M., & Kidd, S. (2017a). Removing dams, constructing science: Coproduction of undammed riverscapes by politics, finance, environment, society and technology. *Water Alternatives*, *3*(3), 769.

Grabowski, Z. J., Matsler, A. M., Thiel, C., McPhillips, L., Hum, R., Bradshaw, A., ... & Redman, C. (2017b). Infrastructures as socio-eco-technical systems: Five considerations for interdisciplinary dialogue. *Journal of Infrastructure Systems*, *23*(4), 02517002.

Graf, W. L. (2005). Geomorphology and American dams: the scientific, social, and economic context. *Geomorphology*, *71*(1-2), 3-26.

Guarino, J. (2013). Tribal advocacy and the art of dam removal: The Lower Elwha Klallam and the Elwha Dams. American Indian Law Journal 2(1): 114-145.

Hardiman, J.M., and Allen, M.B. (2015). Salmon habitat assessment for conservation planning in the lower White Salmon River, Washington: US Geological Survey Open-File Report 2015-1100, 24 p., http://dx.doi.org/10.3133/20151100.

Holling, C.S., Gunderson, L.H., Ludwig, D. (2001). Chapter 1: In quest of a theory of adaptive change. In Gunderson, L. H. (2001). *Panarchy: understanding transformations in human and natural systems*. Island press.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. 2007. Completion of the 2001 National Land Cover Database for the Conterminous United States. *Photogrammetric Engineering and Remote Sensing*, Vol. 73, No. 4, pp 337-341.

Hull, R.B. and Robertson, D.P. 2000. The language of nature matters: We need a more public ecology. In Gobster, P.H. and Hull, R.B. (Eds), Restoring nature: Perspective from the social sciences and humanities, pp. 97-118. Washington, DC: Island Press.

Hunn, E. S., & Selam, J. (1991). *Nch'i-wana,"the big river": Mid-Columbia Indians and their land*. University of Washington Press.

Hunter, I., Simpson, R., Thompson, D., Barrie, R. 2016. Repairing Spillway Damage at Wanapum Dam. Hydro Review September 1st. https://www.hydroworld.com/articles/hr/print/volume-35/issue-7/cover-story/repairing-spillway-damage-at-wanapum-dam.html

Ishiyama, N., Ryo, M., Kataoka, T., Nagayama, S., Sueyoshi, M., Terui, A., ... & Nakamura, F. (2018). Predicting the ecological impacts of large dam removals on a river network based on habitat network structure and flow regimes. *Conservation Biology*.

Jacob, M. M. (2013). *Yakama rising: Indigenous cultural revitalization, activism, and healing*. University of Arizona Press, Tucson, AZ.

Jacoby, K. (2014). *Crimes against nature: Squatters, poachers, thieves, and the hidden history of American conservation*. Univ. of California Press: Berkeley, CA.

Jetté, M. M. (2007). " We Have Almost Every Religion but Our Own": French-Indian Community Initiatives and Social Relations in French Prairie, Oregon, 1834-1837. *Oregon Historical Quarterly*, *108*(2), 222-245.

Jezorek, I.G., and Hardiman, J.M., (2017). Juvenile salmonid monitoring in the White Salmon River, Washington, post-Condit Dam removal, 2016: U.S. Geological Survey Open-File Report 2017-1070, 34 p., https://doi.org/10.3133/ofr20171070.

Klain, S. C., Olmsted, P., Chan, K. M., & Satterfield, T. (2017). Relational values resonate broadly and differently than intrinsic or instrumental values, or the New Ecological Paradigm. *PloS one*, *12*(8), e0183962.

Kohn, E. (2013). *How forests think: Toward an anthropology beyond the human*. Univ. of California Press.

Lach, D., Rayner, S., & Ingram, H. (2005). Taming the waters: strategies to domesticate the wicked problems of water resource management. *International Journal of Water*, *3*(1), 1-17.

Langston, N. (1995). *Forest dreams, forest nightmares: the paradox of old growth in the Inland West*. University of Washington Press.

Latour, B. (1999). Circulating reference: Sampling the soil in the Amazon forest. *Pandora's hope: Essays on the reality of science studies*, 24-79.

Latour, B. (2004). Why has critique run out of steam? From matters of fact to matters of concern. *Critical inquiry*, *30*(2), 225-248.

Lave, R., Doyle, M., & Robertson, M. (2010). Privatizing stream restoration in the US. *Social studies of science*, *40*(5), 677-703.

Lichatowich, J. (2001). *Salmon without rivers: a history of the Pacific salmon crisis*. Island Press. Cambridge, MA.

Limburg, K. E., Hughes, R. M., Jackson, D. C., & Czech, B. (2011). Human population increase, economic growth, and fish conservation: collision course or savvy stewardship?. *Fisheries*, *36*(1), 27-35.

Manuel-Navarrete, D. (2015). "Double coupling: Modeling subjectivity and asymmetric organization in social-ecological systems." Ecol. Soc., 20(3), 26–

36.

Mason, J. (2018). *Affinities: Potent Connections in Personal Life*. John Wiley & Sons.

Moog, O., & Chovanec, A. (2000). Assessing the ecological integrity of rivers: walking the line among ecological, political and administrative interests. *Hydrobiologia*, *422*, 99-109.

Mogren, E. T. R., Shinn, C. W., Cooper, P. J., Evans, L., Cameli, L. M., & Clarke, V. (2014). Cross Road: Complexity, Capacity, and the Future Legitimacy of the Columbia River Gorge Commission.

Nguyen, V. M., Lynch, A. J., Young, N., Cowx, I. G., Beard Jr, T. D., Taylor, W. W., & Cooke, S. J. (2016). To manage inland fisheries is to manage at the social-ecological watershed scale. *Journal of environmental management*, *181*, 312-325.

Nilsen, E. B., Rosenbauer, R. R., Furlong, E. T., Burkhardt, M. R., Werner, S. L., Greaser, L., & Noriega, M. (2007). Pharmaceuticals, personal care products and anthropogenic waste indicators detected in streambed sediments of the lower Columbia River and selected tributaries. *National Ground Water Association, Paper*, *4483*, 15.

Norton, B. G. and Taylor, B.P. (eds) (2002). *Democracy and the claims of nature: Critical perspectives for a new century*. Rowman & Littlefield.

NWSRS. 2018. National Wild and Scenic Rivers System. https://www.rivers.gov/wsr-act.php

ORDF. 2018. Oregon Department of Forestry. Forest Management Act. Division 642. Water Protection Rules: Vegetation Retention Along Streams.

Palmer, M. A., Bernhardt, E. S., Allan, J. D., Lake, P. S., Alexander, G., Brooks, S., ... & Galat, D. L. (2005). Standards for ecologically successful river restoration. *Journal of applied ecology*, *42*(2), 208-217.

Peterson, E. E., Ver Hoef, J. M., Isaak, D. J., Falke, J. A., Fortin, M. J., Jordan, C. E., ... & Som, N. (2013). Modelling dendritic ecological networks in space: an integrated network perspective. *Ecology letters*, *16*(5), 707-719.

Pritchard, S. B. (2011). *Confluence: the nature of technology and the remaking of the Rhône* (Vol. 172). Harvard University Press.

Purcell, M. (2013). *The down-deep delight of democracy*. John Wiley & Sons.

Roni, P., Hanson, K., & Beechie, T. (2008). Global review of the physical and biological effectiveness of stream habitat rehabilitation techniques. *North American Journal of Fisheries Management*, *28*(3), 856-890.

Sandy River Basin Watershed Council (SRBWC). (2017). State of the Sandy. http://sandyriver.org/wp-content/uploads/2017/10/State-of-the-Sandy-.pdf

Schensul, J. J., & LeCompte, M. D. (2012). *Essential ethnographic methods: A mixed methods approach* (Vol. 3). Rowman Altamira.

Schiemer, F. (2000). Fish as indicators for the assessment of the ecological integrity of large rivers. In *Assessing the Ecological Integrity of Running Waters* (pp. 271-278). Springer, Dordrecht.

Sherren, K., Beckley, T., Greenland-Smith, S., & Comeau, L. (2017). How provincial and local discourses aligned against the prospect of dam removal in New Brunswick, Canada. *Water Alternatives*, *10*(3), 697.

Sneddon, C., Barraud, R., & Germaine, M. A. (2017a). Dam removals and river restoration in international perspective. *Water Alternatives*, *10*(3), 648.

Sneddon et al. 2017b Science of the Dammed: Science in contested dam removals. *Water Alternatives, 10(3).*

Song, A., Bower, S., Onyango, P., Cooke, S., Akintola, S., Baer, J., ... & Nunan, F. (2018). Intersectorality in the governance of inland fisheries. *Ecology and Society*, *23*(2).

Spoon, J. (2014). Quantitative, qualitative, and collaborative methods: approaching indigenous ecological knowledge heterogeneity. *Ecology and Society*, *19*(3).

Stephenson, K. (2000). Taking Nature into Account: Observations about the Changing Role of Analysis and Negotiation in Hydropower Relicensing, 25 *Wm. & Mary Envtl. L. & Pol'y Rev*. 473.

Stirling, A. (2010). Keep it complex. *Nature*, *468*(7327), 1029.

Temple, W.B., and Johnson, H.M., 2011, Occurrence and distribution of pesticides in surface waters of the Hood River basin, Oregon, 1999–2009: U.S. Geological Survey Scientific Investigations Report 2011–5082, 84 p.

Turner, N. J., & Berkes, F. (2006). Coming to understanding: developing conservation through incremental learning in the Pacific Northwest. *Human Ecology*, *34*(4), 495-513.

Ulrich, R. 2007. Empty nets: Indians, dams, and the Columbia River. Corvallis, OR: Oregon State University Press.

USGS. (2018). Water Quality Data for the Nation.https://waterdata.usgs.gov/nwis

WAC. 2018. Washington Administrative Code Section 173-201A-020 Definitions.http://apps.leg.wa.gov/WAC/default.aspx?cite=173-201A-020

WA DEC. (2018). Shoreline Management Act. Online at:https://ecology.wa.gov/Water-Shorelines/Shoreline-coastal-management/Shoreline-coastal-planning/Shoreline-Management-Act-SMA, last accessed Jul 1st, 2018.

Wang, D. 2018. Priest Rapids Dam on the Columbia River is Leaking. Oregon Public Broadcasting, March 29.https://www.opb.org/news/article/columbia-river-priest-rapids-dam-leaks/

Western Regional Climate Center. (WRCC) (2017). Climate of Washington.https://wrcc.dri.edu/Climate/narrative_wa.php

Whatmore, S. (2017). Hybrid geographies: rethinking the ‘human’ in human geography. In *Environment* (pp. 411-428). Routledge.

White, R. (2011). *The organic machine: The remaking of the Columbia River*. Hill and Wang.

Wortley, L., Hero, J. M., & Howes, M. (2013). Evaluating ecological restoration success: a review of the literature. *Restoration Ecology*, *21*(5), 537-543.

Conclusion: Whither Conservation in Infrastructure thick Landscapes? A new planetary imaginary and its socio-enviro-technical trajectory

Environmental science and management, along with conservation and restoration sciences, have generally continued to treat ‘the environment’ as a distinct phenomenological and analytical category distinct from social processes and technological artifacts. In this sense, the environment is something ‘out there’ to be affected by changing public attitudes, values, knowledge, or behaviors – a collection of objects and biological entities either imperiled or saved by human action. At the same time, the ‘externalities’ and outputs of human technologies, most notably green house gasses and climate change, but also a host of other issues of concern ranging from toxic contaminants, agricultural chemicals, human waste, and other chemicals of daily life, have also been treated as something external to environmental processes largely seen as otherwise benign and requiring protection from harm. Thus, conservation and environmental science, have at their root an ontological framing that reinforces the Cartesian duality of humans and nature.

And yet the physical sciences providing the conceptual and methodological foundations for these scientific practices make it obvious that there can be no separation between the human and the environmental: our very bodies are composed of the waters we drink, the air we breathe, and the foodstuffs we consume. Following the most positivist and most philosophically purified ‘western scientific' constructs thus leads us back to an eternal truth shared by all major philosophical systems; we are all connected, the human is the natural.

Such a finding is not comforting, nor particularly useful for addressing the many negative impacts humans have had on each other, ourselves, and other non-human forms of life, in the variegated quest for economic progress and political conquest. Nature, as a discursive field and rhetorical resource, is broad enough to encompass an infinity of moral positions on how humans should relate to one another and to the non-human world (Rayner and Heyward, 2013). Such an infinite series of possibilities however, has not halted the search for perennial and universal moral frameworks of guiding 'right' relations between humans and non-humans which continues to occupy philosophers around the planet, not least those concerned with issues of representation and extra-human democracy (Minteer and Taylor 2002).

While the principles guiding right relationships between society and nature have received much attention and articulate elaboration, not least in the evolution of 'biocultural' models of conservation (Rozzi et al. 2006; Turner and Berkes 2006). Despite a panoply of moral principles, such approaches have expended little theoretical or empirical energy understanding how the issues they raise apply in landscapes already profoundly transformed by human infrastructures (Hughes, 2004), and what moral principles we should apply to the politics of both physical artifacts (Winner 1980), and ways of representing the natural world via technological means (Wynne, 2016).

To address these twin concerns, it is tempting to trace back to Hulme's postulate that morality is inherently a human construction, one which can find no, and should not attempt to find, any corollaries in the non-human world. Nature indeed may be replete with examples of both cruelty and cooperation – morality lies in our choosing one course of action over another. I reject such a postulation just as vigorously as I reject the Cartesian duality above, and I am not alone; recent research on animal psychology (Rowlands 2015) reinforces long held understandings of animal morality held by Indigenous observers of the animal world (Cajete 1999). Without delving into the semantic and methodological depths of such studies, it appears clear that human and non-human animals have long evolved systems of relating to one another for mutual benefit codified behaviorally as well as culturally (Kropotkin 2012).

In the Pacific Northwest, such systems evolved over millennia; codifying relations between humans and the land in ways that protected fragile ecological processes and reinforced others for mutual benefit (Hunn and Selam 1990; Jacob 2013). While these traditional forms of knowledge were ruptured by settler colonial practices of resource extraction and despoliation of the land, they have remained remarkably intact despite waves of cultural, ecological, biological, and epistemological genocide reinforced by large scale infrastructural alterations of the land and hydroscape.

The question of conserving salmon then, cannot be isolated from its social processes of articulating and enacting more or less moral ways of relating to Indigenous societies. Complicating this picture, which has long been studied by anthropologists and ethicists, is the role of human technologies and formal systems of knowing in constraining and defining possible courses of action.

This dissertation attempts a synthesis of applying concepts of the co-production of knowledge and social power, with the co-production of landscapes, society, and infrastructure. I have hoped to make it clear that there is no such thing as an environment in the Mid Columbia River that is not somewhat affected by human activity in its creation. At the same time, with regards to social processes deciding how to relate to the environment, it should also be clear that there are limited ways of directly experiencing environmental forces; rather the ways in which the environment is known is always dependent upon our perceptions and affinities with the extra-human world, and increasingly mediated by complex systems of constructing knowledge around the environment, including sophisticated technologies of counting, hatching, and tracking fish.

I have argued here that these infrastructurally mediated environments, environments composed of assemblages of human technologies, earth systems, and the activities of non-human life forms, are no less deserving of our interest or our affinities. Similar to Bruno Latour's argument for the need to 'love our monsters' (Latour 2011), the way out of the technological nightmares of modernity may actually be in embracing and understanding how our social reality has become dependent upon our technological creations. While dams, power lines, rail lines, roads, telecommunications, pit-tags, and fish traps, are all temporary creations, they are continuously rebuilt by humans motivated by affinities no less genuine or real than those seeking deep affective relationships with landscapes. So I would add to Latour's argument for a need to 'love the machine' in order to transform it to meet the desires of living in a more compassionate and loving way, a need to better love our fellow humans involved in the co-production of our irreducibly complex landscapes. It is tempting to escape into the simplicity of ignorance, to withdraw into the individualist specter still haunting the mythology of the American west. And yet as Donald Worster made abundantly clear in *Rivers of Empire* (1985), the myth of the rugged western individual was always made possible by the expenditures of big government; be it in the US army evictions of Indigenous peoples and cash settlements for territorial claims, government built dams and irrigation infrastructures, and government subsidized transportation networks, the myth of the individual was always perpetuated by powerful interests seeking to dominate the landscape for their own ends.

For this work, I have attempted an analysis of a more productive framing of infrastructural complexity in contemporary landscapes (Chapter 1), combined with an empirical analysis of how the infrastructures of river landscapes are changing at large in the so-called 'USA' (Chapter 2), how we may more robustly understand the causal mechanisms by which dams come to be removed, and how their removals may galvanize or hinder broader efforts to restore human river relations (Chapters 3 and 4). As part of that work I have undertaken an ethnography of relative elites; who are also often marginalized actors in the broader processes of designating appropriate uses of land and rivers. Overall this dissertation has only offered a slice of the social life of these basins, and should be criticized for its omission of a more in depth look at the social life beside the irrigation ditch (as proposed by Wortser 1985), including the contentious politics of using immigrant and naturalized labor in pesticide intensive agricultural industries, or a more in depth ethnography of Native fisher communities. In this sense I have strayed from the standard practices of applied anthropology realm and not attempted an ethnography of the sub-altern, but one of relative elites and engaged individuals of diverse means and backgrounds in an effort to understand their knowledge and their motivations for wading into the complex political, social, and scientific terrain of removing dams and restoring rivers. It is my humble aspiration to share at least as much knowledge as I have been granted.

In the end, I hope I have provided some methodological provocations and novel information to inform ongoing efforts of restoring both ecological integrity and right relationships between humans and rivers in my case study areas and elsewhere. The quest for transdisciplinary understanding, never mind knowledge creation, has been fraught with difficulties and many learning moments. While this collection of papers and writing seeks to partially fulfill my doctoral dissertation requirements, I am left with the thought that the work I undertake here is the work of perhaps not one, but many lifetimes. Blessings be to those that undertake it, for in rivers is the life of the world.

References for conclusion:

Cajete, G. (2000). Native science: Natural laws of interdependence.

Hughes, T. P. (2004). *Human-built world: How to think about technology and culture*. University of Chicago Press.

Hunn, E. S., & Selam, J. (1991). *Nch'i-wana," the big river": Mid-Columbia Indians and their land*. University of Washington Press.

Kropotkin, P. (2012). *Mutual aid: A factor of evolution*. Courier Corporation.

Jacob, M. M. (2013). *Yakama rising: Indigenous cultural revitalization, activism, and healing*. University of Arizona Press.

Latour, B. (2011). Love your monsters. *Breakthrough Journal*, *2*(11), 21-28.

Minteer, B. A., & Taylor, B. P. (Eds.). (2002). *Democracy and the claims of nature: Critical perspectives for a new century*. Rowman & Littlefield.

Rayner, S., & Heyward, C. (2013). The inevitability of nature as a rhetorical resource. *Anthropology and Nature*, 125-146.

Rowlands, M. (2015). *Can animals be moral?*. Oxford University Press.

Rozzi, R., Massardo, F., Anderson, C. B., Heidinger, K., & Silander Jr, J. A. (2006). Ten principles for biocultural conservation at the southern tip of the Americas: the approach of the Omora Ethnobotanical Park. *Ecology and Society*, *11*(1).

Turner, N. J., & Berkes, F. (2006). Coming to understanding: developing conservation through incremental learning in the Pacific Northwest. *Human Ecology*, *34*(4), 495-513.

Winner, L. (1980). Do artifacts have politics?. *Daedalus*, 121-136.

Worster, D. (1985). *Rivers of empire: Water, aridity, and the growth of the American West*. Oxford University Press, USA.

Appendix A. Timeline of Key Events in Social, Environmental, and Technological narrative of the mid Columbia Region outwards in space and back in time.

DATE (CE)	EVENTS
~2 mya	approximate origin of contemporary salmonid species and drainages in the region
time immemorial	Receiving of original instructions, development of complex trade networks and river governance, conservative estimates of 11-16 million salmon returns annually
~18k YBP	last glacial maximum
15-13k YBP	Missoula floods
11500 YBP	Beg. of archaeological record indicating formation of extensive trade networks around Celilo Falls
2k-200 YBP	Development of customary laws and contemporary cultural and language groups in CRB
<1800s CE	establishment of British, American, and French-Metis overland and maritime trade
1763 CE	British Proclamation banning settlement on Tribal lands without crown treaty and consent
1802/3 CE	US Army Corps of Engineers (USACE) formed to for exploration of Louisiana purchase lands
1824 CE	Trail of Tears; Rivers and Harbors Act gives USACE powers to 'enhance' waterways
1830 CE	Indian Removal Act displaces Eastern Tribes into 'unsettled lands' west of Mississippi
1843 CE	Opening of Oregon Trail, CA Gold Rush
1846 CE	Creation of Oregon Territory by Treaty (US-UK) of 1846
1851 CE	Indian Appropriations Act funds population transfers and treaty purchases in US territories
1855 - ~1863 CE	Treaties grant right of settlement to US citizens, reserve Tribal rights to reservation lands and usual and accustomed places,' violation by militias sparks Yakama, Coeur de Lane, and Nez Perce wars
1869 CE	Establishment of Grant's 'Policy of Peace': emphasizes cultural assimilation and reservations
1871 CE	Indian Appropriations Act: designates Natives as 'wards,' but upholds validity of prior treaties
1886 CE	Rivers and Harbors Act: requires USACE permits for obstructions on navigable waterways
1887 CE	Dawes Act: creates Allotments on reservation lands, allows for sale of 'excess' land to white settlers
1889 CE	Indian Appropriations Act: further opens 'unassigned' Native lands to settlers
1899 CE	Federal Refuse Act: Gives USACE mandate to permit pollution
1902 CE	Reclamation Act: Authorizes Bureau of Reclamation (BoR) to 'reclaim arid lands'
1905 CE	*US vs. Winans* affirms Native interpretation of treaty rights for river and fishing access
1908 CE	*Winters Decision* extends prior appropriation to treaty water rights both on and off reservation, sets preference for state court adjudication; First Hydro-electric dam built in Debdon, UK
1911 CE	Record catch of 49,480,000 lbs for all salmonids in Columbia River

1910s CE	Cannery and Railroad booms, development of gas powered marine fisheries, explosion in Salmon demand during WWI, Condit completed 1913; Marmot complex completed 1912
1920s CE	Residential school era, fishery declines, extensive dam building, Powerdale completed 1923
1920 CE	Federal Water Power Act creates FERC to regulate private and public hydropower development
1927 CE	Rivers and Harbors Act mandates USACE to survey and build dams on mainstem Columbia
1930s CE	Salmon Catch 50% of early 1900s totals
1931 CE	USACE 308 reports propose 10 mainstem Columbia dams for hydropower
1934 CE	Indian Reorganization Act creates tribal councils under BIA, repurchases some land for reservations
1938 CE	Bonneville Project and Mitchell Acts create federal power and hatchery system
1941 CE	Grand Coulee Dam Completed; BoR proposes 142 dams in CRB; Hanford Nuclear Res. created
1942 CE	*Tulee v. Washington* affirms treaty fishing right precedence over state law except for 'conservation'
1944 CE	Columbia River Basin Project provides federal irrigation and power from Grand Coulee Dam
1945 CE	Congress sets aside lands as mitigation sites for In Lieu fishing sites
1948 CE	Vanport Floods create 'demand' for flood protection
1949 CE	Pick Sloan Act sets precedent for joint river planning by USACE and BoR
1952 CE	McCarran Amendment grants states jurisdiction over water rights cases involving federal rights
1954 CE	'Termination' attempts elimination of tribes and treaty land; McNary dam completed
1957 CE	*Whitefoot Decision* affirms fishing sites as tribal property; BPA joint ventures with regional utilities
1959 CE	Priest Rapids dam completed; Celilo Falls inundated by Dalles Dam
1962 CE	Washington Public Power Supply System (WPPSS) begun at Hanford, ongoing nuclear waste issues
1960 CE	Columbia River Treaty signed, tribes not consulted, ecosystem not considered
1960-70s	Rise of AIM and 'Power' movements; forced sterilization of Native and POC women in USA
1964 CE	Western Inter-tie completed allowing sales of CRB power to CA
1968 CE	*Puyallup v WA Dept. of Game* limits tribal commercial season above Bonneville, incites protest fishing and two separate legal cases; Wild and Scenic River (WSR) Act signed
1969 CE	*Belloni Decision* reaffirms Tribal rights to 'fair and equitable harvest' and 'meaningful consultation' when states regulate for 'conservation,' declares River Indians under treaty Tribe authority
1972/3 CE	Clean Water and Endangered Species Acts signed
1974 CE	*Boldt Decision* states fair share = 50%, and affirms recognized tribes administration of treaty fishing
1975 CE	Lower Granite Dam (lower Snake) completed; *Alexander v. Morton* dismissed denying permanent residency at in-lieu fishing sites

1976 CE	*Caeppart v United States* upholds federal water right process; *Colorado River Conservation District v. United States* sets preference for state level adjudication of 'unified' water rights; US Fisheries Conservation and Mgmt. Act creates 200 mile Exclusive Economic Zone on coast
1977 CE	Creation of Columbia River Intertribal Fish Commission; Columbia River Fish Management Compact affirms treaty tribes co-management and review of season dates
1979 CE	legal cases set legal obligation to regulate marine fishery to protect treaty fishery
1980 CE	NW Power Act passed by US Congress formalizes co-management of river for power and fish; *US v Washington Phase II* affirms treaty right to protection of habitat
1981 CE	Riggins Fish Riots in ID; Salmon Scam initiated by FBI prior to Lacey Act Amendments
1982 CE	*Reinhardt decision* affirms state (Idaho) cannot abrogate treaty (Nez Perce) fishing rights
1984 CE	Attempted evictions of in lieu site fishers on Columbia River
1985 CE	Pacific Salmon Treaty: reduces Canadian and Alaskan harvest, adds tribal representatives
1986 CE	Snake river Coho go extinct; Electric Consumer Protection Act provides 'equal consideration' of environmental and social issues in power relicensing decisions; White Salmon designated as WSR
1988 CE	Sandy River designated as WSR
1991 CE	eviction case closed in favor of River Indians; Snake River Sockeye listed as endangered; PacifiCorp files intent to renew Condit License
1992 CE	NMFS issues first BioP on Fed. Col. River Power Sys. (FCRPS) finding 'no jeopardy'; Snake River fall and Spring/Summer Chinook listed as threatened
1993 CE	NMFS BioP challenged; Hood River Watershed Group Formed; Condit Dam license expires
1994 CE	FERC allows removals through relicensing; Judge Marsh orders new BiOP; NW Forest Plan finalized
1995 CE	NMFS finds FCRPS in jeopardy, recommendations challenged by American Rivers; CRITFC develops 'Spirit of the Salmon Plan'
1997 CE	Am. Rivers v NMFS upholds challenge to 1995 BiOP; upper CR and Snake River Steelhead listed as threatened; Portland General Electric starts considering license options for Marmot Dam
1998 CE	Bull trout listings; Pacificorp begins to file new license application for Powerdale Project
1999 CE	CRITFC calls for Lower Snake dam removal; Edwards Dam on Kennebec River removed against owner's desires; Chinook, chum, and steelhead listings; Condit Settlement Agreement signed
2000 CE	4th BiOP finds FCRPS jeopardizes fish
2003 CE	Judge Redden finds 4th BioP flawed; Powerdale Settlement Agreement Signed by all parties
2004 CE	5th BiOP on FCRPS claims dams are part of baseline habitat, included hatchery fish returns as meeting conservation targets; NPCC begins sub-basin planning process for Columbia Tributaries
2005 CE	Redden finds fifth BiOP arbitrary and capricious, orders additional spill; Lower Col. Coho listed
2007 CE	Marmot Dam removed

2008 CE	Columbia Basin Fish Accords, creates large fund for restoration programs, and establishes Tribes as co-managers and co-defendents in CRB; 6th BiOP establishes 'trending towards recovery' standard
2009 CE	Hood River receives WSR designation
2010 CE	Powerdale Dam Removed; 2010 BiOP published; second Condit Settlement Agreement signed
2011 CE	Redden rejects 2010 and 2008 BiOPs, orders spill; PacifiCorp removes Condit Dam
2013 CE	CRITFIC Spirit of Salmon Plan Updated
2014 CE	Hood River Watershed Action Plan Updated; FCRPS BiOP challenged
2015 CE	Judge Simon rules that comprehensive EIS of FCRPS should include Snake Dam Removal
2018 CE	Klickitat county drafts Shoreline Master Plan; Supreme Court upholds culvert removal in WA state

Appendix B. Watershed Futures Survey

Watershed Futures Survey

Portland State University   College of Liberal Arts and Sciences   School of the Environment

P.O. Box751, Portland, Oregon 97207-0751   Tel 503-725-3162 Fax 503-725-3166 changh@pdx.edu

Thank you for participating in the "Comparing Watershed Futures Project: A survey of stakeholders in the Hood, Klickitat, Sandy, and White Salmon Watersheds." and demand on water resources. We would like to know how watershed stakeholders anticipate and respond to such change, and in particular what role dam management decisions may play in changing the way rivers are utilized and experienced.   We need your help in identifying strategies for improving water management, information generation, and making decision making more diverse and inclusive. As part of this study we want to understand what stakeholders value about their rivers and watersheds, their attitudes on governance, and their broader world view on the role of humans in the landscape. The survey will take approximately 15-20 minutes. Feel free to write in/provide comments on individual questions. Use the buttons on the bottom right to go forwards or backwards.

Thank you for your time and support of this study,

Zbigniew "Z" Grabowski
Student, School of the Environment
(860) 617-4106, zbig@pdx.edu

Heejun Chang PhD
Professor, Department of Geography
(503) 725-3162, changh@pdx.edu

Q62 By continuing, you agree to participate in this study, and you acknowledge that you are free to stop participating at any time, are free to not answer specific questions, can choose to be given back copies of your responses, and will be given all resulting research materials.Your participation is completely voluntary and confidential. This study is conducted under the supervision of the Institutional Review Board of Portland State University, if you have questions or concerns about your participation in this study or about your rights as a research participant, please contact the Human Subjects Research Review Committee at:

PSU Office of Research Integrity Market Center Building, 1600 SW 4th Ave., Suite 620,
Portland, OR 97201   503-725-2227 or 877-480-4400

Q95 In the following section please tell us a little about the primary watershed where you feel you have a stake in its future. Feel free to select multiple watersheds (for instance if you live in one but work in the other), but please note that this will increase the amount of time you spend on the survey.

Q8 In which watershed(s), are your primary activities based? (Choose multiple if applicable)
☐ Hood River (1)
☐ Klickitat River (2)
☐ Sandy River (3)
☐ White Salmon River (4)

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Hood River Is Selected

Q9 Please briefly (list) describe your primary activities, and the parts of the Hood River Watershed they are located in.

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Hood River Is Selected

Q100 Do you participate in any collaborative watershed groups? (e.g. Watershed Council, Informal meet ups, formal government/elected organizations such as county commissions or irrigation district boards) If YES, please list.

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Hood River Is Selected

Q15 Please rank the value (1 = most valuable, 7 = least valuable) of the Hood River Watershed as:
______ A place to live (1)
______ A place to support a land based economy (e.g. timber, farming) (2)
______ A place providing high quality drinking water (3)
______ A place I feel connected to (4)
______ Habitat for salmon and other wildlife (5)
______ A place to recreate (6)
______ A community (7)

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Hood River Is Selected

Q24 Do you value anything else about the Hood River Watershed? If yes please explain.

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Klickitat River Is Selected

Q10 Please briefly (list) describe your primary activities, and the parts of the Klickitat River Watershed they are located in.

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Klickitat River Is Selected

Q101 Do you participate in any collaborative watershed groups? (e.g. Watershed Council, Informal meet ups, formal government/elected organizations such as county commissions or irrigation district boards) If YES, please list.

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Klickitat River Is Selected

Q17 Please rank the value (1 being most valuable, 7 being least valuable) of the Klickitat River Watershed as:
______ A place to live (1)
______ A place to support a land based economy (e.g. timber, farming) (2)
______ A place providing high quality drinking water (3)
______ A place I feel connected to (4)
______ Habitat for salmon and other wildlife (5)
______ A place to recreate (6)
______ A community (7)

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Klickitat River Is Selected

Q23 Do you value anything else about the Klickitat Watershed? If yes please explain.

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Sandy River Is Selected

Q11 Please briefly (list) describe your primary activities, and the parts of the Sandy River Watershed they are located in.

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Sandy River Is Selected

Q102 Do you participate in any collaborative watershed groups? (e.g. Watershed Council, Informal meet ups, formal government/elected organizations such as county commissions or irrigation district boards) If YES, please list.

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Sandy River Is Selected

Q18 Please rank the value (1 being most valuable, 6 being least valuable) of the Sandy River Watershed as:
______ A place to live (1)
______ A place to support a land based economy (e.g. timber, farming) (2)
______ A place providing high quality drinking water (3)
______ A place I feel connected to (4)
______ Habitat for salmon and other wildlife (5)
______ A place to recreate (6)
______ A community (7)

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Sandy River Is Selected

Q22 Do you value anything else about the Sandy River Watershed? If yes please explain.

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) White Salmon River Is Selected

Q12 In which parts of the White Salmon River Watershed are your activities located?

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) White Salmon River Is Selected

Q103 Do you participate in any collaborative watershed groups? (e.g. Watershed Council, Informal meet ups, formal government/elected organizations such as county commissions or irrigation district boards) If YES, please list.

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) White Salmon River Is Selected

Q19 Please rank the value (1 being most valuable, 7 being least valuable) of the White Salmon River Watershed as:
______ A place to live (1)
______ A place to support a land based economy (e.g. timber, farming) (2)
______ A place providing high quality drinking water (3)
______ A place I feel connected to (4)
______ Habitat for salmon and other wildlife (5)
______ A place to recreate (6)
______ A community (7)

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) White Salmon River Is Selected

Q16 Do you value anything else about the White Salmon watershed?

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Hood River Is Selected

Q20 What are the main issues facing the future of the Hood River Basin? (select all that apply)

☐ Economic growth and viability (1)
☐ Changes in land use and management (2)
☐ Regulatory uncertainty and change (3)
☐ Extreme weather (4)
☐ Population growth/development/demographic change (5)
☐ Water quality degradation (6)
☐ Wildfires (7)
☐ Increasing recreation and tourism (8)
☐ Sustainability (of environment, society and economy) (9)
☐ People's connection to place and the land (10)
☐ Aging/inadequate infrastructure (11)
☐ Water availability (12)
☐ Cost of housing (15)
☐ Other (13)

Display This Question:
If Other Is Selected

Q21 What are your other concerns about the future?

Display This Question:

If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Hood River Is Selected

Q31 What general solutions are viable to address the issues you identified above ? (select all that apply)

- ☐ Better data/information (1)
- ☐ Improved land management (2)
- ☐ More collaboration between watershed stakeholders (3)
- ☐ Payments for Ecosystem Services (4)
- ☐ Habitat restoration (5)
- ☐ More technical and financial assistance and for sustainability projects (6)
- ☐ More Regulation (7)
- ☐ Less Regulation (8)
- ☐ Better Regulation (9)
- ☐ Technological innovation/change (10)
- ☐ More/Better Infrastructure (11)
- ☐ Other (12)

Display This Question:

If What general solutions are viable to address the issues you identified above ? (select all that a... Other Is Selected

Q35 What other solutions are viable to address issues?

Display This Question:

If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Klickitat River Is Selected

Q25 What are your main concerns about the future of the Klickitat Basin? (select all that apply)

☐ Economic growth and viability (1)
☐ Changes in land use and management (2)
☐ Regulatory uncertainty and change (3)
☐ Climate change and extreme weather (4)
☐ Population growth/development (5)
☐ Water quality degradation (6)
☐ Wildfires (7)
☐ Increasing recreation and tourism (8)
☐ Sustainability (of environment, society and economy) (9)
☐ Lack of people’s connection to place and the land (10)
☐ Aging/inadequate infrastructure (11)
☐ Water availability (12)
☐ Housing costs (13)
☐ Other (14)

Display This Question:

If What are your main concerns about the future of the Klickitat Basin? (select all that apply) Other Is Selected

Q28 What are your other concerns about the future?

Display This Question:
If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Klickitat River Is Selected

Q32 What general solutions are viable to address the issues you identified above? (select all that apply)

☐ Better data/information (1)
☐ Improved land management (2)
☐ More collaboration between watershed stakeholders (3)
☐ Payments for Ecosystem Services (4)
☐ Habitat restoration (5)
☐ More technical and financial assistance and for sustainability projects (6)
☐ More Regulation (7)
☐ Less Regulation (8)
☐ Better Regulation (9)
☐ Technological innovation/change (10)
☐ More/Better Infrastructure (11)
☐ Other (12)

Display This Question:
If What general solutions are viable to address the issues you identified above? (select all that ap... Other Is Selected

Q36 What other solutions are viable to address issues?

Display This Question:

If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Sandy River Is Selected

Q26 What are your main concerns about the future of the Sandy River Basin? (select all that apply)

☐ Economic growth and viability (1)
☐ Changes in land use and management (2)
☐ Regulatory uncertainty and change (3)
☐ Extreme weather (4)
☐ Population growth/development (5)
☐ Water quality degradation (6)
☐ Wildfires (7)
☐ Increasing Recreation and Tourism (8)
☐ Sustainability (of environment, society and economy) (9)
☐ Lack of people’s connection to place and the land (10)
☐ Aging/inadequate infrastructure (11)
☐ Water availability (12)
☐ Housing costs (13)
☐ Other (14)

Display This Question:

If What are your main concerns about the future of the Sandy River Basin? (select all that apply) Other Is Selected

Q29 What are your other concerns about the future?

Display This Question:

If In which watershed(s), are your primary activities based? (Choose multiple if applicable) Sandy River Is Selected

Q33 What general solutions are viable to address the issues you identified above? (select all that apply)

- ☐ Better data/information (1)
- ☐ Improved land management (2)
- ☐ More collaboration between watershed stakeholders (3)
- ☐ Payments for Ecosystem Services (4)
- ☐ Habitat restoration (5)
- ☐ More technical and financial assistance for sustainability projects (6)
- ☐ More Regulation (7)
- ☐ Less Regulation (9)
- ☐ Better Regulation (10)
- ☐ Technological innovation/change (11)
- ☐ More/Better Infrastructure (12)
- ☐ Other (13)

Display This Question:

If What general solutions are viable to address the issues you identified above? (select all that ap... Other Is Selected

Q37 What other solutions are viable to address issues?

Display This Question:

If In which watershed(s), are your primary activities based? (Choose multiple if applicable) White Salmon River Is Selected

Q27 What are your main concerns about the future of the White Salmon Basin? (select all that apply)

☐ Economic growth and viability (1)
☐ Changes in land use and management (2)
☐ Regulatory uncertainty and change (3)
☐ Extreme weather (4)
☐ Population growth/development (5)
☐ Water quality degradation (6)
☐ Wildfires (7)
☐ Increasing Recreation and Tourism (8)
☐ Sustainability (of Environment, Society and Economy) (9)
☐ Lack of people's connection to place and the land (10)
☐ Aging/inadequate infrastructure (11)
☐ Water availability (12)
☐ Housing costs (13)
☐ Other (14)

Display This Question:

If What are your main concerns about the future of the White Salmon Basin? (select all that apply) Other Is Selected

Q30 What are your other concerns about the future?

Display This Question:

If In which watershed(s), are your primary activities based? (Choose multiple if applicable) White Salmon River Is Selected

Q34 What general solutions are viable to address the issues you identified above? (select all that apply)

☐ Better data/information (1)
☐ Improved Land Management (2)
☐ More collaboration between watershed stakeholders (3)
☐ Payments for Ecosystem Services (4)
☐ Habitat Restoration (5)
☐ More technical and financial assistance and for sustainability projects (6)
☐ More Regulation (7)
☐ Less Regulation (8)
☐ Better Regulation (9)
☐ Technological innovation/change (10)
☐ More/Better Infrastructure (11)
☐ Other (12)

Display This Question:

If What general solutions are viable to address the issues you identified above? (select all that ap... Other Is Selected

Q38 What other solutions are viable to address issues? (please put none if none)

Q96 In the following section please answer the following questions meant to examine attitudes about appropriate human - nature relationships. For each statement, select the response which is most indicative of your thoughts and feelings. Feel free to provide comments about the statements in the space below.

Q38 Nature has no underlying order, and while we can only learn through trial and error, human ingenuity can overcome natural limits.
○ Strongly agree (1)
○ Somewhat agree (2)
○ Neither agree nor disagree (3)
○ Somewhat disagree (4)
○ Strongly disagree (5)

Q51 Comment:

Q39 Nature is balanced without human influence, and we should strive to optimize nature's functions for human use while maintaining its inherent stability.
○ Strongly agree (1)
○ Somewhat agree (2)
○ Neither agree nor disagree (3)
○ Somewhat disagree (4)
○ Strongly disagree (5)

Q54 Comment:

Q40 Nature is unstable and chaotic, small changes can be catastrophic, and we must be careful when making decisions to protect livelihoods.
○ Strongly agree (1)
○ Somewhat agree (2)
○ Neither agree nor disagree (3)
○ Somewhat disagree (4)
○ Strongly disagree (5)
Q52 Comment:

Q41 Nature is resilient, ecosystems alternate between stable and unstable states, our management must promote desirable cycles and avoid negative traps.
○ Strongly agree (1)
○ Somewhat agree (2)
○ Neither agree nor disagree (3)
○ Somewhat disagree (4)
○ Strongly disagree (5)
Q56 Comment:

Q42 Humans, plants and animals are all related, management should take into account the perspective of non-humans.
○ Strongly agree (1)
○ Somewhat agree (2)
○ Neither agree nor disagree (3)
○ Somewhat disagree (4)
○ Strongly disagree (5)

Q53 Comment:

Q43 Humans rely upon ecosystems for their well-being
○ Strongly agree (1)
○ Somewhat agree (2)
○ Neither agree nor disagree (3)
○ Somewhat disagree (4)
○ Strongly disagree (5)

Q55 Comment:

Q44 Native Americans have a special relationship with the land.
○ Strongly agree (1)
○ Somewhat agree (2)
○ Neither agree nor disagree (3)
○ Somewhat disagree (4)
○ Strongly disagree (5)

Q57 Comment:

Q45 Human infrastructure (roads, irrigation systems, dams, bridges, power lines, pipelines, etc..) should be built in a way that does not harm ecosystems.
○ Strongly agree (1)
○ Somewhat agree (2)
○ Neither agree nor disagree (3)
○ Somewhat disagree (4)
○ Strongly disagree (5)

Q58 Comment:

Q46 Innovative technologies (e.g. automated soil moisture monitoring, precision agriculture, water and fish monitoring) can greatly improve human relationships with nature.
○ Strongly agree (1)
○ Somewhat agree (2)
○ Neither agree nor disagree (3)
○ Somewhat disagree (4)
○ Strongly disagree (5)

Q59 Comment:

Q47 Expert scientific knowledge should guide decision-making more than local experience.
○ Strongly agree (1)
○ Somewhat agree (2)
○ Neither agree nor disagree (3)
○ Somewhat disagree (4)
○ Strongly disagree (5)

Q60 Comment:

Q97 Thank you again for taking the time to take the Watershed Futures Survey. Please tell us a little bit more about yourself and the type of work that you do. Remember, answers are strictly confidential.

Q1 Occupation(s) (list in order of primacy if multiple)

Q91 Organization/Business/Agency (if applicable)

Q93 Years with that organization/business/occupation

Q6 What are your organization's/business's objectives/goals?

Q7 What are your personal responsibilities within the organization/business?

Q92 Age

Q3 Gender

Q4 Ethnicity/Race

Q5 Highest level of education completed

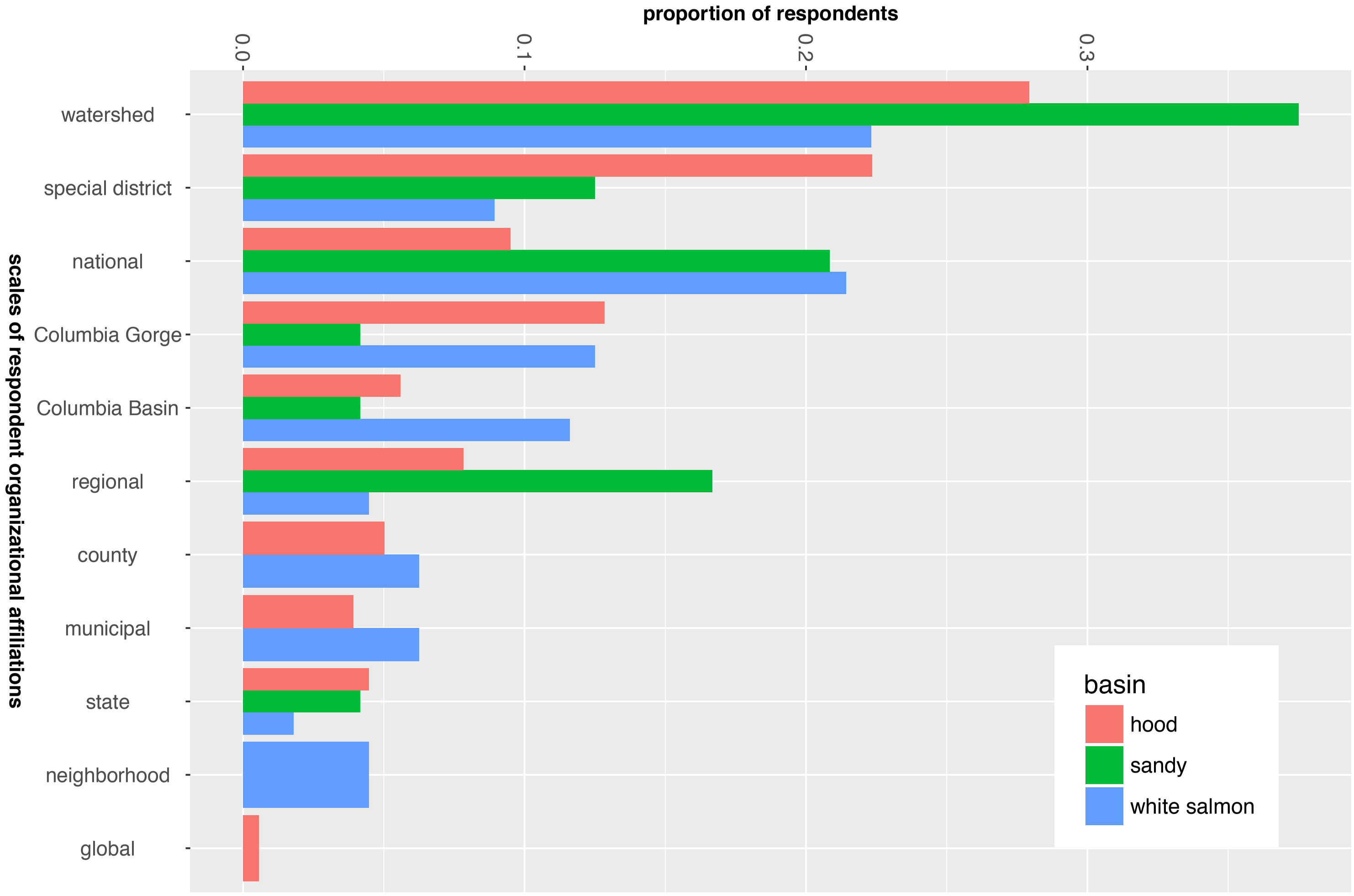
Q48 Would you like to participate in a follow up interview to this survey?
- ○ Yes (1)
- ○ Maybe (2)
- ○ No (3)

Display This Question:
    If Would you like to participate in a follow up interview to this survey? Yes Is Selected
    Or Would you like to participate in a follow up interview to this survey? Maybe Is Selected

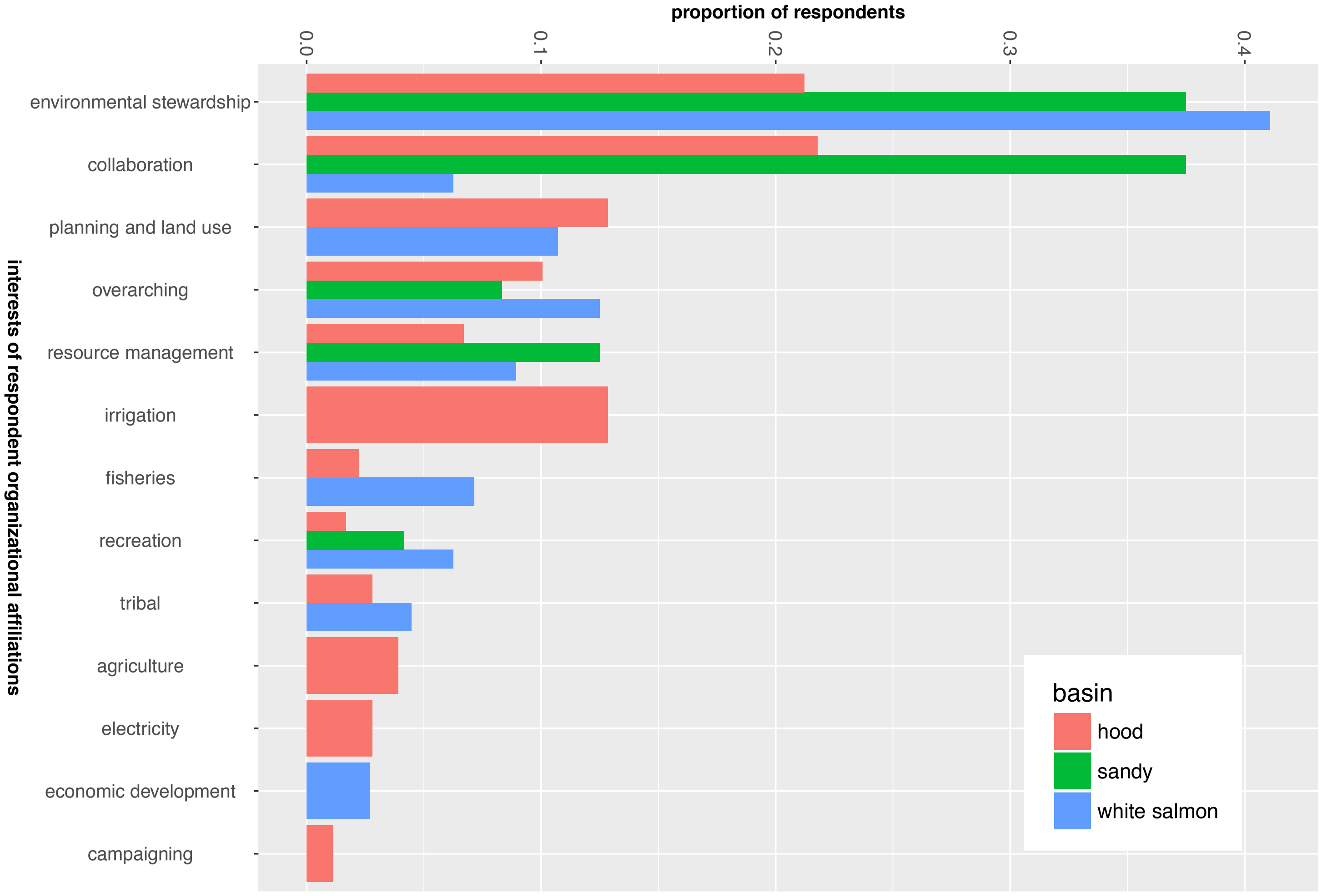
Q49 Thank you for considering the possibility of a follow up interview, please provide your name and preferred contact information in the space below.

Q50 Any final thoughts/comments about this survey or the issues it raises?

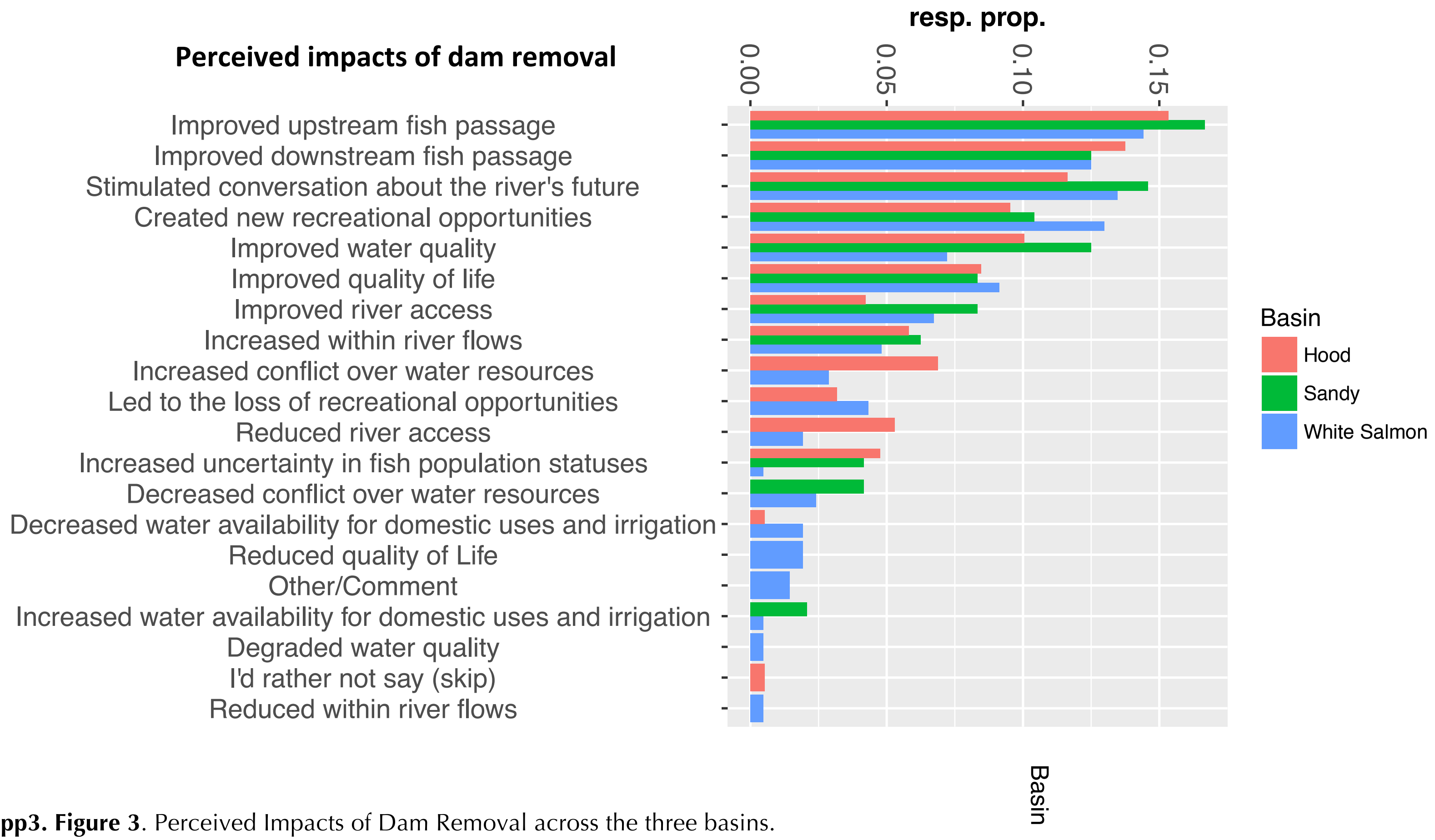
Appendix C: Ancillary Figures for Chapter 4



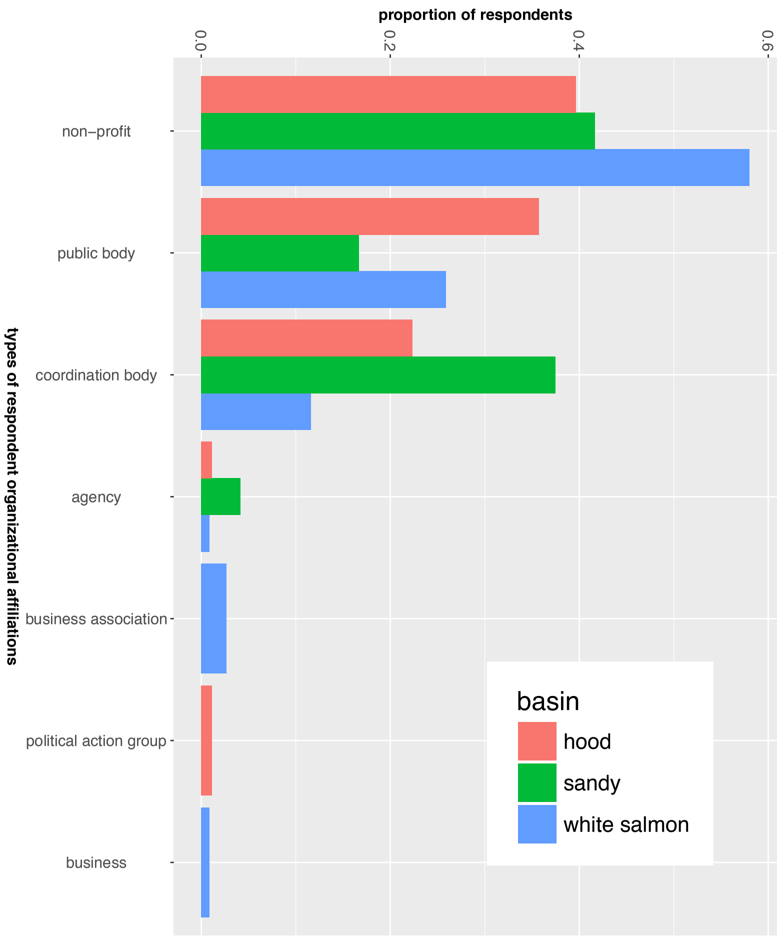
App3. Figure 1. Spatial and administrative scales of survey respondent organizational affiliations across the three watersheds



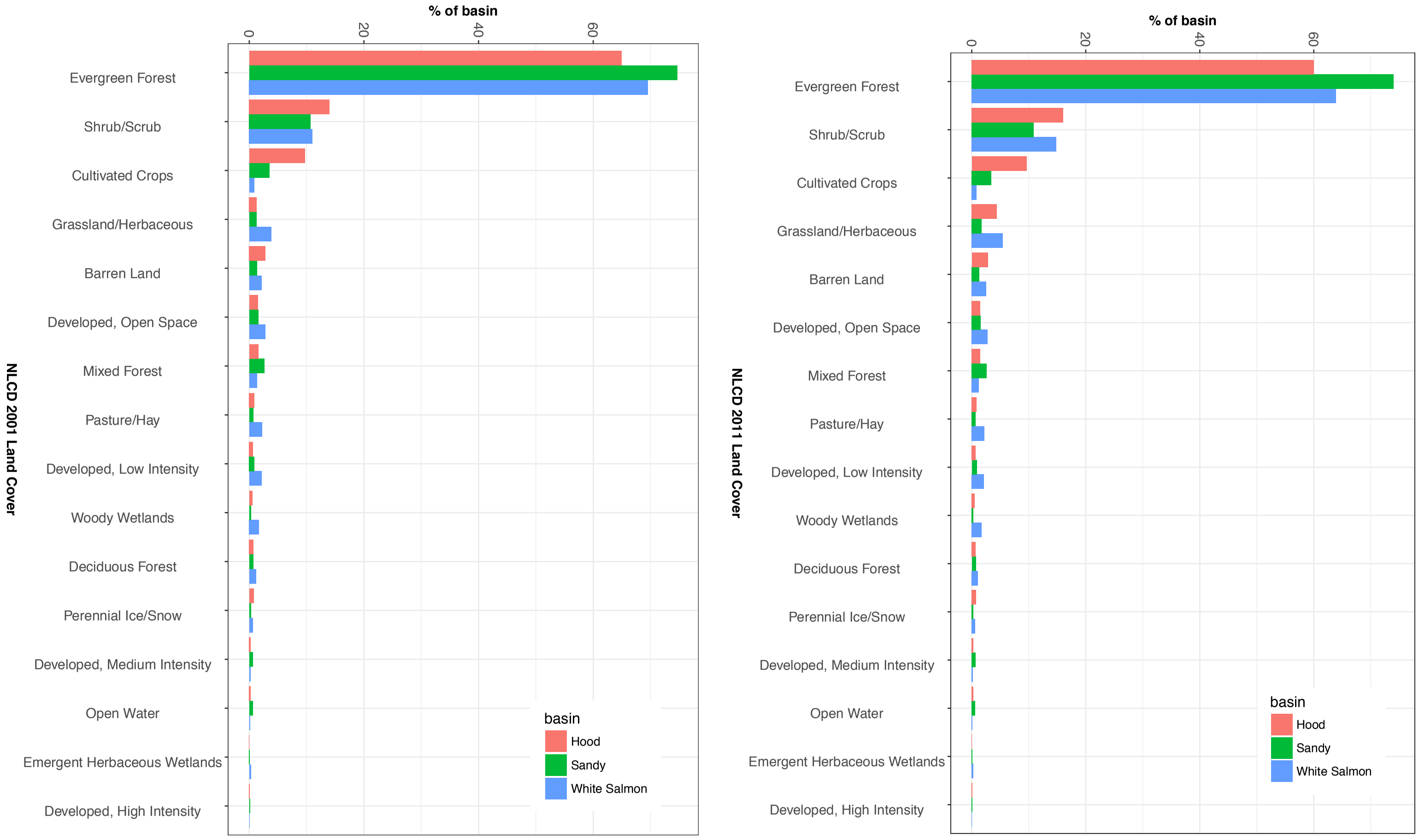
App3. Figure 2. Interests of survey respondent organizational affiliations across the three watersheds.



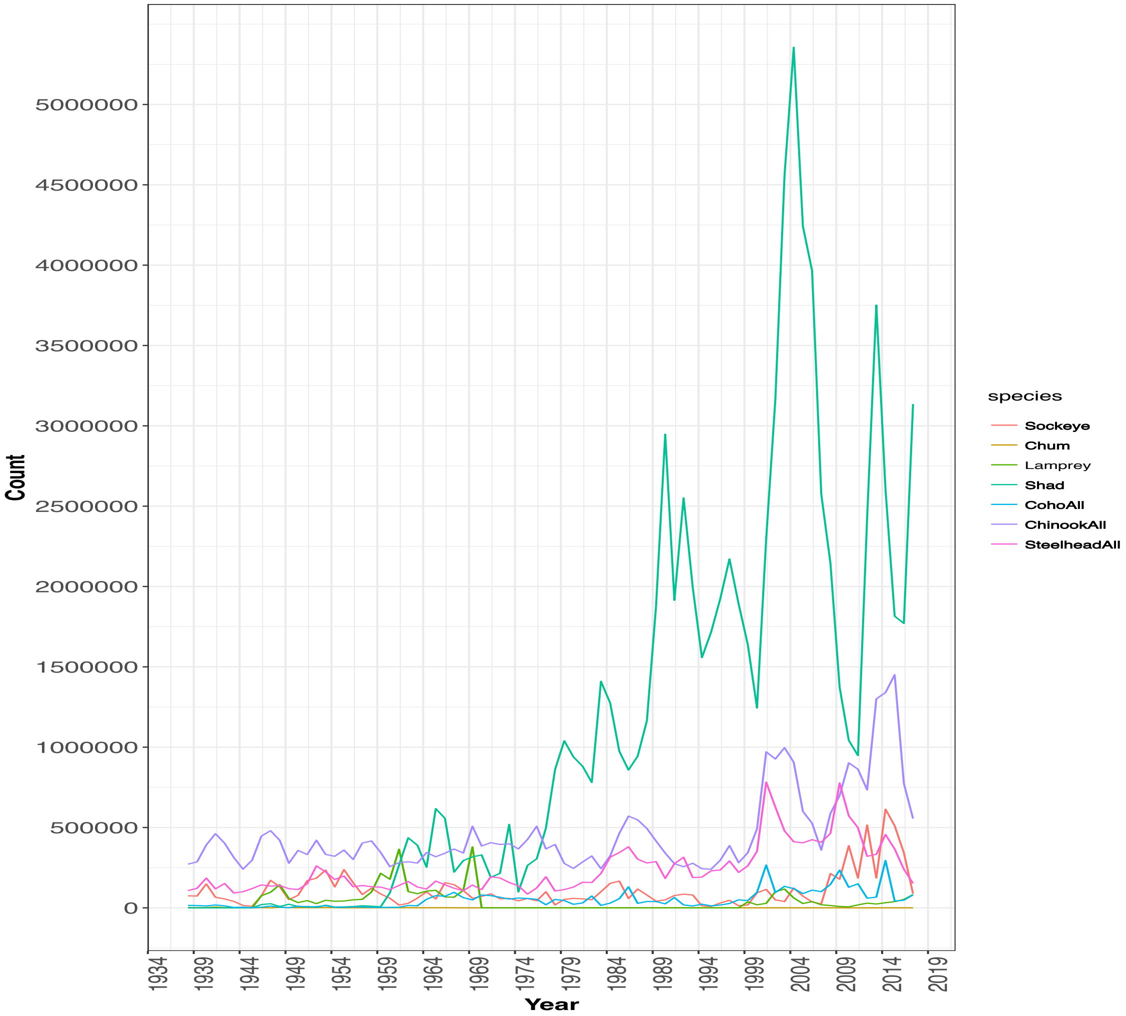
App3. Figure 3. Perceived Impacts of Dam Removal across the three basins.



App 3. Figure 4. Types of organizations survey respondents affiliated with in the three basin



App3. Figure 5. 2001 (Left) and 2011 (Right) National Land Cover Data (NLCD) data set basin land cover for the Hood, Sandy, and White Salmon basi



App 3. Figure 6. Annual fish counts at Bonneville Fish ladder. Data Source: Fish Passage Center (2018).

Appendix D. Stream Temperature Summary Statistics

SITE	BASIN	Agency	S_DADMin	S_DAD Max	meanT	avg_range	max_range	mean_flash	flash_means	days_min >17C	days_min > 20C	pr_>17C	Pr > 20C	tot_hr_deg_acc	n
COL R AT DALLES	Columbia	USGS	19.96	22.47	21.22	0.39	0.80	0.0014	0.0088	66	56	100	94	33613	1584
AT WASHOUGAL	Columbia	USGS	19.87	22.66	21.23	0.78	1.40	0.0028	0.0095	64	49	100	94	32611	1536
COLUMBIA RIVER AT BONNEVILLE	Columbia	USGS	19.9	22.21	21.04	0.36	0.80	0.001	0.0084	64	49	100	91	32319	1535
W_FK_ABV_E_FK	Hood	Z	9.38	16.55	12.78	3.34	4.47	0.0054	0.032	0	0	0	0	20238	6336
HR_BLW_E_W_FK_CONFL	Hood	Z	9.77	17.64	13.62	3.86	5.29	0.002	0.0312	0	0	4	0	21578	19008
RED_HILL_CREEK_AT_LOLO_PASS	Hood	Z	6.84	10.78	8.74	1.59	2.60	0.0013	0.0348	0	0	0	0	13844	19008
W_FK_HR_ABV_LK_BR	Hood	Z	8.76	15.11	11.68	2.84	4.24	0.0017	0.0369	0	0	0	0	18498	19008
HOOD_R_MOUTH	Hood	Z	11.8	19.8	15.86	3.31	4.42	0.0015	0.0305	0	0	29	1	25115	19008
W_FK_BLW_LK_BR	Hood	Z	8.6	14.72	11.5	2.52	3.80	0.0015	0.0335	0	0	0	0	18223	19008
E_FK_ABV_DOG_R	Hood	Z	6.5	16.01	10.76	5.76	7.55	0.0037	0.0474	0	0	0	0	17050	19008
E_FK_BLW_DOG_R	Hood	Z	6.59	15.91	10.85	5.36	7.35	0.0035	0.0453	0	0	0	0	17190	19008
DOG_R_ABV_E_FK	Hood	Z	7.56	12.71	10.24	2.14	2.97	0.0015	0.0359	0	0	0	0	16213	19008
LK_BR_ABV_W_FK	Hood	Z	7.89	13.29	10.37	2.24	3.29	0.001	0.0269	0	0	0	0	16426	19008
LADD_CRK_AT_LOLO_PASS	Hood	Z	6.59	13.09	9.09	3.65	5.83	0.002	0.0532	0	0	0	0	14396	19008
E_FK_ABV_W_FK_CON	Hood	Z	9.14	18.34	13.65	5.12	6.86	0.002	0.032	0	0	8	0	21626	19008
Sandy_R_Blw_Clr_Crk	Sandy	Z	8.35	19.07	12.88	6.5	9.50	0.010	0.049	0	0	12	0	20404	6336

Sandy_R_Abv_Bvr_Crk	Sandy	Z	15.47	23.06	19.04	2.31	3.33	0	0.0343	43	11	79	37	30162	19008
Beaver_Crk_Mouth	Sandy	Z	13.96	26.04	18.18	6.19	12.97	0.0026	0.0321	19	0	65	21	28804	19008
Sandy_Abv_ZigZag	Sandy	Z	8.01	19.22	12.66	6.92	10.15	0.0037	0.0529	0	0	11	0	20053	19008
Sandy_R_at_Marmot_Dam_Site	Sandy	Z	11.74	19.61	15.48	3.45	5.45	0.0014	0.0409	0	0	28	1	24564	18725
Sandy_blw_marmot_dam	Sandy	Z	11.9	19.4	15.52	3.13	5.12	0.0013	0.0406	0	0	27	0	24524	19592
Sandy_R_mrmtbr_blw_slmn	Sandy	Z	10.66	19.06	14.41	4.15	6.61	0.0019	0.0395	0	0	15	0	22826	19008
SMN_R_NR_GOVT_CMP	Sandy	Z	6.39	11.38	8.75	2.5	3.95	0.002	0.0412	0	0	0	0	13866	19008
Salmon_R_abv_Sandy_Brtwood_Br	Sandy	Z	11.1	19.58	15.07	3.68	5.81	0.0016	0.0367	0	0	22	1	23865	19008
Bull Run Near Multnomah Falls	Sandy	USGS	10.71	15.07	12.53	1.68	3.20	0.0025	0.0332	0	0	0	0	19848	6334
N FK BULL RUN NEAR MULT FALLS	Sandy	USGS	8.84	13.27	10.7	1.84	2.70	0.0035	0.0257	0	0	0	0	16957	6332
S FK BULL RUN RIVER	Sandy	USGS	11.06	15.64	13.38	1.1	1.90	0.0017	0.0231	0	0	0	0	21191	6335
BULL RUN R AT LARSON'S BRIDGE	Sandy	USGS	11.74	18.11	14.52	3.05	6.00	0.0044	0.0237	0	0	8	0	23005	6336
LITTLE SANDY RIVER NR BULL RUN	Sandy	USGS	10.91	18.67	14.53	2.81	5.00	0.004	0.0363	0	0	12	0	23020	6336
LinneyAtSalmon	Sandy	USFS	7.69	10.24	8.76	1.52	2.32	0.0138	0.0262	0	0	0	0	10938	1239
Salmon_FB	Sandy	USFS	10.75	17.31	13.11	3.25	4.81	0.0198	0.0341	0	0	1	0	18576	1406
Mud_Creek	Sandy	USFS	8.05	12.93	10.05	3.16	4.33	0.0254	0.0335	0	0	0	0	14239	1403
Little_Sandy_1228	Sandy	USFS	9.4	14.67	11.81	1.96	3.58	0.013	0.0409	0	0	0	0	17041	1428
Zigzag_FB	Sandy	USFS	9.67	13.86	11.36	2.25	3.51	0.0155	0.0331	0	0	0	0	16104	1405

Little_Sandy_at_Waterfall	Sandy	USFS	9.7	16.55	12.57	2.82	4.98	0.0177	0.0412	0	0	1	0	18133	1430
Clear_Creek_Trap_Site	Sandy	USFS	10.86	16.6	13.41	2.98	4.77	0.0174	0.0311	0	0	0	0	19011	1405
Gordon_Cr	Sandy	USFS	8.53	12.08	10.28	0.66	1.33	0.0046	0.0308	0	0	0	0	14809	1425
Little_Sandy_Homestead	Sandy	USFS	10.44	15.43	12.71	1.83	3.78	0.0108	0.0354	0	0	0	0	18321	1431
Salmon_River_Trp	Sandy	USFS	11.85	20.05	15.01	4.43	6.64	0.0232	0.0389	0	0	21	1	21279	1406
SalmonAtLinney	Sandy	USFS	9.32	14.05	11.21	2.55	3.90	0.0179	0.036	0	0	0	0	13995	1239
Sandy_FB	Sandy	USFS	9.48	19.07	12.89	6.54	10.11	0.0397	0.053	0	0	13	0	18279	1405
Still_Creek_Trap_Site	Sandy	USFS	10.86	15.6	12.64	2.7	4.06	0.017	0.0254	0	0	0	0	17919	1404
WS_BLW_TRT_CR	W Salmon	Z	7.24	13.79	10.43	2.72	3.71	0.0018	0.043	0	0	0	0	16519	19008
WS_MOUTH	W Salmon	Z	8.33	13.16	10.39	2.69	3.41	0.002	0.0192	0	0	0	0	16453	19008
WS_ABV_TRT_CRK	W Salmon	Z	6.86	12.5	9.54	2.52	3.50	0.0019	0.0447	0	0	0	0	15117	19008
WS_ABV_BUCK_CR	W Salmon	Z	8.13	11.99	9.64	2.02	2.57	0.0015	0.0162	0	0	0	0	15276	19008
WS_BLW_BUCK_CR	W Salmon	Z	8.19	12.08	9.74	2.07	2.54	0.0015	0.0165	0	0	0	0	15432	19008
WS_AT_GRN_TRUSS	W Salmon	Z	8.46	15.44	12.01	2.82	3.54	0.0016	0.0394	0	0	0	0	19030	19008
WS_BLW_RATTLESNAKE_CRK	W Salmon	Z	8.02	10.88	9.22	1.35	1.70	0.0011	0.0152	0	0	0	0	14612	19008
White_Salmon_at_Husum	W Salmon	USGS	8.16	10.57	9.18	0.97	1.43	0.0085	0.0142	0	0	0	0	14543	1584
Rattlesnake	W Salmon	USGS	12.2	21.83	17.23	3.62	5.12	0.0168	0.0306	11	0	54	12	27288	1584
Mill_Creek	W Salmon	USGS	10.6	14.82	12.47	1.71	3.12	0.0107	0.025	0	0	0	0	19747	1584
Buck_Creek	W Salmon	USGS	10.65	16.73	13.83	2.37	3.27	0.0138	0.0257	0	0	0	0	21903	1584
White Salmon at base	W Salmon	UCD	8.2	12.77	10.05	2.51	3.17	0.0206	0.0176	0	0	0	0	15916	1584
Buck Creek at	W	UCD	9.97	14.49	12.26	1.81	2.59	0.011	0.024	0	0	0	0	19417	1584

DNR Bridge	Salmon							9	2						
Upper White Salmon	W Salmon	UCD	6.83	11.64	9.16	2.21	3.29	0.0198	0.043	0	0	0	0	14502	1584
Trout Lake Creek at old creamery rd	W Salmon	UCD	13.63	20.62	16.93	4.06	8.28	0.0189	0.0378	5	0	51	7	11374	672