Adapting International Freshwater Agreements for Fish Conservation

by
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Abstract

International freshwater treaties govern the cooperative use of waters in the world’s major shared river basins but have a poor track record when it comes to species protection. Covering over forty percent of the earth’s land surface, shared basins are highly relevant to biodiversity conservation efforts with most water treaties directly affecting species and their habitats in some way. Using the Columbia River Treaty and the river basin it governs as a case study, I focus on understanding barriers to the inclusion of species conservation in the formulation and implementation of these agreements. An opening chapter illustrates the absence of, or ambiguity regarding, species conservation in the formal texts of the global collection of agreements and describes four contributing barriers: a) complexity avoidance, b) undervalued species, c) poorly understood trade-offs, and d) institutional norms. In the second chapter, I focus on b) using a welfare economics approach to assess the capacity of the Columbia River to provide four ecosystem services derived from salmon. The approach illustrates how non-zero estimates of economic value for a species can be developed in a transboundary river basin. In Chapter 3, I focus on c) by applying multi-attribute utility optimization across salmon conservation, hydropower production, and agricultural irrigation to forecast optimal flows in the Hanford Reach segment of the Columbia River. This chapter shows how, in a simulated environment, optimization can be used to explore alternative transboundary water sharing strategies that balance trade-offs across multiple values. In Chapter 4, I focus on d) using a method called incident analysis to examine a prior conflict between Canada and the US over US efforts to conserve an endangered species of sturgeon. This study provides insights regarding the Columbia River Treaty’s adaptive capacity to respond to evolving species conservation needs.

Keywords: species conservation; transboundary water agreements; economic valuation of ecosystem services; trade-off optimization; species conservation norms in freshwater treaties; international incidents

Dedication

This thesis is dedicated to all the humans and non-humans who depend on shared rivers and lakes.

Acknowledgements

Becoming interdisciplinary is not for the faint of heart – let this be a warning. By “effectively removing all barriers to communication between different races and cultures”, The Babel fish in Douglas Adams’ Hitchhiker’s Guide to the Galaxy, “has caused more and bloodier wars than anything else in the history of creation.” As a sub-species of the Babel fish, interdisciplinarians are well familiar with the trials and risks of translating across academic languages and cultures. For those of us in training, the battles happen (mostly) in our minds, which is why some of us take a decade to complete our degrees if we avoid spiralling into madness and complete them at all. Thankfully, the lucky among us have allies in our quest without whom our dissertations would be indecipherable puddles of mental goop, or worse, siloed mumblings from a single discipline (gasp). Like the Babel fish itself, the School of Resource and Environmental Management at Simon Fraser University is “probably the oddest thing in the universe” in that it is full of such allies, most of whom are weary from their own interdisciplinary journeys but still committed to raising us younger fish out of the primordial muck of dis-integrated science and research. For me, chief among these allies was my Supervisor Dr. Murray Rutherford who, in addition to many other virtues, demonstrated a good deal of patience with my curiosity. It was Dr. Rutherford who first diagnosed me with intellectual attention deficit disorder. Knowing this was half the battle. The other half was…wait…squirrel!....

Special gratitude also goes to my committee members, Drs. Knowler, and Cox, both of whom introduced me to their respective domains of environmental economics and fish population ecology. My preliminary attempts to fill some of the interstitial spaces between environmental policy and these domains grew into something more ambitious than any of us expected. I owe them thanks for their willingness to humour my ideas and guide me toward better ones.

One thing that always fascinated me about the Babel fish is the evolutionary trade-offs it contends with. The species feeds on brainwaves in a symbiotic relationship, so it is highly dependent on its host environment. During the development of this dissertation, the quality of my ‘host environment’ was largely dictated by the people closest to me to whom I am indebted: my parents, Gail and Dave Morton, my partner, Liz Williams, and my friend and colleague Jason Tockman. I hope that your investments in me with your time, emotional support, aid with medical expenses during some very challenging years,

intellectual bantering, and 3am defense preparations were, on balance, more symbiotic than parasitic! Thank you for seeing me through this. I could not have done it without any single one of you. Lastly, I would like to express deep gratitude to my dear grandfather, Sidney Morton, who stepped in with financial support at a critical juncture. Pop, you may not know this, but that timely and unexpected assist made all the difference.[1]

Oh, and the answer is, indeed, 42.

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[1] This dissertation was also funded by scholarships from the Social Sciences and Humanities Research Council, the Pacific Institute for Climate Solutions, the School of Resource and Environmental Management, and Simon Fraser University.

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1.1. Introduction

Global biodiversity loss is a pressing environmental problem that threatens the planet's ability to supply critical ecosystem services and to continue supporting human well-being (Ceballos et al. 2015). Scientists have sounded the alarm regarding accelerated human-caused species losses, which are widely believed to signal a sixth mass global extinction event already well underway (Raven et al. 2011, Pimm et al. 2014, Cafaro 2015, Ceballos et al. 2015, Ceballos et al. 2017). Despite directly affecting species and their habitats, international freshwater treaties have a poor track record when it comes to species protection. With rare exceptions, conservation measures for specific species are absent from major transboundary freshwater agreements globally.[2] Yet because these agreements govern the shared use of waters in major river basins covering over forty percent of the earth's land surface, they are highly relevant to biodiversity conservation efforts (OSU 2011, Brels, Coates and Loures 2009).

The concentration of aquatic, avian, and terrestrial species-at-risk varies across the world's major transboundary basins, with the highest concentrations occurring in the Mississippi, Amazon, Danube, Nile, Congo/Zaire, and Mekong basins (Figure 1.1) (IUCN Red List 2019). Many of these species are impacted by development activities that are enabled by freshwater treaties, placing them at greater risk by intensifying ecological alterations and degrading habitats (Sneddon and Fox 2006). Partly in recognition of this challenge, the signatories of the Convention on Biological Diversity (CBD) included bi- and multi-lateral freshwater treaties in their 2008 recommendation to strengthen existing international environmental agreements as a means to implement the CBD's goals (CBD 2008; Belbin and VanderZwaag 2016). The CBD recommendation signalled a need to

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[2] *e.g., The Pacific Salmon Treaty (2019) and the Yukon River Salmon Treaty (2001) both contain articles regarding the protection of salmon during the freshwater portion of their life cycles.*

better align water management with global conservation goals, to build agreements that are more agile in response to evolving conservation needs, and to address incongruities between international treaties and domestic conservation laws. My aim with this dissertation is to advance understanding about how these needs can be addressed.

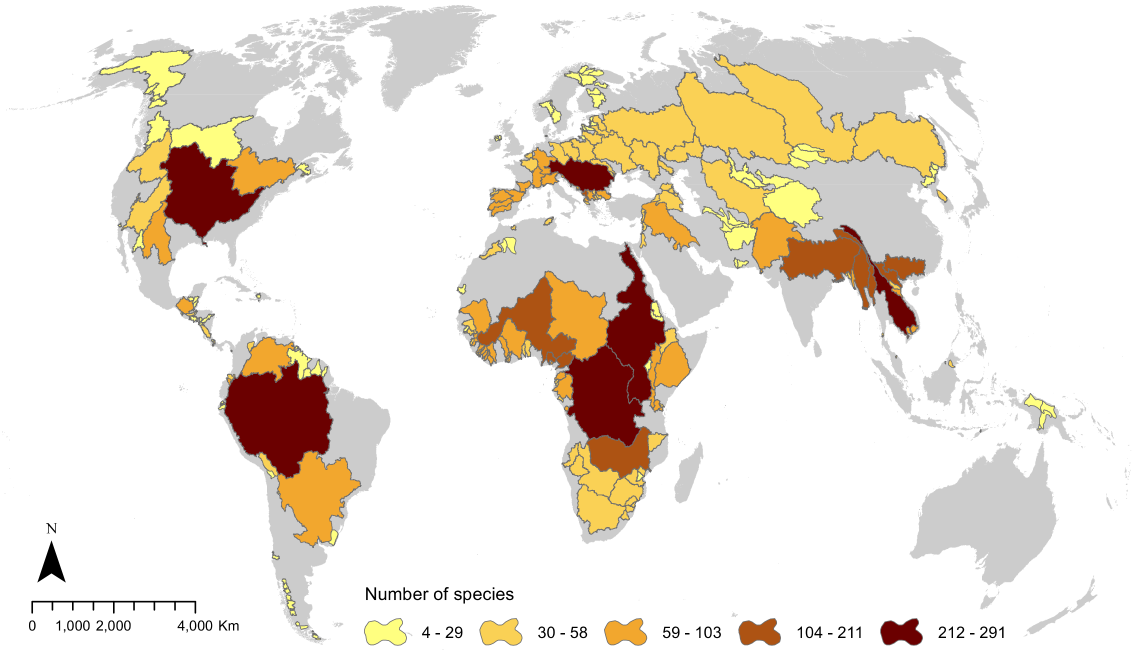

Figure 1.1. Number of freshwater species-at-risk in major transboundary river basins (not comprehensive)

Source: IUCN Red List (2019) (extant freshwater species assessed as critically endangered, endangered, vulnerable, and near threatened – includes fishes, amphibians, reptiles, birds, plants, mammals, dragonflies/damselflies, shrimps, crabs and crayfishes); OSU (2012); Winkel-Tripel projection

This introductory chapter sets the global context for the chapters that follow by reviewing the world's major river basin agreements through a species conservation lens. Using literature review, various treaty documents, Oregon State University's International Freshwater Treaties Database, and its International Water Event Database, I explore recent environmental protection trends in freshwater agreements and what the data can tell us about why these agreements tend to omit species conservation. I then raise the question of whether, despite this omission, these agreements can adapt to increasing species conservation needs, which is the thematic focus of Chapter 4. I also introduce the Columbia River Treaty case. This treaty, and the river basin it governs, forms the basis of all three core chapters in this dissertation (Chapters 2, 3 and 4). Lastly, after briefly situating my species conservation lens within the broader transboundary water literature, I provide a summary overview of the contents of this document.

1.2. Recent trends

While affected species remain largely ignored in the formal written texts of bi- and multi-lateral international freshwater agreements, the focus of broader international water laws and policies is currently changing in a more pro-environmental direction (Giordano et al. 2013). In addition to the CBD's goals noted above, the 2015 United Nations' (UN) Sustainable Development Goals explicitly include transboundary cooperation for the protection and restoration of aquatic and riparian ecosystems (United Nations 2015). The UN Convention on the Law of Non-navigational Use of International Watercourses (Watercourses Convention) includes obligations to protect ecosystems, control pollution, and prevent the introduction of invasive species (UN General Assembly 1997). The UN Economic Commission for Europe's (UNECE) Convention on the Protection and Use of Transboundary Watercourses and International Lakes adopts the concept of Integrated Water Resources Management (IWRM) and incorporates principles like pollution control and environmental protection of surface and groundwater (UNECE 2013; Wouters and Vinogradov 2003). The South African Development Community's (SADC) Regional Strategic Action Plan on Integrated Water Resources and Development Management commits parties to negotiate cross-border IWRM agreements and to develop a common methodology for determining environmental flow needs (SADC 2011). The UN Convention on Migratory Species lists endangered migratory freshwater species (CMS 2011) and specifies joint conservation obligations for states that share these species' ranges (CMS 1979).

These developments reflect efforts during the 20th century to formulate a consistent international legal framework that is specific to shared river basins and inclusive of environmental protection. Many of the modern principles build upon decisions of the International Court of Justice (ICJ), or can be traced to norms and practices set out in the existing global collection of bi- and multi-lateral river basin agreements, and commitments made by participating states during the 1992 United Nations *Conference on Environment and Development* (UNCED) (Conca, Wu, and Mei 2006). While these developments are encouraging, meeting the conservation goals of water programs has proven challenging worldwide (Gilman, Abell, and Williams 2004; Medema, McIntosh, and Jeffrey 2008), and the content of most river basin agreements remains silent regarding species conservation.

More than half of the 274 major freshwater agreements in the International Freshwater Treaties Database (IFTD)[3] acknowledge environmental values in some way (see Figure 1.2 and Figure 1.3), but almost all of these agreements either completely ignore, or are vague regarding affected species, making no reference to targeted conservation measures and not naming individual species. Only a handful of basins have agreements that contain commitments to protect species (Figure 1.2),[4] most of which are framed in broad rather than precise terms within formal treaty texts (see Table 1.1).

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[3] *While other treaty databases do exist, the IFTD remains the most comprehensive single source for bi- and multi-lateral freshwater agreements, with 644 entries and full text for over 400 documents spanning 1820-2007. The IFTD database contains a coding scheme established in the literature and pre-coded text, including for many agreements that do not have downloadable full-text versions available. This latter feature permits a consistent and larger sample across a wider time span than other studies that rely on a mix of sources, new coding schemes, and selective date-ranges (e.g. Conca et al (2006); Giordano et al. (2013)). Other databases of potential interest to readers include the UN Food and Agriculture Organization's legal database (FAOLEX), the American Society of International Law's International Legal Materials (ILM), the UN Treaty Collection (UNTC), and Mitchell's (2014) International Environmental Agreements (IEA) Database.*

[4] *English translations of some agreements in the IFTD are not available and were not included in this assessment.*

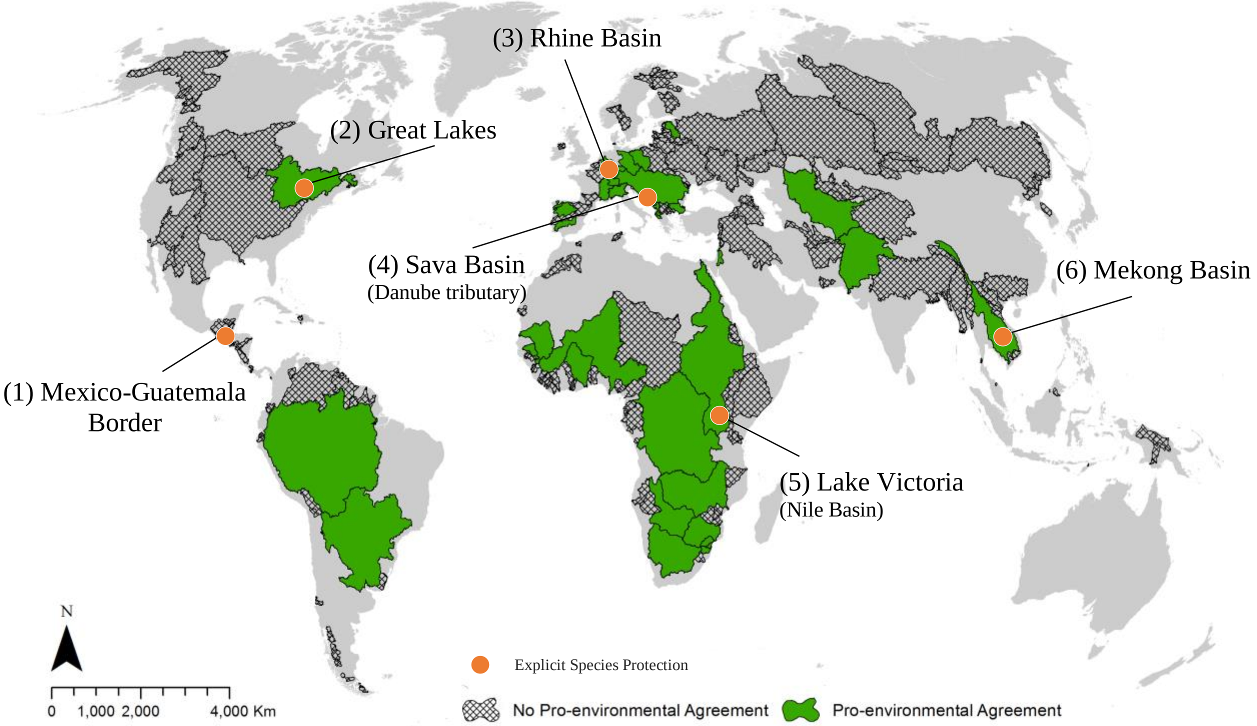


Figure 1.2. Major transboundary river basins with bi- or multi-lateral agreements containing articles addressing water quality, environmental protection/services, fisheries management, and/or water conservation during droughts*

Source: OSU 2012; Winkel-Tripel projection
*Sub-basin agreements and global agreements not included

Table 1.1. Summary of international freshwater treaties in the International Freshwater Treatiies Database (IFTD) with explicit content regarding species conservation

Agreement Name	Countries	Freshwater Basin(s)	Agreement Section(s)	Relevant text
1976 *Convention on the Protection of the Rhine against chemical pollution*	Germany, France, Luxembourg, the Netherlands, Switzerland, EEC	Rhine	Article 1(2c)	Requires signatories to "…take into account, within reason…conservation and development of *natural species*, *both fauna and flora*…"
1988 *Agreement between the United Mexican States and the Republic of Guatemala on the protection and improvement of the environment in the border area*	Mexico, Guatemala	Grijalva, Candelaria, Coatan Achute, Suchiate	Article 4, 4(c), 4(d)	Obliges parties to establish working groups to conduct studies about "the protection and improvement of the environment in the border area …. including the *protection of threatened or endangered species*", to "…take the necessary measures for the *protection of threatened or endangered species*", and to "coordinate efforts…to prevent illicit trade in *threatened and endangered plant and animal species*"
1995 *Agreement on the cooperation for the sustainable development of the Mekong River Basin*	Cambodia, Laos, Thailand, and Vietnam	Mekong	Chapter 3, Article 3	Requires parties' cooperation to "…protect the environment, natural resources, *aquatic life and conditions*, and ecological balance of the Mekong River Basin from pollution or other harmful effects…"
2002 *Framework Agreement on the Sava River Basin*	Bosnia-Herzegovina, Croatia, Slovenia, and Serbia	Sava	Article 11	Commits the parties to "…cooperate…in a sustainable manner…that shall provide for…water in sufficient quantity and of appropriate quality for the preservation, protection and improvement of aquatic eco-systems (*including flora and fauna* and eco-systems of natural ponds and wetlands)…"

Agreement Name	Countries	Freshwater Basin(s)	Agreement Section(s)	Relevant text
2003 *Protocol for Sustainable Development of Lake Victoria*	Kenya, Uganda and Tanzania	Lake Victoria	Article 3(m), 4(f), 6(d), 6(e)	Commits parties to apply the precautionary and polluter pays principles with respect to *wildlife*, "…*fish and other aquatic species*…" , "…*migratory species* of wild animals", and "…*endangered species* of wild fauna and flora".
2012 amendment to the 1978 Canada-US *Great Lakes Water Quality Agreement* (Annex 7)	Canada, USA	Great Lakes	Article III	Includes specific performance measures for key pollutants affecting species: "The sum of the concentrations of DDT and its metabolites in *whole fish*…should not exceed 1 microgram per gram", and "The concentration of total polychlorinated biphenyls in fish tissues…should not exceed 0.1 microgram per gram *for the protection of birds and animals which consume fish*".

One exception is the Canada-USA Great Lakes Water Quality Agreement, which includes specific performance measures designed to protect "birds and animals which consume fish" from key bioaccumulated pollutants (Table 1.1). None of the other major transboundary freshwater agreements in the IFTD express explicit performance metrics for species protection, and, although some treaties include conservation goals for fish, they focus primarily on commercial goals like managing for sustainable harvest rather than broader environmental goals like conserving biodiversity or protecting species at risk (see for example the 1954 Convention on Great Lakes Fisheries; the 1975 Uruguay-Argentina Statute of the River Uruguay; the 1994 Agreement between the Government of the People's Republic of China and the Government of Mongolia on the Protection and Utilization of Transboundary Waters; and the 1994 Convention on Cooperation for the Protection and Sustainable Use of the Danube).

1.3. Why have freshwater treaties omitted species conservation?

As for any policy process, the substantive content of international freshwater negotiations is influenced by decisions about what issues are included in the negotiating agenda. These decisions are affected by normative expectations about appropriate state behavior *(*see Hofferberth and Weber 2015; Finnemore and Sikkink 1998; Keck and Sikkink 1998; Keck and Sikkink 1999, Florini 1996*)* observed at multiple levels of governance including international and domestic scales (Putnam 1988; Conca, Wu, and Mei 2006). The influence of norms on agenda setting can impede the inclusion of species conservation even when positive environmental outcomes are a mutually shared value between parties. To better understand why treaty negotiators might seek to exclude or dilute explicit species conservation content during the negotiation and codification of treaty texts, in this section I explore some potential barriers to the inclusion of this content. First, I discuss the role of complexity and its perceived impact on durable, consensus-based agreements, examining the claim that "simple agreements are successful agreements" using empirical evidence from the IFTD and International Water Event Database (IWED) (OSU 2008). Second, I raise the issue of undervalued species that are therefore excluded from cost-benefit comparisons (the focus of Chapter 2). Third, I consider how poorly understood trade-offs can lead to the exclusion of species conservation values (the focus of Chapter 3). I then shift direction from the codification of formal treaty content to consider the major role that institutional norms can play in the interpretation of that content during day-to-day implementation (the focus of Chapter 4).

1.3.1. Avoiding complexity in favour of flexibility and consensus

A sentiment I often heard expressed by treaty experts during this research is that "simple agreements are successful agreements". This heuristic is rooted in the belief that more complex negotiations have a greater risk of failure (e.g. Bercovitch 1986; Moore 1986; Bercovitch and Langley 1993; Bercovitch and Jackson 2001; van der Schalk et al. 2009). State decision-makers are "boundedly rational" actors with a limited capacity to process information. When faced with complexity they seek cognitive shortcuts to achieve agreement (Oppermann and de Vries 2011). Technically and politically complicated environmental issues like species conservation may therefore be excluded from negotiating agendas to avoid overwhelming the process and to control the risk of high administrative costs associated with implementation. The empirical evidence I present in this section suggests that environmental protection content does ‘complexify’ agreements and may make cooperation more challenging. But it also suggests that certain types of environmental protection content are associated with higher levels of cooperation than other thematic content. In the analyses that follow, I use pre-coded thematic content from the IFTD to (a) visually and quantitatively examine whether the inclusion of environmental protection articles in freshwater treaties affects an agreement’s complexity more than does other content. I also (b) combine the IFTD data with IWED data to test the effect of pro-environmental articles on cooperation.

For (a), I rely on network analysis using the *igraph* and *tnet* packages in R (R Core Team 2016; Csardi and Nepusz 2006; Opsahl 2009) and, based on thematic co-occurrences within each of the IFTD’s 274 major agreements, compare differences in complexity across two IFTD subsamples – one with agreements that contain environmental protection articles, and the other with agreements that do not.

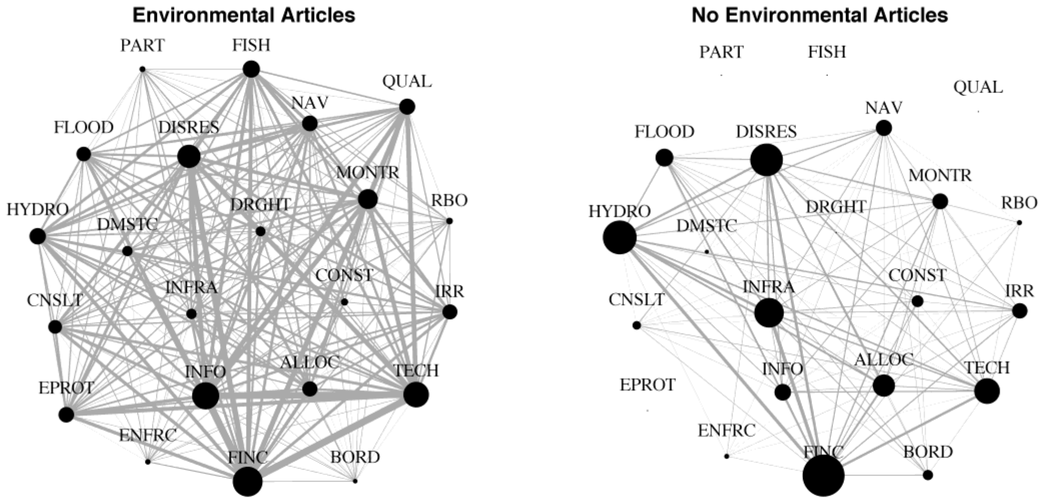
For (b) I use binomial logistic regression to test differences in the level of co-riparian cooperation before and after the signing of agreements with environmental protection articles. I do this test first with agreements classified as either containing environmental protection content or not (ENV; Eq. 1), and next with thematic content disaggregated by the pre-coded IFTD themes to see if different types of content are associated with different levels of cooperation (THEME; Eq. 2).

$$hydro\ relations = \beta 0 + \beta 1 \times ENV + \beta 2 \times\ PRD + \beta 3 \times RGN \tag{1}$$

$$hydro\ relations_i = \beta 0_i + \beta 1_i \times\ THEME_i +\ \ \beta 2_i\ \times PRD + \beta 3_i\ \times RGN \tag{2}$$

In both cases, I use “hydro relations” as the dependent variable, which is derived from the IWED scale for shared water conflict/cooperation events (-7 to 7, from most antagonistic to most cooperative with 0 indicating a neutral event) (OSU 2008). I convert this scale to binary form with 0 indicating antagonistic events and 1 indicating cooperative events and remove neutral events from the dataset. Following Conca, Wu, and Mei (2006) I also control for the effects of time period (before and after 1990; PRD), and global region where agreements signed in Africa, Asia and South America are treated as the ‘global South’ and those signed in Europe and North America treated as the ‘global North’ (RGN).

Results indicate that including environmental issues in water treaties is, indeed, associated with increased agreement complexity (Figure 1.3). Agreements containing articles that address water quality (QUAL), environmental protection/services (EPROT), fisheries management (FISH), or environmental flow needs during drought (DRGHT) demonstrate a disproportionately large number of thematic co-occurrences relative to the number of agreements in each sample (11% of possible compared with 5% of possible for agreements without environmental articles). Administrative themes like information sharing (INFO), technological exchange (TECH), financial arrangements (FINC), and consultation (CNSLT) are also more prominent in these types of agreements, suggesting that associated administrative costs are likely higher.



	Number of Agreements	Number of Issues	Number of Co-occurrences
Environmental Articles	154	22	3999 (11% of possible)
No Environmental Articles	120	18†	963 (5% of possible)

Figure 1.3. Networks of issue co-occurrence for agreements with and without environmental articles*

*Node size is based on each node’s proportion of weighted degree centrality in the given network. Tie thickness is based on frequency of co-occurrences.

†EPROT, QUAL, FISH and DRGHT issues are excluded by definition.

The inclusion of environmental articles in water treaties is also associated with reduced levels of cooperation. Applying the aggregate version of the binomial logistic regression model, the probability of cooperation decreases from 82% to 67% after basin-states sign agreements that include QUAL, EPROT, FISH, and DRGHT thematic content (odds=0.45, ±95% CI =0.33-0.60, p<0.001). Supporting this finding, a frequency distribution of the data (Figure 1.4) shows that although most of these events were cooperative (results below 0 represent antagonistic events), on average the quality of that cooperation reduced from 3 (explicit cultural/scientific agreement or support) to 1 (minor cooperative exchanges) on the IWED scale.

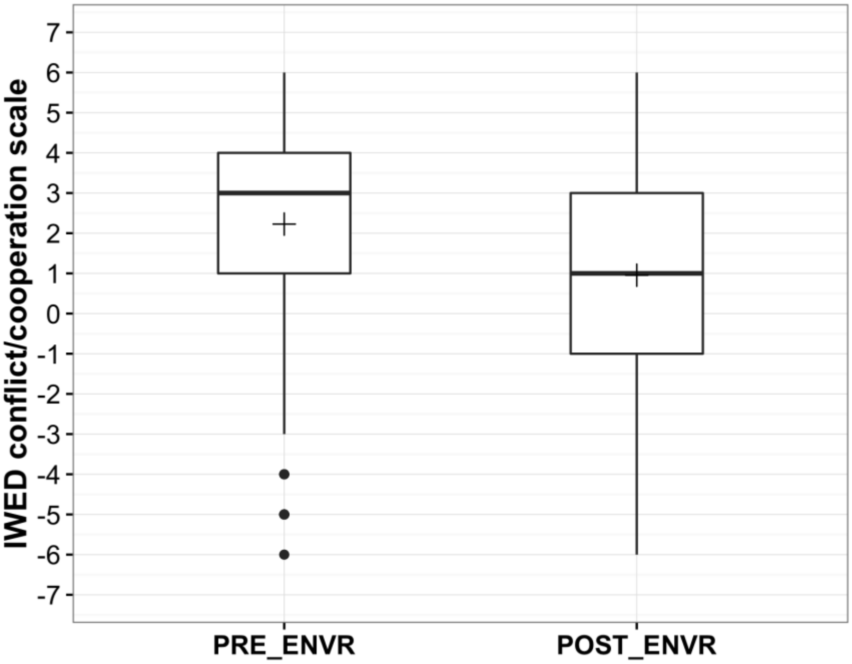


Figure 1.4. Frequencies of conflict and cooperation events in basins before and after agreements with pro-environmental content

"+" symbols indicate mean values, "•" symbols indicate outliers, horizontal black lines indicate median values, n=2941; POST_ENVR = 2620; PRE_ENVR = 321.

However, for the disaggregated binomial logistic regression models, all statistically significant effects are negative *except* for the EPROT theme, which represents "environmental protection/services" (Figure 1.5). If agreement content related to this theme is present in a basin prior to an event, that event is nearly 1.8 times more likely to be cooperative rather than antagonistic (odds ratio = 1.76, ±95% CI = 1.44-2.14, p<0.001). The other environmental protection themes (QUAL, FISH, DRGHT) all tend toward the negative end of the odds-ratio scale (<1) but are not statistically significant. Hydropower (HYDRO), irrigation (IRR), water allocation (ALLOC), and construction (CONST) are negatively associated with cooperative events.

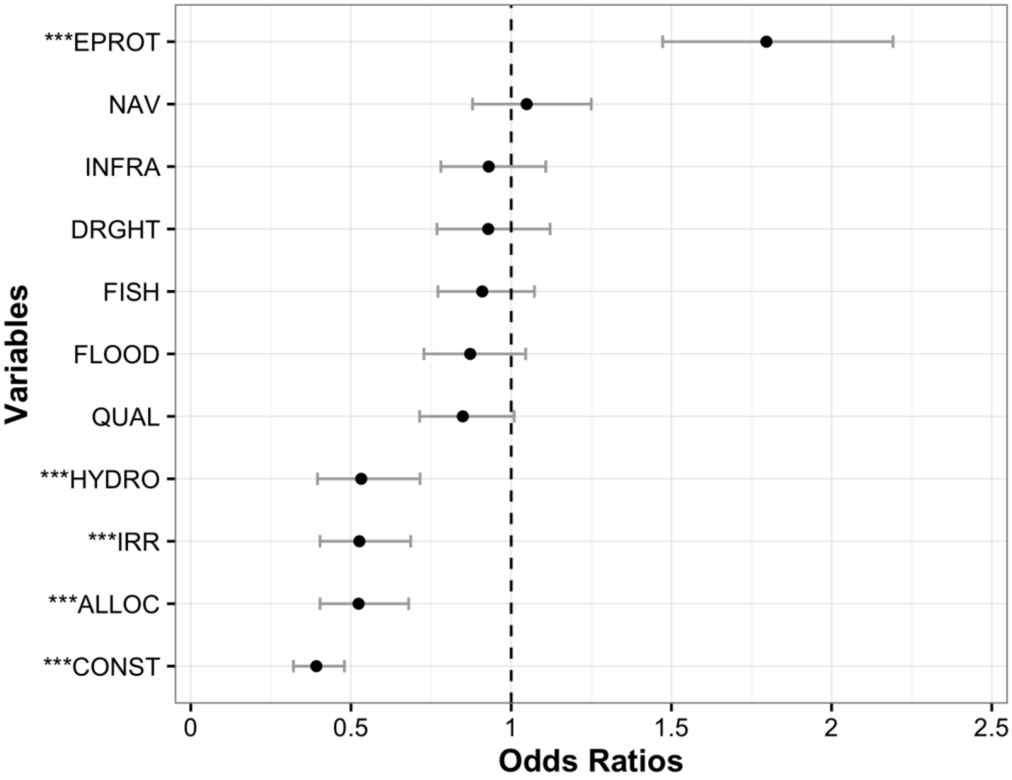


Figure 1.5. Effects on odds of cooperation (vs. conflict) if prior history of content-type exists*

**Points show how many times higher the odds are of each issue-type being associated with cooperative relations. Statistically significant deviations from 1 are indicated: *p<0.05, **p<0.01, ***p<0.001, and ±95% confidence intervals are shown in grey.*

While there are many confounding variables that make it difficult to establish a direct causal link between thematic treaty content and increased or decreased cooperation (i.e., the timing of different types of cooperation may follow a pattern unrelated to the presence/absence of environmental articles, or no pattern at all; there may be differences in the extent to which ‘big’ species conservation issues or ‘small’ species conservation issues contribute to complexity, etc.), the data shown in Figure 1.3,

Figure 1.4, and Figure 1.5 indicate that states and state negotiators may have grounds to suspect the possibility of this causal link. Based on information from the IFTD and IWED, this link may be negative at an aggregate level. But disaggregating across specific types of thematic content shows that unlike most other thematic content, environmental protection/services (EPROT) is associated with higher odds of cooperation, suggesting that "simple agreements are successful agreements" may be an oversimplification.

Another common belief expressed by treaty experts during the research for this dissertation is that flexible agreements are more durable and easier to agree upon. An absence of precise language and commitment regarding species conservation measures may reflect the desire of negotiators to uphold this flexibility. Agreements which are broad enough to accommodate shifting interpretations over time are probably more likely to retain long-term relevance. What is viewed by decision-makers as important today may evolve, often due to unpredictable events outside the purview of a treaty-based institutional arrangement such as changes in knowledge (e.g., fish biology), environmental changes (e.g., climate change), changes in societal values, the creation of new domestic laws, political shifts in power, or increased influence of other interested groups or nations. Direct species conservation objectives in treaties may introduce the need for a degree of precision that is perceived by negotiators as undermining an agreement's ability to respond to change and uncertainty over time. The fact that many treaties do contain pro-environmental content (e.g., water quality objectives) but steer clear of specifics regarding affected species supports this point. Negotiators may feel it necessary to broaden environmental objectives, instead prioritizing foundational but non-specific biophysical characteristics like water quality to find agreement, particularly when species conservation objectives compete with other values. The 1995 Mekong Agreement, for example, has been criticized for prioritizing consensus over environmental protection and "watering down" more targeted pro-environmental content (see Table 1.1) to help facilitate agreement across the parties, which have strong interests in hydropower, irrigation, and flood control benefits (Sneddon and Fox 2006).

However, a counterpoint to the above argument is that the degree of specificity decision-makers may wish to avoid in terms of species conservation is often applied to other values like hydropower and flood control (e.g., the Columbia River Treaty). This fact suggests that treaty negotiators may fear being 'locked in' by too much specificity differently for different values. In Chapter 4, I show how ignoring the needs of affected species can directly cause state-state conflicts when one country's domestic conservation laws become misaligned with its international freshwater commitments. In the conclusion to this dissertation, I propose that to maintain responsiveness to increasing species conservation needs (and differing needs across borders), transboundary freshwater agreements may need to embrace complexity by being more explicit about species conservation in ways that are still flexible and durable – similar to how the more commercial values like hydropower are traditionally approached. Decision support tools are available to aid in this endeavour and these tools are becoming increasingly capable of handling complexity as computing technologies advance.

1.3.2. Undervaluing species

Before entering a freshwater agreement with neighbouring states, countries generally perform some sort of analysis of benefits and costs. The extent to which affected species enter this calculus can have major implications for habitat condition and species survival, but, by omission, their value is often set at zero. As an example, early investigations into the feasibility of the Canada-USA Columbia River Treaty concluded that any societal benefits from wetland, fish, and wildlife conservation "would be so small in comparison to power and flood management values" that further study was not required (Canada, United States of America 1964). In a foundational cost-benefit analysis, Krutilla (1967) notes that the prior construction of Grand Coulee Dam in the US had completely halted salmon migrations upstream to Canada well before Columbia Treaty negotiations began, so any effects of the hydro-system on salmon were considered "a domestic problem for the United States…not related to the cooperative use of Treaty storage" (p.27). Today, these statements seem absurd given the range of species, including salmon, sturgeon, and whitefish, now considered under coordinated Canada-US operations and during treaty re-negotiations underway at time of writing (see Section 1.5), but it is emblematic of how affected species are traditionally viewed in water treaties relative to other more commercial values.

While economic valuation of ecosystem services is a widely supported practice (Arrow et al., 1993), standardized valuation of the full range of services is difficult. Ecosystem services that are bought and sold in a market and thus have market prices permit relatively straightforward estimations of economic value (e.g., electricity). Species are more complicated because they provide both “use” and “non-use” values to humans, some of which have no direct market price (e.g., recreational fishing, biodiversity). Additionally, measuring changes in the “production” of a species and the services it provides due to changes in habitat conditions is challenging.

In cases where the economic value of species conservation *is* considered, treaty negotiators typically assess that value based on trade-offs with other priorities that are easily measurable. For example, the anticipated loss in hydropower production resulting from species conservation practices might be treated as a proxy for the value of that species. Since hydropower production has a clear market value, this proxy is easier to estimate. But such “foregone benefits” methods do not truly capture consumer and producer surplus and therefore cannot reveal true economic welfare measures. Environmental economists use these approaches only as a last resort in non-market valuation.

In this dissertation I proceed from the assumption that the foregone benefits approach potentially overlooks the value to society associated with a broad range of ecosystem services many species provide (Daily, 1997). Some of these services deliver value through direct use, for example fish production services support commercial and recreational fishing. Other services, called non-use values[5], provide value to society indirectly through the provision of cultural or spiritual significance, biodiversity, or the sense of satisfaction derived from knowing a species exists (i.e., existence value) (Young and Loomis 2014).

Without a reasonable measure of value for the ecosystem services provided by a species, it is difficult for treaty negotiators to properly assess costs and benefits alongside other values like hydropower production or agricultural irrigation. This challenge presents a barrier to the inclusion of species conservation in international freshwater agreements, leading to their absence in cost-benefit assessments and, subsequently, from negotiating agendas.

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[5] *This nomenclature is associated with the concept of Total Economic Value (TEV) (Pearce and Turner, 1990). Another way of classifying types of ecosystem services is the Millennium Ecosystem Assessment’s (2005) provisioning, regulating, supporting, and cultural services.*

1.3.3. Poorly understood trade-offs

The process of making decisions about water allocation across different sectors can also be challenging, often requiring decision-makers to evaluate difficult trade-offs (Perrone et al. 2014). In their synthesis of applied structured decision-making in environmental management, Gregory et al (2012) state that “the only ‘bad’ trade-offs are the ones we make unknowingly, or without fully appreciating their implications” (p.208), and that decision-makers “cannot think clearly about value trade-offs without some consideration of the consequences” (p. 209). A typical approach to trade-off evaluation in water management is to prioritize desired ecosystem services based on a “value criterion” such as economic value, impact on human safety, or ecological impact. But reliance on a single value criterion overlooks important information, which can lead to decision making based on poorly understood trade-offs that may miss important opportunities for meeting species conservation objectives, effectively removing them from negotiating agendas.

A more informative approach is to compare explicit gains and losses across multiple value criteria for different alternatives or sets of alternatives (Gregory et al. 2012). Accomplishing this comparison in a robust way requires an understanding of biophysical processes and their relationship with the ecosystem services provided. For commercial objectives like hydropower production or agricultural irrigation it is relatively easy to construct these relationships for use in quantitative models – the more water that flows in a river and can be stored or diverted, the more potential for hydropower or irrigation diversions exists. The timing of human demand for these services is also fairly predictable. For affected species, these relationships are more complex and are often poorly understood by decision-makers. For example, too much flow during fish nesting and rearing could lead to scouring of redds, too much variation in flow could lead to dewatering and stranding of eggs and juveniles, and too little flow could slow migrations, raise stream temperatures, and increase vulnerability to predators. Life-stage needs of multiple species may also overlap in opposite ways (e.g., upstream and downstream migration timing). One response to dealing with these complexities is to ignore them, another is to develop oversimplified or biased decision criteria which can distort the actual trade-offs at stake. These strategies can lead to poorly informed negotiating points that are vulnerable to contestation and, therefore, exclusion.

1.4. Can freshwater treaties adapt to increasing species conservation needs?

If formal treaty texts represent what is truly invoked and applied in practice, the preceding barriers to including species in the codification of international freshwater agreements are cause for pessimism regarding the potential for transboundary species conservation in international river basins. While Chapter 2 and Chapter 3 of this dissertation offer approaches to two of these challenges (undervalued species, and poorly understood trade-offs), political and legal scholars know that formal rules written in treaties are not always “rules-in-use” and that norms about treaty interpretation change and evolve over time based on the expectations of elite political actors (Reisman 1984; Willard 1984). International freshwater treaties tend to have very long (e.g., 60 years) or no explicit revision cycles (OSU 2012), so this normative aspect of treaty implementation offers potentially fertile ground for integration of species conservation in the world’s collection of bi- and multi-lateral freshwater agreements.

As in the Mekong example (Sneddon and Fox 2006), treaty arrangements that appear on paper to be comparatively inclusive of environmental values may nevertheless exclude targeted conservation values in practice. Alternatively, a seemingly rigid treaty on paper with no species conservation content may be quite open to conservation values in practice if the expectations of influential actors about rules-in-use are aligned with those values. In evaluating the capacity of these agreements to adapt to increasing species conservation needs, an important question is therefore whether the normative expectations of political elites are flexible enough to accommodate these needs *despite the fact* that formal treaty texts fail to reflect them. This question is the focus of Chapter 4 of this dissertation.

1.5. The case of the Columbia River Treaty

In the three core chapters of this dissertation (Chapters 2-4), I focus on a single case – the Columbia River Treaty (CRT, or ‘the Treaty’) between Canada and the US, and the river basin it governs. This agreement is a relevant example since it is silent on the topic of species conservation despite having significant implications for a variety of terrestrial and aquatic species, including several species-at-risk in both countries (Bankes 2004; Belbin and VanderZwaag 2016). Ratified in 1964, the agreement is an acclaimed example of transboundary water cooperation due to its 50/50 split of hydropower benefits between the two countries. This “benefits sharing” represents an archetypal application of international water law’s equitable utilization principle (Ketchum and Barroso 2006; Paisley 2002). Some of the CRT’s defining features include:

a) The construction of four dams, two on the Columbia River in Canada (Mica and Keenleyside dams), one on the Duncan River in Canada (Duncan Dam), and one on the Kootenai River in the US (Libby Dam),

b) Flood management provided to the US by Canada using Treaty dams and reservoirs, the first 60 years of which were paid for in advance by the US in a single lump sum payment that helped finance construction of the Canadian dams,

c) The Canadian Entitlement, which is Canada’s annual share of US hydropower benefits resulting from construction and operation of the Treaty dams to support US power production,

d) Establishment of three agencies as the Canadian and US ‘Entities’ empowered to implement the Treaty (BC Hydro in Canada, and Bonneville Power Administration and the US Army Corps of Engineers jointly in the US). After Treaty ratification, the Province of BC was included as part of the Canadian Entity for purposes of administration of the Canadian Entitlement.

e) Annual negotiation and agreement between the Entities on an Assured Operating Plan (AOP) for each year, finalized six years in advance of the actual operating year, that is also used to establish the Canadian Entitlement, and a Detailed Operating Plan (DOP) finalized each year for the upcoming year (Canada, United States of America, 1964).

f) The ability to diverge from usual implementation of AOPs and DOPs by mutual agreement between the Entities (e.g., various Non-power Uses Agreements (NPUAs) have been signed annually since the 1990s to accommodate different interests, including fish conservation to a limited extent (British Columbia, 2013)).

Examining the CRT from a species conservation perspective is timely. For more than a decade, Canada and the US have been preparing for a key policy window in the Treaty. The agreement states that as of 2024, either country is free to withdraw from the agreement provided ten years' advance warning is given (Canada, United States of America, 1964, Article XIX(2)). In 2013 and 2014 the US and Canada issued position statements signalling a desire to continue cooperating under the agreement, but also to make changes including, notably, modernizing the agreement to better reflect current environmental values (US Entity 2013, British Columbia 2014).

The Canadian position statement emphasizes the pre-eminence of hydropower and flood management, but acknowledges that ecosystems are important in the planning and implementation of the Treaty (British Columbia 2014). In the position statement, the Province of British Columbia lists fourteen principles, which include sharing downstream benefits from a wider range of ecosystem services than just power and flood management (i.e., ecosystems, water supply, recreation, and navigation), "exploring" ecosystem improvement mechanisms "inside and outside the Treaty", consulting with First Nations on a government-to-government basis, engaging with communities, and incorporating climate change adaptation in Treaty planning and implementation. The list also contemplates the notion of restoring salmon populations, which are currently extirpated from the Canadian portion of the Basin by US dams[6], but defers responsibility for salmon to the Canadian federal government and states that salmon migration is "not a Treaty issue".

The US statement is less explicit about the prioritization of hydropower and flood management, instead conjoining these with ecosystems, water supply, recreation and navigation in enabling the "greatest possible shared benefits in the United States and Canada." (US Entity 2013). The US Entity lists nine principles including treating the "health of the Columbia River ecosystem" as a shared benefit, relying on the best available science, and pursuing a "more coordinated use of the Treaty and Canadian non-Treaty storage under the Treaty" to increase the ability to meet ecosystem and other needs. The US principles also acknowledge the important implications of climate change

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[6] With the exception of restored sockeye populations in the Okanagan Basin, which starts in British Columbia and drains into the Columbia River in Washington.

and the desire to create a “resilient, adaptable, flexible, and timely” Treaty. Expanding on these principles, the US statement differs from its Canadian counterpart in providing specific details about American species conservation objectives, stating that,

> *A modernized Treaty should provide streamflows from Canada with appropriate timing, quantity, and water quality to promote productive populations of anadromous and resident fish and provide reservoir conditions to promote productive populations of native fish and wildlife.*

and,

> *The United States should pursue a joint program with Canada, with shared costs, to investigate and, if warranted, implement restored fish passage and reintroduction of anadromous fish on the main stem Columbia River to Canadian spawning grounds.*

The US statement does not explicitly contemplate Native American rights, stating only that “A modernized Treaty should recognize and minimize adverse effects to tribal, First Nations, and other cultural resources in Canada and the United States.”

At the time of writing, Canada and the US are actively negotiating revisions to the CRT and are codifying how ecosystem values, including species conservation, will be included in a modernized agreement. Following up on its commitments under the United Nations Declaration on the Rights of Indigenous People (UNDRIP), Canada has afforded the *Syilx*/Okanagan, Ktunaxa, and Secwepemc Nations seats as observers at the negotiating table (Global Affairs Canada 2019). Given Indigenous Nations’ strong interest in protecting ecosystem functions and restoring salmon populations to the upper Columbia Basin, this historically unprecedented “seat at the table” for Indigenous peoples will no doubt influence how salmon and other species are considered in the negotiating agenda. Indeed, on July 29, 2019 Canada signed a Letter of Agreement (outside the CRT) with the Province of British Columbia and the three Nations to collaboratively explore restoration of extirpated salmon populations to the Canadian portion of the Basin (British Columbia 2019). This action may signal a shift from British Columbia’s original 2014 position statement about the place of salmon re-introduction in the Treaty.

1.6. Transboundary water research mirrors freshwater treaties

In this dissertation I contribute to filling a key gap in the existing body of research about transboundary freshwater management. Mirroring the treaties themselves, the transboundary freshwater literature largely ignores the close ties between conservation management and the shared management of international rivers and lakes. One reason for this omission is that the disciplinary home of transboundary water research in international law, political science, and international relations has encouraged a research emphasis on legal aspects of transboundary water governance and state-level politics (e.g. Wolf 1998, Paisley 2002, Zeitoun and Warner 2006). While these efforts reveal valuable insights, such as water treaties' highly successful history as platforms for cooperation (Wolf 1998), and more nuanced understandings that emphasize asymmetrical power relations and underlying tensions between cooperating states (Zeitoun and Warner 2006), they rarely consider the ecosystems being governed. The state-level orientation that is typical of international relations research also mutes the importance of interactions between domestic environmental regulation and transboundary water institutions – a relationship that is particularly relevant in the context of species conservation. I contribute to filling this gap by focusing in Chapter 2 and Chapter 3 on quantitative approaches to dealing with two of the key barriers to the inclusion of fish conservation in international freshwater treaty negotiations: (1) undervalued fish species, and (2) poorly understood trade-offs (barriers previously described in Sections 1.3.2 and 1.3.3 respectively). In Chapter 4, I shift focus to acknowledge the importance of how formal treaty content, once agreed upon, is actually interpreted in practice.

1.7. Summary of this dissertation

In this introductory chapter I discussed the omission of formal species conservation commitments in freshwater treaties globally and suggested that this omission may be explained, in part, by negotiators' aversion to complexity in favour of flexibility and consensus, a tendency to undervalue species relative to other values, and the limited ability of negotiators to understand fully the species-related trade-offs at stake. The 'complexity aversion' topic is treated in detail in the current chapter. The remainder of this dissertation is organized as a collection of three publishable manuscripts, two of which address the latter two barriers and one that examines the potential for institutional norms to support transboundary species conservation despite a lack of formal mandate at the treaty level. As described, I focus on the Columbia River Basin and the Canada-US Columbia River Treaty in all three manuscripts. At time of writing, the first of these papers (Chapter 2) is published, while the other two are awaiting submission.

In Chapter 2, I apply a welfare economics approach to assess the capacity of the Columbia River to provide a selection of four ecosystem services derived from salmon. The methods described in Chapter 2 illustrate the feasibility of developing robust “non-zero” estimates of economic value for species in transboundary river basins that can be used by negotiators to avoid undervaluing species and to contemplate alternative flow management regimes that may increase these benefits.

In Chapter 3*,* using a decision analysis framework, I apply multi-attribute utility optimization across salmon conservation, hydropower production, and agricultural irrigation to forecast optimal flows in Hanford Reach a stretch of important salmon habitat in the US portion of the Columbia River. This approach permits evaluation of an annually renewed Non-Power Uses Agreement under the CRT, wherein Canada supplies 1 MAF of annual flow augmentation to the Reach between May and July. Trade-offs associated with this sub-agreement are poorly understood. This Chapter illustrates an approach to transparently balancing the benefits of alternative transboundary flow augmentation volumes across multiple values that can be easily communicated with Treaty negotiators.

In Chapter 4, I apply a method called incident analysis to assess the CRT’s adaptive capacity to respond to evolving species conservation needs. This method exploits the tendency of international conflicts to reveal expectations of influential actors about how treaties should be interpreted and applied, and in this case, how species conservation should be approached. To examine whether CRT institutional norms are flexible enough to accommodate evolving species conservation needs, I examine a conflict between Canada and the US over US efforts to conserve an endangered species of sturgeon using Treaty-flows.

Chapters 2 and 3 emphasize fairly traditional approaches to decision-making that assume rational judgements about management alternatives. With its focus on institutional norms, Chapter 4 veers away from these more technocratic approaches to build a deeper understanding of the broader governance context and how institutional norms influence such judgements.

Each chapter shines its own unique light on the advantages of integrating species conservation more explicitly into transboundary freshwater treaties. I conclude with a summary of my findings.

Appendix 1.A. Description of themes in the Oregon State University's International Freshwater Treaties Database

Themes	Description
Border issues	Delineation, adjustment or re-affirmation of border between basin sharing states.
Construction	Construction of physical works to help meet development goals (e.g. barrages, canals, dykes, dams)
Consultation	Agreements to and/or procedures for consultation with other signatory states prior to actions affecting shared waters.
Dispute resolution	Specification of procedures for dispute resolution.
Domestic policy harmonization	Agreements to harmonize domestic water policies for shared waters.
Drought management	Offsetting of low season flow reductions (e.g. for protection of fish).
Enforcement	Agreements to and/or procedures for enforcement of established rules.
Environmental services & protection	Agreement to engage in the protection of environmental services.
Financial arrangements	Distribution of financial responsibilities and/or sharing of benefits from development.
Fishing regulation	Regulation for sustainability of shared fisheries (e.g. quotas).
Flood control	Construction of dams, levies and other flood control strategies to generate flood protection benefits.
Hydropower	Construction of dams to generate power production benefits.
Information sharing	Agreements to and/or procedures for sharing water-related information.
Infrastructure	Investment in physical works to help meet development goals (e.g. barrages, canals, dykes, dams).
Irrigation	Diversions from natural water bodies for agricultural benefit.
Monitoring	Agreements to and/or procedures for joint monitoring.
Navigation	Alteration and use of waterways for transport of people and goods (e.g. locks, canals).
Participation of co-riparians	Expression of intent to include co-riparians ("stakeholders") in decision-making.
River basin organizations	Formation of joint organizations for basin-wide water governance.
Technological exchange	Agreements to and/or procedures for sharing water-related technology.
Water allocation	Assignment of water volumes to meet development goals.
Water quality	Rules and guidelines for maintaining water quality (e.g. pollution control).

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Chapter 2. The value of a transboundary fish is greater than zero

This chapter was previously published as the article "Valuation of Fish Production Services in River Basins: a Case Study of the Columbia River", co-authored by C Morton, D Knowler, C Brugere, D Lymer, and D Bartley in Ecosystem Services and has been reprinted with permission from Elsevier © 2017. I authored the majority of the text and exclusively completed and authored the data analysis, tables and figures.

Abstract

This study uses a bio-economic model to assess the capacity of the Columbia River to provide a selection of four ecosystem services and estimates the actual use of those services in terms of net economic welfare. Our findings reinforce the observation that Columbia River habitat supports production of valuable fish species that provide: (i) food production from commercial fishing, (ii) recreational fishing, (iii) tribal subsistence fishing, and (iv) nutrient cycling services. Relative to the status quo, a 10% greater prioritization of salmon conservation via shifts in the flow regime would generate an increase of $4.8 million/yr in the net economic benefit from these services. A return to pristine flow conditions would raise this value to $19.5 million/yr. Re-prioritizing hydropower production to average 1976–1980 flow levels would result in a $3.5 million/yr loss of net economic benefits. Recreational fishing is the most important ecosystem service we assessed. Under some scenarios, this sector generates twice the value of the next largest sector (commercial fishing). Although managers have placed greater emphasis on fish conservation in recent decades, opportunities for gains in economic welfare from fish production in the Columbia River may not be fully exploited, particularly considering that our conservation scenario only minimally alters the flow regime relative to the hydropower priority scenario.

2.1. Introduction

The world’s rivers provide numerous benefits to society commonly referred to as ‘‘ecosystem services”. Capturing the total economic value (TEV) of these benefits can be a complex and uncertain task, but is nevertheless advocated by various researchers and can be used as a decision tool by resource managers (Pearce and Turner, 1990). The TEV of an environmental resource or ecosystem is the sum of its use and non-use values[7]. Non-use values are intrinsic to the resource and arise from the value people place on its existence. Use values arise from activities such as resource extraction, harvest, and recreation and more indirectly from various ecosystem services such as nutrient cycling, watershed protection or groundwater recharge. For example, rivers support fish populations, which are valued for use (e.g. commercial fishing, subsistence fishing, recreational fishing, nutrient cycling) and non-use (e.g. existence, cultural and spiritual) purposes (Daily, 1997).

In addition to fish production, river systems provide other services such as aesthetics, water supply for domestic and agricultural uses, water quality regulation, natural flood control (wetlands), opportunities for shipping and transportation, opportunities for recreation, and natural features that permit the construction of dams for hydroelectric power production and engineered flood control. Many of these uses compete with fish production systems, especially in larger rivers, and create tradeoffs among the various services that comprise the TEV of these rivers. For example, prioritizing hydropower development may cause fish production benefits to decline due to habitat degradation from blocked migration routes, or a less favorable flow regime. Hydropower is particularly relevant as it is increasingly attractive in many basins as a means to reduce greenhouse gas (GHG) emissions.

It is challenging for resource managers to assess such tradeoffs without some measure of value for each service. The total value of fish production services is

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[7] *Many researchers also use the classification of ecosystem services according to the Millennium Ecosystem Assessment (2005), including provisioning, regulating, supporting, and cultural services. We chose to adopt the TEV framework instead.*

particularly complicated to evaluate due to the range of non-use and use values as well as the need to measure changes in production resulting from changes in habitat quality.

To support river managers' decision-making, we develop an approach for valuing several ecosystem services associated with fish production in any river basin where the natural hydrograph is significantly altered from its natural state by dams. As a case study, we use the production of Pacific Salmon (Onocorhynchus spp.) in the Columbia River Basin in the Pacific Northwest region of North America. We consider how changes in river management for hydropower production and salmon conservation affect: (i) productivity of Columbia River salmon populations, and (ii) resulting economic welfare implications for commercial fishing, subsistence fishing, recreational fishing and fish-related nutrient cycling.

Valuation of ecosystem services is a widely supported practice (Arrow et al., 1993), although standardized valuation of the full range of ecosystem services has proven difficult. Few studies focus on changes to net (rather than gross) economic welfare from fish production (Grantham and Rudd, 2015), including those caused by dam operations. Analyses that consider the impacts of hydropower production on fish production tend focus on only one or two ecosystem services provided by fish production (e.g. recreational fishing), and/or do not incorporate biological relationships linking salmon populations and altered flow regimes (Loomis, 1996; Douglas and Taylor, 1999; Layton et al., 1999).

There is general agreement among hydropower, flood control and conservation managers in the Columbia Basin that the altered flow regimes of the mainstem and major tributaries have had a substantive negative impact on salmon productivity (NPCC, 2014). However, to understand the resulting change in economic benefit from fish production, it is first necessary to establish a relationship between salmon survival and flow regimes at different stages of hydropower development. Our analysis draws on methods introduced by Knowler et al. (2003), including: (i) use of bio-economic modeling to estimate net economic benefits that are consistent with economic theory, rather than measuring only changes in revenue; (ii) estimation of general stock recruitment relationships for basin-wide aggregate salmon populations (i.e. not just local streams and sub-populations); and, (iii) incorporation of habitat quality into the stock recruitment relationship.

In this paper we estimate the value of the Columbia River salmon production system under four development scenarios that emphasize hydropower production and salmon conservation to different degrees. The primary objective of our evaluation is to assess how net economic benefits derived from Columbia River salmon change when habitat quality is altered to accommodate different management objectives and associated flow regimes[8]. We conclude with a discussion of results and potential improvements for future efforts.

2.2. Study Area

The Columbia River is a large river in the Pacific Northwest region of North America that flows 2000 km from Canadian Rocky Mountains to the Pacific Ocean. It is the fourth largest river in the United States by volume and collects runoff from a drainage basin roughly the size of France (_671,000 km2), spanning portions of seven American states (Washington, Oregon, Idaho, Montana, Wyoming, Utah, Nevada) and one Canadian province (British Columbia) (Muckleston, 2003).

The river's annual cycles are driven by thawing/melting of snowpack. Daily discharge at the river mouth averages 7504 m3/s (265,000 cfs) but can be as high as 15,744 m3/s (556,000 cfs) during peak floods in May/June[9] (FPC, 2015).

The Columbia Basin holds one of the most engineered river networks in the world with over 300 publicly and privately owned dams that provide flood control, irrigation, hydropower production, navigation, and recreation opportunities. Fourteen of these dams are located directly on the river's mainstem. A key location on the Columbia is The Dalles, Oregon, which is the standard reference point for mainstem flow

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[8] *We refer to changes in "net economic benefit" to capture changes in consumer and/or producer's surplus resulting from changes in management or policy. Note that care is needed in interpreting "net economic benefit" as specific to fish production. Welfare gains stemming from increased hydropower production and/or other valued components are not considered here. We discuss the implications of this intentional omission in the Discussion and Conclusion sections.*

[9] *Maximum daily average of hourly flow measurements 1980–2015 (i.e. after hydropower and flood control development).*

measurements dating as far back as 1878 and is the focal point for measuring habitat quality in this study (Figure 2.1).

Figure 2.1. Columbia River basin with case study section of mainstem highlighted.

Sources: ESRI (2013), USGS (2014b,c), WA-DOE (n.d.), NRCAN (2014), DataBC (2014), Cory Langhoff, Pers. Comm. November 2011, Northwest Habitat Institute.

2.3. Methods

In this section we detail the methods used to produce our valuation results when habitat quality is altered to accommodate different management objectives and flow regimes.

2.3.1. Scenario development

We focus on impacts of hydropower and flood control as the primary sources of development affecting salmon production in the Columbia River It should be noted however that Huppert et al. (2004) concluded that there might be ‘‘some negative effects on fisheries and passive use values tied to salmon and steelhead runs” (p. viii) if water diversions for domestic and agricultural water supply were to increase. We select four indicator services for evaluation based on the following criteria: (i) expected economic significance; (ii) data availability; and, (iii) feasibility in terms of available valuation methods. The services thus selected include commercial fishing, subsistence fishing, recreational fishing and salmon-related nutrient cycling.

We also assume economic welfare changes are associated with change in the primary sector only and we do not consider postharvest processing or related downstream industry impacts. We adapt the approach from Knowler et al. (2003), which is consistent with welfare measurement, where habitat quality is an input to production, and where our model is based on stock estimates for a fishery managed for constant adult spawner exploitation and escapement. Applying these assumptions, we begin with an initial level of habitat quality and salmon survival under status quo flow conditions (scenario 1) then vary the level of environmental quality in three additional scenarios (Table 2.1). Differences in net economic benefit provided by salmon across scenarios provide measures of social gain or loss associated with the modeled changes.

Table 2.1. Proposed development scenarios

	Description	Anticipated effects
Scenario 1 Status quo	Average current annual hydrograph at The Dalles (2000-2014)	Benefits from salmon production and other ecosystem services remain unchanged
Scenario 2 Hydropower Priority	Increased prioritization of hydropower and flood control (average hydrograph at The Dalles 1976-1980)	Benefits of salmon-based ecosystem services decrease. Hydropower/flood control benefits increase.
Scenario 3 Conservation Priority	Decreased prioritization of hydropower and flood control (10% increase toward natural hydrograph relative to Scenario 1)	Benefits of salmon-based ecosystem services increase. Hydropower, flood control benefits decrease.
Scenario 4 Pristine Conditions	Zero hydropower regulation and no diversions for agriculture (reconstructed “natural” hydrograph – see Footnote 5)	Benefits of salmon-based ecosystem services increase. Hydropower, flood control benefits are zero.

2.3.2. Modeling fish population dynamics with an environmental influence

We develop a biological model linking changes in habitat quality to changes in fish productivity. By varying the level of environmental quality in the biological model according to our development scenarios, we determine salmon abundance (and total harvest in the case of fishery uses). Derivation of the habitat quality parameters for each scenario is described below, followed by an explanation of the biological model and the economic welfare estimation for each ecosystem service.

Habitat quality estimation

Natural or ‘‘unregulated” river conditions serve as the reference point for our modeling. We develop a habitat quality index based on differences in the annual hydrograph between regulated and unregulated conditions as measured at The Dalles. To illustrate, Figure 2.2 compares the hydrographs of our three development scenarios with an average unregulated hydrograph from the predevelopment era (i.e. Scenario 4 –

Pristine Conditions). The closer the hydrograph gets to natural conditions, the more ideal we assume these conditions are for the fish production system[10].

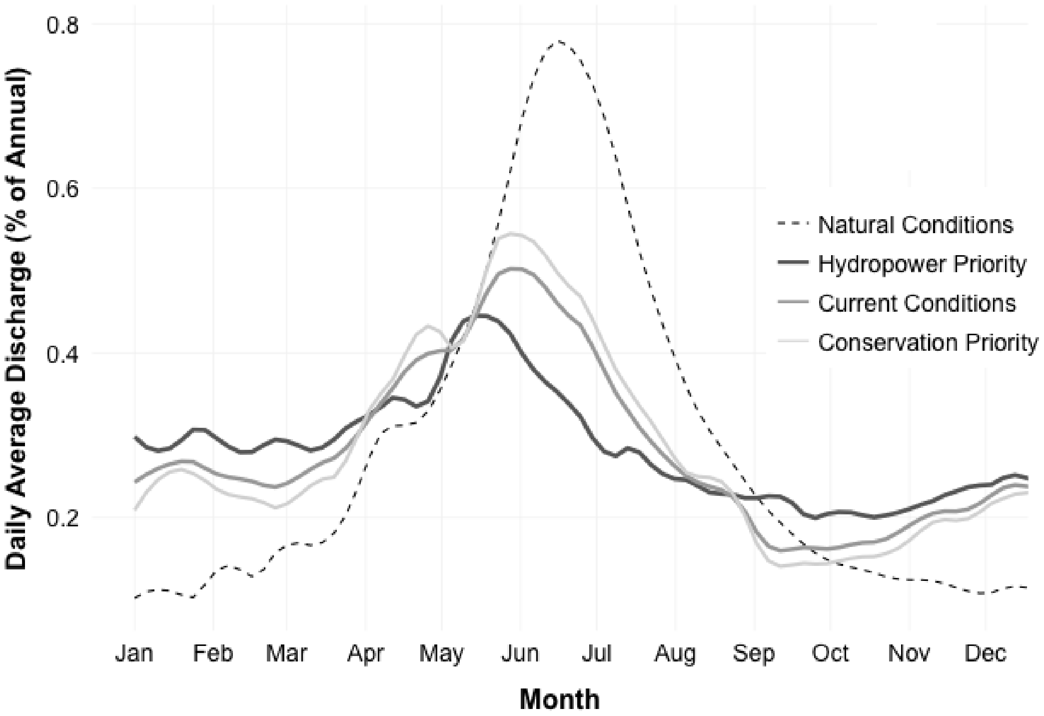

Figure 2.2. Annual hydrographs at the Dalles for development scenarios. The grey dotted line represents a pre-development hydrograph based on 1878–1888 average flows at The Dalles (Scenario 4 – Pristine Conditions). Current conditions (middle gradient of grey) are based on 2000–2014 average discharges at The Dalles and represent Scenario 1 – Status Quo. The darkest solid line represents Scenario 2 – Hydropower Priority and is based on observed discharge immediately following the completion of the last Columbia River Treaty dam (1976–1980 average), which preceded most river management for salmon conservation. The lightest solid line assumes a 10% improvement in regulation for conservation from current conditions and represents Scenario 3 – Conservation Priority. For sensitivity testing, we later consider a second river management scenario consisting of a 20% improvement in regulation for conservation.

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[10] *Data for "pristine conditions" (Scenario 4) are obtained from Bonneville Power Administration's (BPA) 2010 Level Modified Streamflows database (available at: http://www.bpa.gov/power/streamflow/default.aspx). The database includes natural flow scenarios that estimate daily discharge values at The Dalles from 1970 to 2000 assuming zero hydropower regulation and no diversions for agriculture. All other discharge data are from the US Geographic Survey at The Dalles gauge station USGS 14105700 (USGS, 2014a). Data used for Fig. 2 are available from the authors in tabular form as monthly discharge, both volumetrically and as proportions of annual discharge.*

We use the annual averages of the daily percent change between discharge from natural conditions and regulated flows to produce an index of habitat quality where 1 is equivalent to pristine habitat conditions (i.e. no difference from natural flows) and zero is a hypothetical fully degraded state (i.e. no flow – which is implausible in this system). The equation we use is: $1-\frac{\sum_{i=0}^{n}\frac{Qnat_i-Qreg_i}{Qnat_i}}{numYr}$, where for each day (*i*), *Qnat* is unregulated flow, *Qreg* is regulated flow, and *numYr* is the number of days in the year. Appendix A shows index results for the 31-year period of our dataset with corresponding egg-to-spawner survival rates, which are derived in Appendix B.

We fit a linear function between habitat quality index values and egg-to-spawner survival (Fig. 3) and use the function to adjust the egg-to-spawner survival rate based on different levels of habitat quality. The fitted linear equation we estimated is:

$$S = 0.001309HQI + 0 \tag{1}$$

where *S* is egg-to-spawner survival at a given *HQI*, – the habitat quality index value from Appendix 2.A. Using values of *S*, we generate a ‘‘survival adjustment”, which is an adjustment of survival rates determined by subtracting *S* under pristine conditions from *S* under each of the development scenarios. We recognize that the data shown in Figure 2.3 are poor for developing a relationship and for assigning an appropriate functional form because the observed points all fall within a relatively narrow range of *HQI*. For this reason we have relied on some common sense assumptions to build the relationship by using the data as a predictor of slope through the origin, and we have erred on the side of caution by selecting a linear model. Note that the linear function is forced through the origin to reflect our view that survival would be zero at *HQI* = 0 (i.e. a hypothetical completely dry riverbed year-round). Uncertainty increases as the function approaches *HQI* = 1 as shown by the 95% confidence band, suggesting the relationship should be interpreted with a measure of caution given the amount of statistical noise inevitably captured in the data set. The band is fairly uninformative at <*HQI* = 0.25 and >*HQI* = 0.75 due to a lack of observed data, but it is heuristically useful in that the greater uncertainty indicated at *HQI* = 1 does capture the fact that we have no information about survival for pristine conditions in the Columbia River and it provides a useful range for sensitivity analysis. Further, we do know that egg to spawner survival in other large, dammed, and snowmelt driven basins in the Pacific Northwest (e.g. the Skagit) can be as high as 0.0018 so our assumptions are quite conservative with predicted survival at HQI = 1 being near the observed data set's maximum survival (0.0013) (Ward et al., 2015). Higher survival rates than the observed maximum observations we use are likely to occur under unobserved pristine conditions. Lastly, we chose a linear model for its parsimony, ease of interpretation, and conservative predictions. Fitting a more biologically plausible sigmoidal function of the form $y = (n - M)/\left(1 + ((x/k)^s)\right) + M$ (n = lower asymptote, M = upper asymptote, k = inflection point, s = slope) with lower asymptote forced near the origin at HQI = 0 and adding the top three egg to spawner survival rates observed in Pacific Northwest streams by Ward et al. (2015) as data points at HQI = 1 (Duwamish 0.0015; Upper Skagit 0.0018, and Nisqually 0.0018) resulted in a nearly identical standard error (~0.0003), a near linear curve through the data, and a maximum survival rate of 0.0015 – slightly higher than that predicted by the linear model (Ward et al., 2015). Table 2.2 shows survival rates and survival adjustments for habitat quality indices corresponding to each of our development scenarios using the relationship shown in Figure 2.3.

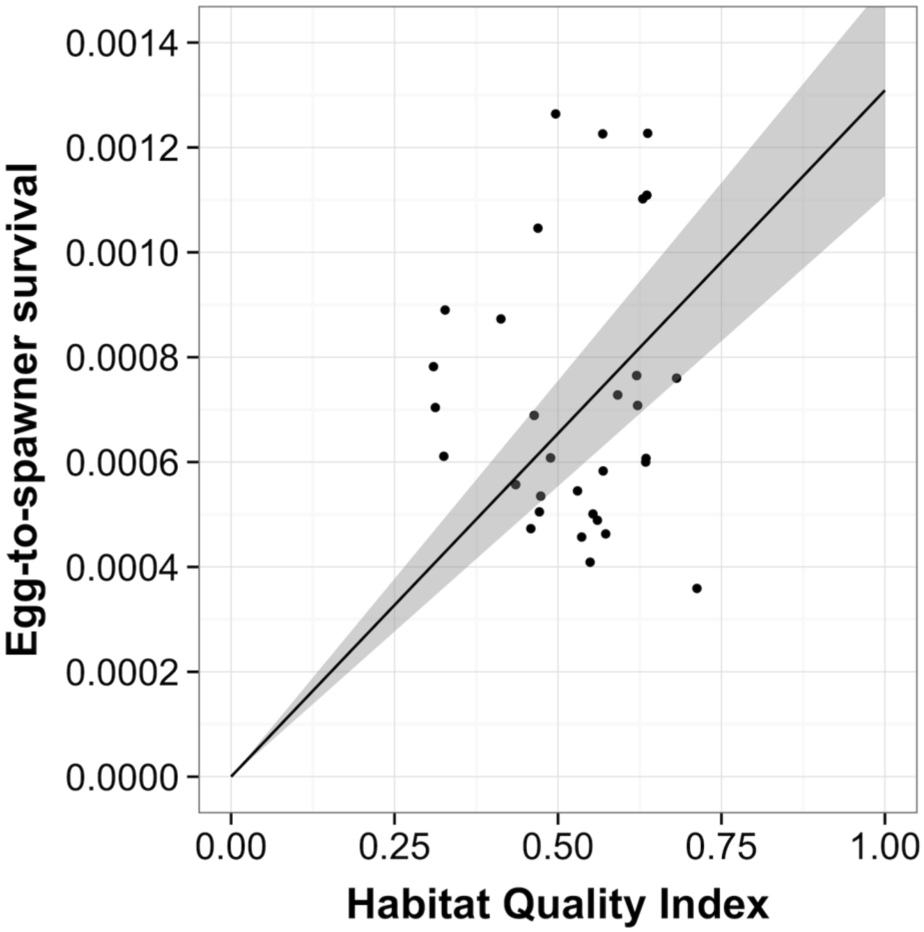

Figure 2.3. Salmon survival vs. habitat quality index (Eq. (1)).
The shaded area represents 95% confidence interval; R-squared = 0.85; p < 0.001. [*Corrigendum:* For the special case of regression through the origin, R-squared is calculated based on Eisenhauer (2003, p.78 - Eqn. 4') and should be interpreted accordingly. See text above for further explanation.]

Table 2.2. Habitat Quality Indices, Predicted Survival, and Survival Adjustments for Development Scenarios

	Index Value	Predicted Survival	Survival Adjustment*
Scenario 1 Status Quo	0.63	0.00082467	-0.00048433
Scenario 2 Hydropower Priority	0.57	0.00074613	-0.00056287
Scenario 3 Conservation Priority	0.72	0.00094248	-0.00036652
Scenario 4 Pristine Conditions	1	0.00130900	0.0000000

* Determined as predicted survival for given scenario minus pristine survival

One limitation of the approach outlined above is that it does not consider possible differential effects from higher and lower flow periods relative to pristine conditions and instead assumes deviations either way have equivalent impacts. Increased discharge and decreased discharge have very different biological meanings. Our approach is intentionally low dimensional and considers each annual hydrograph as a ‘habitat’ in its entirety. This approach can be justified by the fact that the different hydrographs represent changes in amplitude across different versions of a general functional form with similar wavelength and frequency that is consistent with many western US dam hydrographs. Regardless, we also tested the separate effects of higher and lower flow periods by obtaining unique annual index values for each flow type. Using regression analysis, we found no statistically significant relationship between the separate index values and survival rates.

Biological model

Following Knowler et al. (2003), we model salmon recruitment to the exploitable stock as a modified Beverton-Holt stock recruitment function making use of the habitat quality survival adjustment derived earlier. We adjust the number of recruits for harvest rates, ocean mortality and inter-dam loss to arrive at total exploitable stock numbers. The equation is as follows:

$$R(X_{t-n} - h_{t-n};\ \bar{Q}) = \frac{a(s+\bar{Q})(X_{t-n}-h_{t-n})}{\left(1+\frac{a}{b}(X_{t-n}-h_{t-n})\right)\left(int\cdot oc\cdot(1-h1)\cdot(1-h2)\cdot(1-h3)\right)} \qquad (2)$$

where $R(X_{t-n} - h_{t-n})$ is recruitment to the exploitable stock, a is the productivity parameter defined as the weighted average number of eggs produced per spawner across all species; s is the predicted egg-to-spawner survival rate under pristine conditions (*HQI* = 1, Eq. (1)) for all salmon species 1970–2000; $\bar{Q}$ is an adjustment to s derived from the habitat quality index (Table 2.2); b is the weighted capacity parameter, or the weighted maximum number of eggs that are produced in the Columbia River; int is the inter-dam survival rate; oc is the natural marine survival rate; $h1$; $h2$; $h3$ are average ocean, downriver, and upriver harvest rates respectively; X is the total exploitable stock of all salmon species; and h is the total harvest of all species from the exploitable stock. Weighting proportions for a and b are as follows: Chinook 42.90%, Coho 14.72%, Steelhead 22.10%, Sockeye 4.08%, Chum 0.11%[11].

For the Beverton-Holt relationship (Eq. (2)), we set a at 3336, which is the weighted average of all the average female fecundities of each species. The Beverton-Holt b parameter is 2,087,340,236 eggs, which is the maximum number of eggs estimated using the historic weighted adult return data for all species (Eq. (B.1), Appendix 2.B). Inter-dam survival (int) is 0.759 based on estimated rates in Harnish et al. (2013) for Fall Chinook. While this rate only captures inter-dam survival from the river mouth to past Priest Rapids Dam it is conservative in terms of overall estimated inter-dam survival. Most salmon using the mainstem do not traverse the full set of dams to Priest Rapids. About 58% of total salmon abundance originates in the lower Columbia below Bonneville Dam where no inter-dam losses occur (IEAB, 2005). Many of the fish that do move further upstream spawn in tributaries below Priest Rapids. In addition, only four run of river dams exist on the mainstem upstream of Priest Rapids before salmon passage is entirely cut-off by Chief Joseph and Grand Coulee. Since these dams are run of river, we assume their effects are minimal on this relatively smaller proportion of the population. We include sensitivity analyses for int in Appendix 2.D. Natural ocean survival is 0.8 based on personal communications with staff at the Pacific Northwest National Laboratory for Fall Chinook (Ryan Harnish, PNNL, pers. comm., December 30, 2014). The ocean, downriver and upriver harvest rates are 0.1640, 0.2165, and 0.0689 respectively and are calculated as average exploitation rates across all species 1970–2000 inclusive of commercial, recreational and tribal subsistence fisheries (note that only Chinook and Coho have a regulated ocean fishery). Data derivations for the population modeling are available in Appendix B. All other biological parameters are summarized in Appendix 2.C.

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[11] *Determined using 1970–2000 average proportions of estimated number of eggs per species per year (this study).*

2.3.3. Economic welfare estimation

In this section we outline our methods for estimating economic welfare derived from each of the ecosystem services evaluated.

Commercial fishing

We used abundance and harvest results from the biological model as inputs to a production function (Hanley and Spash, 1993), together with estimates for cost of fishing effort, fish catchability and price per fish, to derive changes in welfare in the commercial fishery. First, we define the annual net economic benefits in the fishery as:

$$W = ph - cE \tag{3}$$

where W is the net economic benefit from the commercial salmon catch; ph is the gross benefits from salmon catch (price p × harvest h); and cE is the cost incurred by the commercial fishery (unit cost c × effort E), expressed so as to take into account that it is managed as both a troll ocean fishery and a gillnet river fishery with different costs of effort. We assume salmon are sold into an international market with a fixed exogenously determined price.

We use the 2013 fishing year for our baseline assumptions about the commercial fishing price and cost parameters. To determine a price per-fish, we rely on a weighted average price per kilogram for ocean and in-river caught Chinook and Coho multiplied by a weighted average caught weight per fish. Price and caught weight data are available from the Pacific Fishery Management Council (2014a,b) and we account for differences in value for ocean and in-river caught fish. All values are adjusted to 2013 prices using the US Gross Domestic Product Implicit Price Deflator. We determine a single commercial price for a combined Chinook/Coho salmon by first calculating a weighted-average caught weight per fish using harvest proportions by species from Table 2.B.2 in Appendix 2.B (Chinook: 46.25%; Coho: 52.50%) and average whole fish caught weights. Average Chinook caught weights are 7.53 kg/fish (16.67 lbs/fish) in-river and 4.98 kg/fish (10.99 lbs/fish) in ocean. Average Coho caught weights are 4.18 kg/fish (9.22 lbs/fish) in-river and 2.53 kg/fish (5.58 lbs) in ocean. The weighted-average combined caught weight is 4.72 kg (10.41 lbs). We then use ex-vessel price data for California, Oregon and Washington in-river and ocean fisheries and the same harvest proportions to calculate a weighted average price per kg ($1.69/kg or $3.72/lb), which we multiply by the weighted-average caught weight per fish to arrive at $38.72/fish.

Next, we assume the seasonal average number of days at sea for gillnet salmon boats at 33.34 and for trollers at 43.9 based on cost per boat-day estimates for ocean troll and river gillnet salmon fisheries. Per-day cost of fishing effort for gillnet in 2013 is $930 and $711 for trolling (Carl Lian, US Marine Fisheries Service, pers. comm., June 29, 2015). Using the total harvest proportions for in river and ocean fisheries (Table 2.B.2), this works out to a weighted average cost of $766.11, including both fixed and variable costs. To determine fishing effort in total number of boat-days, we use a production (catch) function model from Knowler et al. (2003), but invert the expression to isolate fishing effort (E) as the unknown variable. We estimate the catchability coefficient per the following expression (Argue et al., 1983; Knowler et al., 2003):

$$E = \frac{1}{q}\left(LN(X) - LN(X-h)\right) \tag{4}$$

where q is the catchability coefficient (q = 0.00003 for the Strait of Georgia Chinook and Coho fishery, Argue et al., 1983), E is fishing effort in boat-days, X is the total exploitable stock of Chinook and Coho and h is the commercial fishing harvest for these two species. Inserting the relevant variable values for exploitable stock, long run harvest and catchability into the above expression yielded a long run effort level of 12,541 boat-days per year for Scenarios 1 and 3, and 12,464 boat-days per year for Scenarios 2 and 4. Net welfare results are reported in Section 2.4.

Recreational fishing

For the recreational fishery, we follow Gislason et al. (1996), who studied commercial and recreational salmon fisheries in the Canadian Fraser River system. Their method assumes that increases in fish availability do not increase fishery values proportionally, since many dimensions of the recreational fishing experience (e.g. being outdoors, social aspects) are unaffected by fish availability. The approach also assumes that increases in fish availability translate into increased numbers of fishing days (as catching a fish now has a higher probability) and an increase in the willingness-to-pay per fishing day. We use the mid-range of Gislason et al.'s elasticity values for WTP per trip and fishing days and thus estimate the elasticity per 10% change in catch success as 1.5% (WTP/trip) and 2.75% (fishing days).

Huppert et al. (2004) estimate an average catch/trip of 1.13 fish for recreational fishing on the Columbia River and 1.14 fish/trip for recreational ocean fishing in Washington. Using these estimates, recreational catch results for the status quo scenario, and the allocation between ocean and river-based catches (85% and 15% respectively, Table 2.B.2), we determine the number of days involved in the recreational catch. This value is adjusted by first dividing the new annual recreational catch under each scenario by the initial number of recreational fishing days to obtain a new estimate of catch success. Dividing this latter value by the initial catch success (1.13 or 1.14 fish per day), we then obtain the proportional increase in catch success. Second, we multiply this proportional change by the elasticity values expressed above and by the initial number of recreational fishing days to yield the new estimate of fishing days. We use a similar procedure to adjust the WTP value per fishing day, assuming that the average fishing trip is one day. Net welfare results are reported in Section 2.4.

Tribal subsistence fishing

The tribal subsistence share of annual catch in the Columbia River is about 1% (Table 2.B.2). We assume that these fish are used primarily for household consumption. In reference to non-timber tropical forest products, Godoy et al. (1993) state that goods for the market and goods for the home should be valued differently. Specifically, ‘‘products consumed at home or exchanged with kin should be valued at their traditional retail purchasing price” (p. 225). Following this approach we collected several whole fish retail prices for each species by spot-checking different online fish markets that sell Washington and/or Columbia River salmon and steelhead[12]. We assume the same cost

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[12] *Chinook price is from the Wild Salmon Seafood Market (http://wildsalmonseafood. com) based on an average weight per whole fish of 6.80 kg (14.99 lbs) and an advertised price of $31.97/kg ($14.50/lb), Sockeye price is the average between the Seattle Fish Company (http://www.seattlefish.com) (average 2.5 kg (5.5 lbs) at $28.04/kg ($12.72/lb)) and the Wild Salmon Seafood Market (average 2.95 kg (6.5 lbs) at $28.64/kg ($12.99/lb)). Steelhead price is from Fitt's Seafood (http://www.fitts.net) (average 4.54 kg (10 lbs) at $33.05/kg ($14.99/lb)). All prices were accessed July, 2015.*

of effort per trip as for gillnet commercial fishing in-river, which was the closest available proxy for tribal fishing costs. Net welfare results are reported in Section 2.4.

Nutrient cycling

Nutrient cycling between marine and terrestrial aquatic ecosystems is an ecosystem service provided by Columbia River salmon. Here we follow Knowler et al. (2001) and use a replacement cost approach to determine the total benefit of salmon-based nutrient cycling. This approach estimates the value of an asset by calculating the cost of replacing its services, often with a human-produced substitute (Knowler and Lovett, 1996). In this case we use the price of fertilizer pellets applied during forest restoration efforts on the Keogh River in British Columbia. Applied to salmon by weight, these prices indicate a replacement cost of about $0.036/kg ($0.016/lb) (adjusted from Knowler et al.'s, 2001 CDN to 2013 USD using historic exchange rates and the US GDP Implicit Price Deflator)[13].

On the central coast of British Columbia, salmon are known to import as much as 266 g/m2 of nitrogen to streams during mass migrations (Harding and Reynolds, 2014), but the digging of nests during spawning also suspends sediment and results in the export equivalent of 55% of this imported nutrient (Moore et al., 2007). In addition, juvenile migrations are estimated to export an average of 22% of the nitrogen and 30% of the phosphorous imported by their parents in the Columbia Basin (Kohler et al., 2013). With the caveat that these figures are specific to different regions, they suggest a net import for nitrogen at roughly 23% of total nitrogen contained in the biomass of returning adult salmon and we adopt this assumption for our analysis. To calculate total biomass we assume only fish that die in the river contribute to total nutrient import, so we add total spawning populations and inter-dam losses and multiply by an average in-river weight per salmon of 4.72 kg (10.40 lbs) (weighted average across all species migrating upriver). We then reduce the result to 23% of total biomass to arrive at net import of

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[13] *Any use of the replacement cost approach is understood to overstate value and is considered an inferior valuation method (Ellis and Fisher, 1987). However, in the absence of better estimates of this ecosystem service value, and since the estimated value is a relatively small portion of total ecosystem service value, we elected to use the replacement cost method.*

nutrients and calculate nitrogen as 3.3% of total salmon biomass following Gende et al. (2004). Finally, we multiply the net biomass values by the per pound replacement cost indicated above. Net welfare results are reported in Section 2.4.

2.4. Results

First, we present our results from the biological model (Table 2.3). To obtain these results, we set the average escapement for all species from 1967 to 2000 (780,036 spawners) as the constant escapement. Commercial, recreational and tribal subsistence harvests are determined using the proportions identified in Table 2.B.2 (Appendix 2.B). Table 2.4 shows net biomass import results for Columbia River salmon. Finally, Table 2.5 summarizes our valuation results for salmon-related ecosystem services supported by the Columbia River by type of ecosystem service and by development scenario. As a sensitivity analysis, we also include an additional scenario (Scenario 3b) with +20% regulation for salmon conservation. Sensitivity analyses for other key parameters are provided in Appendix 2.D.

Table 2.3. Total exploitable stock and harvest results by fishing type (number of fish).*

		Harvest			
	Exploitable stock	Commercial (Chinook + Coho only)	Recreational	Tribal Subsistence	**Total**
Scenario 1 Status Quo	2,579,400	586,629	160,941	9,075	756,645
Scenario 2 Hydropower Priority	2,333,743	528,079	144,878	8,049	681,006
Scenario 3 Conservation Priority	2,947,886	670,433	183,932	10,218	864,583
Scenario 4 Pristine Conditions	4,094,286	926,454	254,171	14,121	1,194,746

*The level of precision indicated here is an artifact of model outputs and is not intended to suggest the model can deliver results to the last fish. Results should be interpreted to the nearest 1000.

Table 2.4. Biomass results for adult salmon returns at Columbia River mouth (number of fish).*

	Adult Returns at River Mouth	Total Biomass (lbs)	Net Import of Nitrogen (lbs)
Scenario 1 Status Quo	1,264,914	16,007,737	121,499
Scenario 2 Hydropower Priority	1,138,666	14,410,044	109,372
Scenario 3 Conservation Priority	1,445,616	18,294,557	138,856
Scenario 4 Pristine Conditions	1,997,660	25,280,779	191,881

*Results are model outputs and should be interpreted to the nearest 1000 in terms of precision.

Table 2.5. Summary of estimated changes in the value of ecosystem services from Columbia River salmon production under four alternative development scenarios ($USD 2013).*

	Net economic benefit/yr	Difference from Status Quo/yr	Difference from Status Quo as NPV**
Scenario 1 - Status Quo			
Commercial Fishery	$13,107,087	-	-
Recreational Fishery	$21,743,130	-	-
Cultural/Subsistence	$1,531,413	-	-
Nutrient Cycling	$2,001	-	-
Sub-total	*$36,383,631*	-	-
Scenario 2 - Hydropower Priority			
Commercial Fishery	$10,898,818	($2,208,269)	($22,082,690)
Recreational Fishery	$20,829,760	($913,370)	($9,133,700)
Cultural/Subsistence	$1,138,256	($393,157)	($3,931,575)
Nutrient Cycling	$1,801	($200)	($1,997)
Sub-total	*$32,868,634*	*($3,514,996)*	*($35,149,963)*
Scenario 3a - Conservation Priority (+10% regulation)			
Commercial Fishery	$16,352,066	$3,244,979	$32,449,789
Recreational Fishery	$23,081,553	$1,338,423	$13,384,228
Cultural/Subsistence	$1,724,335	$192,922	$1,929,216

	Net economic benefit/yr	**Difference from Status Quo/yr**	**Difference from Status Quo as NPV****
Nutrient Cycling	$2,287	$286	$2,859
Sub-total	*$41,160,240*	*$4,776,609*	*$47,766,091*
Scenario 3b - **Conservation Priority (+20% regulation)**			
Commercial Fishery	$18,154,832	$5,047,745	$50,477,450
Recreational Fishery	$23,840,939†	$2,097,809	$20,978,094
Cultural/Subsistence	$1,844,080	$312,667	$3,126,670
Nutrient Cycling	$2,446	$445	$4,447
Sub-total	*$43,842,297*	*$7,458,666*	*$74,586,661*
Scenario 4 **- Pristine Conditions**			
Commercial Fishery	$26,324,305	$13,217,218	$132,172,182
Recreational Fishery	$27,397,179	$5,654,049	$56,540,495
Cultural/Subsistence	$2,162,866	$631,452	$6,314,525
Nutrient Cycling	$3,160	$1,159	$11,592
Sub-total	*$55,887,510*	*$19,503,879*	*$195,038,794*

* Results are model outputs and should be interpreted to the nearest 1,000 in terms of precision

**Net present value

† The magnitude of change in the recreational fishery increases relative to other components as Conservation Priority increases due to elasticity of demand (see Section 3.3.2).

2.5. Discussion and recommendations for further research

Although the Columbia Basin is highly studied and produces a wide array of data, the system is very complex and significant gaps remain in publicly available information for specific sections of the basin. We limited our assessment of ecosystem services to manageable portions of the system by: (i) considering the mainstem as the main driver of changes in production (versus the many tributaries); (ii) constraining the geographic scope primarily to Washington State; (iii) selecting specific ecosystem services for valuation; and (iv) focusing on Columbia River salmonid species, which are the most economically significant species produced by the system. Despite ignoring large areas of the river basin, we feel these restrictions still capture salmon-derived economic welfare benefits because Washington hosts the largest and most productive stretch of the Columbia River. Because we focused only on salmon and specific services, our welfare estimates are conservative and do not reflect the full value produced by fish production in the Columbia Basin. There are over 50 fish species in the system (PNNL, 2015). Other species of particular interest for future study include sturgeon, trout, bass, lamprey and shad.

Our results show that recreational fishing is the most important ecosystem service we assessed (Table 5). Under some scenarios, this sector generates nearly twice the value of commercial fishing, the next largest sector. This result is not surprising since most economic assessments indicate the value of a ‘‘marginal” fish is higher when allocated to the recreational fishery. Although we used an accepted methodology placing high per-fish value on tribal subsistence catch (i.e. at retail prices), the catch is relatively small in comparison to the combined commercial and recreational catch at only one percent of the total harvest of Columbia River salmon. Results for nutrient cycling are also very small because the true net import of nutrients from sea to land via salmon migration is relatively low due to exported nutrients from juvenile migration and the stirring of sediments during redd construction. However small, this contribution should not be neglected. Nitrogen in salmon represents only a small portion of nutrient cycling performed by fish in the Columbia River. Globally in the past, movements by anadromous fish alone provided important transfer of nutrients from the sea to land totaling _140 million kg of P per year, but this import has declined to less than 4% of its original value due to the decimation these fish populations (Doughty et al., 2015).

It is also instructive to examine the welfare change associated with shifts from one development scenario to another. Comparing a shift from the status quo (scenario 1) to Hydropower Priority (scenario 2) versus one to Conservation Priority (scenario 3) is of particular interest. In the former case, there is a net welfare loss of about $3.5 million per year, whereas in the latter case there is a gain in welfare of nearly $4.8 million per year. From a management point of view this result suggests that although greater emphasis was placed on fish conservation in recent decades, opportunities for welfare gain from such actions may not be fully exploited in the Columbia River, particularly considering that our Conservation Priority scenario only minimally alters the flow regime relative to the Status Quo scenario (Figure 2.2). However, care is needed in such interpretations because the welfare gains stemming from increased hydropower production are not considered here and might well outweigh the difference of about $8.3 million per year between the two scenarios. Our assessment of Pristine Conditions (scenario 4) suggests that society is worse off in terms of salmon-based ecosystem services by $19.5 million per year given the current status quo. Again we are disregarding the non-fishery benefits associated with Columbia River development over the past century. Obviously, these benefits have been substantial.

The sensitivity analyses we carried out in Appendix 2.D show that, under the status quo scenario, a 20% increase in the Beverton-Holt ‘a’ parameter would increase our results by $850,959, while a 20% decrease would decrease our results by $1,332,090. Likewise, a 20% increase or decrease in the ‘b’ parameter would have a slightly larger but similar effect. The model is most sensitive to the survival adjustment parameter for all three scenarios except Pristine Conditions, which is most sensitive to changes in the Beverton-Holt ‘b’ parameter. When the survival adjustment parameter is changed to minimum and maximum values per the slopes of the upper and lower limits of the 95% confidence interval in Figure 2.3, scenarios 1–3 show differences from the base case with minimums ranging from $1.9 to 9.0 million less and maximums ranging from $1.7 to 7.8 million more depending on the scenario.

In addition to the biological parameters, our model assumes a constant escapement management target. We based this target on average escapements from 1967 to 2000 (780,036 spawners). In reality, annual escapements vary widely (0.5–1.2 million 1967–2000) and, in particular, could be altered by major shifts in management toward hydropower or conservation priorities. We selected one alternative time-series (1991–2000) to derive a new constant escapement target of 683,580 fish. Considering only the status quo scenario, a reduced management target from an escapement of 780,036–683,580 fish would reduce the welfare generated by the Columbia River fish production system by about $2.9 million per year.

Finally, we can make several recommendations for improving the welfare estimates presented here. Future analyses could model tradeoffs with competing uses such as hydropower production and irrigation. Not only is this type of analysis urgently required (Mach et al., 2015), it is also essential to correctly evaluate the full social costs of any alternative management strategies. In our case, several other competing uses are relatively immaterial to salmon production but may be affected by management changes favoring salmon conservation (Huppert et al., 2004). Agricultural water supply, for example, should be incorporated into any future assessment of tradeoffs. This service is more complex to analyze due to the need to model changes in irrigated land area and subsequent shifts in crop type. Our development scenarios would also affect shipping and transportation but it is unclear to what extent. The net effect may be zero since higher and lower flows are associated with both benefits and costs, thereby creating offsetting effects. Adequately capturing this value is complex since it involves modeling changes in groundings and collisions resulting from different flow regimes (for which there are insufficient public data), changes in available draft, and effects of delays throughout the transportation chain extending across 39 US states.

2.6. Conclusion

In this study we valued food production (commercial and tribal subsistence fishing), recreational fishing, and nutrient cycling services supplied by salmon populations in the Columbia River under a range of development scenarios. Although current management of the Columbia River includes many improvements for fish conservation, our results suggest that a re-prioritization of hydropower production would result in a loss of net economic benefits of $2.2 million/yr from commercial fishing, nearly $1 million/yr from recreational fishing (the most valuable service), $393 thousand per year from tribal subsistence fishing, and $200/yr from nutrient cycling compared to the benefits obtained from these fisheries under the current river management regime. If, on the other hand, increased flow management for salmon conservation is pursued, benefits to society would increase by about $4.8 million/yr, compared to the total annual loss of $3.5 million for a return to hydropower prioritization of the past.

Although our study could be improved with the inclusion of a more complex trade-off analysis, the steps in the bio-economic approach to valuation we have proposed could be replicated in similar studies valuing fish production services in other river basins. This use would support and enhance decision-making regarding aquatic resources allocation and management in other basins with multiple competing uses, and advance our knowledge of the trade-offs and their consequences on the value of aquatic ecosystem services.

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Appendix 2.A. Egg-to-spawner survival rates and habitat quality index measured from 0 to 1 (based on deviations in average daily flow from pristine conditions).*

Year	Survival Rate	Index Value (HQI)	Year	Survival Rate	Index Value (HQI)
1970	0.0006	0.63	1986	0.0011	0.63
1971	0.0008	0.68	1987	0.0007	0.31
1972	0.0006	0.63	1988	0.0008	0.31
1973	0.0005	0.57	1989	0.0005	0.47
1974	0.0005	0.54	1990	0.0005	0.53
1975	0.0005	0.55	1991	0.0006	0.44
1976	0.0005	0.47	1992	0.0013	0.50
1977	0.0009	0.41	1993	0.0007	0.46
1978	0.0006	0.49	1994	0.0005	0.46
1979	0.0006	0.33	1995	0.0004	0.71
1980	0.0004	0.55	1996	0.0005	0.56
1981	0.0008	0.62	1997	0.0011	0.64
1982	0.0012	0.57	1998	0.0007	0.59
1983	0.0007	0.62	1999	0.0006	0.57
1984	0.0012	0.64	1999	0.0010	0.47
1985	0.0009	0.33	2000	0.0011	0.63
Pristine	0.0013	1			
No flow	0.0000	0			

*Survival rates are total number of returning spawners counted below Bonneville dam less inter-dam loss and in-river harvest divided by total estimated number of eggs. Index values are one minus the annual average of daily percent change between regulated and unregulated flows (so pristine conditions are at 1 and fully degraded conditions are at 0).

Appendix 2.B. Salmon population model estimates for the Columbia River

To examine the effects of habitat quality on salmon populations, we rely primarily on aggregate harvest and escapement data for major Columbia River salmon species compiled from the Pacific Fishery Management Council (PFMC) and the Oregon and Washington Departments of Fish and Wildlife (DFW). The average proportions of returning adults at the Columbia River mouth by species are Chinook (45.61%), Coho (26.92%), Steelhead (22.34%), Sockeye (4.99%) and Chum (0.14%) (WDFW, ODFW, 2002). We estimate the total number of salmon of all species surviving to spawn for each return year (1967–2000) using adult returns at the Columbia River mouth and the relationship:

$$SP_{t,i} = AR_{t,j} \times \left(1 - downr_{t,i}\right) \times \left(1 - upr_{t,i}\right) \times int_{t,i} \qquad \text{(B.1)}$$

where AR is the estimated adult returns below Bonneville Dam (the first dam spanning the mainstem) for species i in year t, $downr$ is the downriver exploitation rate, upr is the upriver exploitation rate, and int is the inter-dam survival rate for adult passage past dams from river mouth to spawning locations.

For salmon harvest, we compile the total number of fish harvested in each return year (1967–2000) using commercial, recreational and tribal subsistence harvest data for ocean and in-river fisheries. For ocean recreational fishing (Chinook and Coho), only aggregate statewide data are available for Washington and Oregon respectively. We assume 80% of the recreational ocean catch in these two States is attributable to salmon of Columbia River origin. This figure is consistent with commercial catch proportions applied by the Pacific Salmon Commission Joint Technical Committee (PSC-CTC, 2014). Table 2.B.1 shows results for total harvest of salmon from the Columbia River. Seventy-nine percent of this harvest is attributable to ocean and in-river commercial fishing, 20% to recreational fishing and 1% to tribal subsistence fishing (see Table 2.B.2).

We develop annual exploitation rates for each salmon species in ocean, downriver and upriver areas by dividing harvest totals in each area by the number of exploitable fish. For the ocean fishery, we calculate exploitable stock by adding marine harvest and natural marine mortality to adult returns at the river mouth. Exploitable stock for the downriver fishery corresponds to adult return estimates below Bonneville dam (these incorporate downriver harvest totals). For the upriver fishery, exploitable stock is adult return estimates less downriver harvest[14].

Table 2.B.1. Estimated number of salmon surviving to spawn in the Columbia River system (all species) and estimated number of Columbia River fish harvested (all salmon species, ocean and in-river, all fishing types.

Return Year	Number of fish	No. Fish Harvested	Return Year	Number of fish	No. Fish Harvested
1967	1,881,500	3,134,849	1984	1,706,700	1,770,609
1968	1,478,200	2,807,249	1985	1,876,900	3,057,530
1969	1,670,500	3,006,849	1986	3,181,900	2,440,230
1970	2,324,900	3,381,049	1987	2,229,400	2,716,630
1971	2,063,000	3,169,049	1988	2,409,300	2,387,730
1972	1,628,200	3,035,849	1989	2,055,100	1,843,430
1973	1,730,900	3,145,749	1990	1,262,100	1,428,870
1974	1,440,800	2,890,649	1991	1,965,300	869,470
1975	1,410,500	2,886,949	1992	1,236,500	792,070
1976	1,403,800	2,865,149	1993	947,600	743,370
1977	1,380,500	2,743,749	1994	854,300	713,170
1978	1,315,600	2,748,449	1995	749,500	491,763
1979	1,160,900	2,703,249	1996	906,000	509,763
1980	1,191,600	2,852,849	1997	1,057,500	463,563
1981	1,091,000	1,391,209	1998	858,300	548,863
1982	1,486,500	1,612,909	1999	1,063,100	669,863
1983	1,034,900	1,309,909	2000	1,715,700	630,200

Source: This study; (Pacific Fishery Management Council 2014a; WDFW, ODFW, 2014a,b).

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[14] *We do not consider inter-dam losses as exploitable stock.*

Table 2.B.2. Allocation of total harvest across species and end users for Columbia River salmon, average 1970–2000.

	Ocean harvest			**River harvest**				**Grand Total**
	Commercial	Recreational	Total	Commercial	Recreational	Tribal Subsistence	Total	
Chinook	30.00%	3.00%	33.00%	11.5%	1.25%	0.50%	13.25%	46.25%
Coho	30.00%	12.00%	42.00%	9.5%	1.00%	n/a	10.50%	52.50%
Sockeye	n/a	n/a	n/a	n/a	n/a	0.20%	0.20%	0.20%
Steelhead	n/a	n/a	n/a	n/a	0.75%	0.30%	1.05	1.05%
Chum	n/a	n/a	n/a	neg.	neg.	neg.	neg.	neg.
All Species	60.00%	15.00%	75.00%	21.00%	3.00%	1.00%	25.00%	100%

Source: This study.

To estimate changes in total exploitable stock and harvest under each development scenario, we assume a fishery managed at a constant level of escapement. Total harvest is estimated from total exploitable stock, accounting for natural marine mortality and inter-dam loss, and we apply weighted average harvest rates for river and ocean fisheries, different fishery types and different species. Table 2.B.2 shows proportions used for weighting purposes throughout this study.

We estimate the number of eggs corresponding to the brood year for returning adult salmon by assuming a 1:1 ratio of females to males, and average female fecundity for each salmon species ranging from 3188 (Chinook) to 3500 (Steelhead and Sockeye). We assign brood years of 3 or 4 years, based on predominant adult return ages for each species (Harnish et al., 2013; Manzer and Miki, 1985; Beacham, 1982; Brannon et al., 2004). The equation for calculating number of eggs is:

$$Eggs_{t-n} = \left(\frac{SP_{t-n}}{2}\right) \times fecundity \tag{B.2}$$

where SP is the number of spawners in the corresponding brood year $t-n$; and n is the average adult return age minus 1. We estimate egg-to-spawner survival rates for each species by dividing the number of adult returns less harvest and inter-dam mortality by the number of eggs. Due to lack of available data for other species, we rely on the inter-dam survival rate reported by Harnish et al. (2012) for Fall Chinook salmon (0.759). We do not apply this rate to Chum salmon, which primarily spawn in the lower sections of the river.

Appendix 2.C. Parameter estimates for modelling

Parameter	Units	Value	Source
Aggregate Biological Model (all species)			
Survival adjustment for habitat quality, Q, by development scenario	n.a.	Hydro = -0.000563, Base = -0.000484, Conserv= -0.000367	this study
Density independent recruitment parameter, *a*	n.a.	3336	this study
Density dependent recruitment parameter, *b*	n.a.	2,087,340,236	this study
Predicted egg-to-spawner survival under pristine conditions, *s*	n.a.	0.001072753	this study
Inter-dam survival, *int*	n.a.	0.759	Harnish et al 2012 (Fall Chinook)
Natural ocean survival, *oc*	n.a.	0.8	personal communications with staff at PNNL (Fall Chinook)
Ocean harvest , *h1*	n.a.	0.1640	this study
Downriver harvest, *h2*	n.a.	0.2165	this study
Upriver harvest, *h3*	n.a.	0.0689	this study
Commercial Fishing Welfare Estimation			
Price, p	$per salmon; 2013 USD	29.03	PFMC 2014
Cost, *c*	$per boat-day; 2013 USD	$766.11	NOAA-NMFS 2015
Catchability coefficient, *q*	n.a	0.00003	Argue et al 1983
Fishing effort, *E*	#boat-days/season	Hydro=12,464 Base=12,541 Conserv=12,541	this study
Recreational Fishing Welfare Estimation			
Price, p	WTP per trip	$148.30 (ocean) $184.76 (river)	Olsen, Richards, and Scott 1991
Fishing days, d	per fish	0.877 (ocean) 0.885 (river)	Huppert et al 2004

Parameter	Units	Value	Source
Elasticity of fishing days, e_d	change in days per 10% change in success	2.75%	Gislason et al 1996
Elasticity of price, e_p	change in WTP per 10% change in success	1.5%	Gislason et al 1996
Tribal Subsistence Fishing Welfare Estimation			
Price, p	$per salmon; 2013 USD	Chinook=$217.36; Sockeye=$77.21; Steelhead=$149.90	Seattle Fish Company 2015, Wild Salmon Seafood Market 2015 Fitt's
Cost, c	$per boat-day; 2013 USD	$930	NOAA-NMFS 2015
Catchability coefficient, q	n.a	0.00003	Argue et al 1983
Fishing effort, E	#boat-days/season	Hydro=236 Base=240 Conserv=236	this study
Proportions of harvest by species	%	Chinook=45% Sockeye=16% Steelhead=40%	PFMC 2014
Nutrient Cycling Welfare Estimation			
Price, p	per lb	$0.01647	Knowler et al 2001
Caught weight, w	avg. weighted lbs per whole salmon	12.66 (in-river)	this study
Net import adjustment, N_i	% biomass	23%	this study
Nitrogen/biomass adjustment, N_{ii}	% biomass	3.3%	Gende et al 2004

Appendix 2.D. Sensitivity analysis of key biological parameters (USD 2013)

	Net economic benefit per year	Difference from Base Case per year	Difference from Base Case as NPV
Parameter: Beverton-Holt ‘a’ +20%			
Scenario 1 Status Quo	$37,234,590	$850,959	8,509,588
Scenario 2 Hydropower Priority	$35,274,211	$2,405,577	24,055,766
Scenario 3 Conservation Priority	$42,011,199	$850,959	8,509,588
Scenario 4 Pristine Conditions	$60,268,139	$4,380,629	43,806,287
Parameter: Beverton-Holt ‘a’ -20%			
Scenario 1 Status Quo	$35,051,541	($1,332,090)	($13,320,901)
Scenario 2 Hydropower Priority	$29,875,555	($2,993,079)	($29,930,793)
Scenario 3 Conservation Priority	$39,828,150	($1,332,090)	($13,320,901)
Scenario 4 Pristine Conditions	$50,453,508	($5,434,002)	($54,340,024)
Parameter: Beverton-Holt ‘b’ +20%			
Scenario 1 Status Quo	$37,440,304	$1,056,673	$10,566,735
Scenario 2 Hydropower Priority	$35,929,993	$3,061,358	$30,613,581
Scenario 3 Conservation Priority	$42,216,913	$1,056,673	$10,566,735
Scenario 4 Pristine Conditions	$61,464,366	$5,576,855	$55,768,554
Parameter: Beverton-Holt ‘b’ -20%			
Scenario 1 Status Quo	$34,711,823	($1,671,808)	($16,718,079)
Scenario 2 Hydropower Priority	$29,228,812	($3,639,823)	($36,398,226)
Scenario 3 Conservation Priority	$39,488,432	($1,671,808)	($16,718,079)
Scenario 4 Pristine Conditions	$49,281,756	($6,605,754)	($66,057,538)
Parameter: HQI minimum survival			
Scenario 1 Status Quo	$28,253,448	($8,130,183)	($81,301,827)
Scenario 2 Hydropower Priority	$25,331,340	($7,537,294)	($75,372,944)
Scenario 3 Conservation Priority	$32,185,667	($8,974,573)	($89,745,734)
Scenario 4 Pristine Conditions	$53,999,217	($1,888,293)	($18,882,932)
Parameter: HQI maximum survival			
Scenario 1 Status Quo	$43,453,622	$7,069,991	$70,699,914
Scenario 2 Hydropower Priority	$39,423,051	$6,554,417	$65,544,169
Scenario 3 Conservation Priority	$48,964,512	$7,804,272	$78,042,719
Scenario 4 Pristine Conditions	$57,649,230	$1,761,720	$17,617,196
Parameter: Inter-dam survival +10%*			
Scenario 1 Status Quo	$36,379,356	$7,137,643	$71,376,434

	Net economic benefit per year	Difference from Base Case per year	Difference from Base Case as NPV
Scenario 2 Hydropower Priority	$32,864,221	$6,562,531	$65,625,313
Scenario 3 Conservation Priority	$41,155,550	$7,814,574	$78,145,737
Scenario 4 Pristine Conditions	$55,880,517	$1,761,720	$17,617,196
Parameter: Inter-dam survival -10%*			
Scenario 1 Status Quo	$36,388,855	$7,137,643	$71,376,434
Scenario 2 Hydropower Priority	$32,874,029	$6,562,531	$65,625,313
Scenario 3 Conservation Priority	$41,165,972	$7,814,574	$78,145,737
Scenario 4 Pristine Conditions	$55,896,057	$1,761,720	$17,617,196

**Note that inter-dam survival is used in the denominator of Eq. (2) to back transform number of returning spawners to total exploitable stock. This parameter will therefore have a seemingly counter-intuitive negative relationship with net economic welfare (i.e. an increase in inter-dam survival results in a decrease in welfare).*

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Chapter 3. Optimizing transboundary flow augmentation for fish conservation and other values

This chapter is from the draft manuscript titled "Decision analysis of transboundary flow augmentation strategies for Chinook salmon (Oncorhynchus tshawytscha) in the Columbia River", co-authored by C Morton, R Harnish, and S P Cox, which will be submitted for publication. I authored the majority of the text and exclusively completed and authored the data analysis, tables and figures.

Abstract

Using a decision analysis framework, we apply multi-attribute utility optimization across three valued components (salmon conservation, hydropower production, and agricultural irrigation) to forecast optimal flows in Hanford Reach on the US portion of the Columbia River. Forecasting optimal flows in this way permits evaluation of the current practice under Columbia River Treaty Non-Power Uses Agreements (NPUAs) of augmenting the flow delivered to the Reach from Canadian reservoirs during the months of May through July by 1 million acre feet (MAF) ("flow augmentation") above normal Treaty-determined levels. We also evaluate alternative flow volumes that could improve upon total utility benefits across the three valued components. Multi-attribute utility optimization normalizes utility benefits across different valued components to a common scale for comparison (Keeney and Raiffa 1976, Wheeler et al. 1999). Capitalizing on the ability of models to experiment with many alternatives in a simulated environment, we are able to forecast optimal flows over a large series of different prioritization strategies in which the weighting for each valued component is varied. We also forecast incremental benefits derived from different flow augmentation alternatives over a twelve-year period (1995-2008) and perform a multi-criteria assessment of these results to identify the best flow augmentation volumes given different prioritization strategies. Using models in this way can aid decision-makers by narrowing the range of options to a manageable set of "non-dominated" solutions for consideration, while remaining transparent about uncertainties (non-dominated solutions are those for which no alternative solutions perform better). Our results suggest that optimal flows for any one of the three individual valued components assessed are likely

infeasible during most years given the combined operating constraints on the system. However, depending on how decision criteria are weighted and how each of the three valued components is prioritized, between 1 and 6 MAF of additional flow augmentation above current augmentation practices for Hanford Reach from March-July would still generate improvements in the current average benefits from salmon conservation, hydropower production, and irrigation diversions.

3.1. Introduction

In highly developed river systems, flow augmentation for fish conservation is not always closely tied to the ecological needs of the fish. The range of implementable strategies is often limited by obligations to prioritize other values such as hydropower production, flood management, and irrigation. For internationally shared river basins, this inflexibility can be reinforced by transboundary water agreements, prompting nations to engage in more ad hoc arrangements to protect at-risk fish, such as temporary sub-agreements between nations to adjust flows at specific times during each year. Sub-agreements designed for this purpose are often based on decision-makers' understandings about available storage under normal operations, and may be implemented without duly considering operating alternatives or carefully assessing trade-offs among competing values. Including fish conservation performance in decision-making can help inform these trade-offs in ways that are more capable of meeting the ecological needs of riverine species while still addressing other values.

In this paper, we evaluate optimal flow augmentation in Hanford Reach, USA, a section of the Columbia River. The river is shared by Canada and the USA and has an operating regime strongly influenced by the 1964 Columbia River Treaty (CRT or 'the Treaty'), which is silent regarding fish conservation. Nevertheless, the parties have negotiated sub-agreements for fish conservation annually since 1993 (pers. comm., Kelvin Ketchum, December 2018). Under these 'Non-Power Uses Agreements' (NPUAs), Canada delivers an additional 1 million acre feet (MAF) of storage between May and July each year to help meet flow obligations that US agencies are required to meet under the US Endangered Species Act (ESA) at McNary Dam on the Columbia River in Washington State, and to assist juvenile fall Chinook salmon (*Oncorhynchus tshawytscha*) in their downstream migration (Ketchum and Barroso 2006; USACE, BPA, BoR 2007, p.2-22). Because flow augmentation decisions have been made under an operating regime that is constrained by the Treaty, limited flexibility is available to meet objectives outside hydropower and flood management values. Bonneville Power Administration states that 1 MAF, "…is what could be negotiated with Canada in exchange for benefits for [Canadian] trout…" and may be "…a practical limit on the amount of water we can store in Treaty space and carry into the spring/summer" (pers. comm. Pamela Kingsbury, Bonneville Power Administration June 2012). It is presently unclear whether the 1 MAF volume is optimal given trade-offs with other interests. In addition, fall Chinook pre-smolt survival may be closely tied to flow volumes beginning earlier than May. Further changes to the Treaty are currently under negotiation and are expected to formally incorporate fish conservation values by 2024 (Province of British Columbia 2014; US Entity 2013). Therefore, what is considered 'Treaty space' may change to accommodate these values.

We apply decision analysis (Walters 1986, Walters and Green 1997, Robb and Peterman 1998, MacGregor et al. 2002, Alexander et al. 2006) to clarify the benefits of the 1 MAF volume and of potential additional flow augmentation volumes by evaluating optimal flows in Hanford Reach, a segment of the Columbia River mainstem that is critical for fall Chinook spawning and rearing. To determine optimal flows, we calculate a multi-attribute utility value that normalizes benefits from salmon conservation, hydropower production, and irrigation diversions (the "valued components") to a common scale (Wheeler et al. 1998). We then examine trade-offs among these valued components while considering the effects of different flow augmentation volumes, future flow scenarios, and alternative prioritization schemes. Our research addresses three main questions:

1. What are optimal March-July flow volumes in Hanford Reach given an equal prioritization of fish conservation, hydropower, and irrigation, and how often have these flows been achieved historically?

2. How does prioritization of either fish conservation, hydropower, or irrigation over the other valued components affect optimal flow choices and their historical performance?

3. What flow augmentation strategy is best suited to meeting different management criteria, including: a) least additional flow augmentation required, b) highest multi-attribute utility, and c) most evenly balanced multi-attribute utility across valued components.

Addressing these questions provides a quantitative framework for evaluating transboundary flow augmentation strategies for Columbia River salmon that can be adapted to other species and river segments.

3.2. Site Description

Hanford Reach is an 80 km segment of the Columbia River between Priest Rapids Dam and Richland, WA upstream of the McNary Dam reservoir (Lake Wallula) and the Snake River confluence (Figure 3.1). The reach is the last ecologically intact stretch of the Columbia River upstream of Bonneville Dam that is still available to anadromous fish (Harnish et al. 2014). It contains the only remaining substantial mainstem spawning area for the fall run of Chinook salmon (aka “upriver brights’) and provides habitats for one of the largest spawning populations in the Pacific Northwest (Harnish et al. 2012). These characteristics make the population critical in a region where Chinook salmon face widespread decline (Ma et al. in press, Bottom et al. 2005).

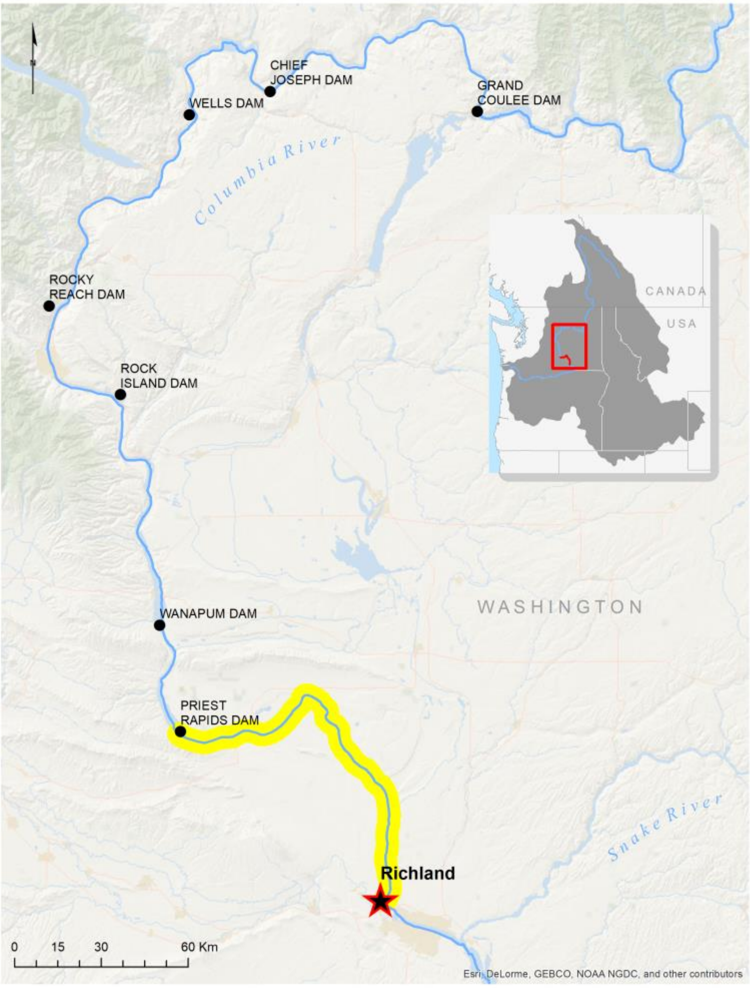

Figure 3.1. Map of study area in Washington, USA showing location of Hanford Reach and Priest Rapids Dam

During incubation and spring emergence periods, fall Chinook in the reach are vulnerable to dewatering and stranding (Becker and Neitzel 1985). These impacts can occur due to insufficient flows and high flow variability, both of which are influenced by hydroelectric dam operations and irrigation diversions upstream. Insufficient flows can also contribute to juvenile (smolt) mortality via slower downstream migration rates, increased vulnerability to predation, stranding, and thermal death (Becker et al. 1981, Becker and Nietzel 1985, Giorgi et al. 1997, Hatten et al. 2009, Harnish et al. 2012, Harnish et al. 2014). Mortality during these life stages contributes to lower adult escapement, reduced opportunities for commercial, recreational and subsistence/cultural fishing (Morton et al. 2017), potential legal challenges under the ESA, depletion of marine-riparian nutrient fluxes (Moore et al. 2007; Harding and Reynolds 2014), and cascading effects up the marine food web (e.g. southern resident killer whales) (Zamon et al. 2007, Hanson et al. 2010).

Current management practice by Columbia River dam operators decreases flows during the fall spawning period to encourage redd formation at lower (deeper) elevations within the Reach, thereafter maintaining a “protection-level minimum discharge” and limiting discharge fluctuations from Priest Rapids Dam during the egg, alevin and fry stages (Harnish et al. 2014). The river segment is the target recipient of 1 MAF of transboundary flow augmentation from Canadian reservoirs under Canada-USA Non-Power Uses Agreements (NPUAs) (Hearns 2008), which helps meet ESA-based discharge targets downstream at McNary Dam during the smolt life stage (USACE et al. 2007). In addition to the NPUAs, three US domestic agreements between mid-Columbia River public utility districts (Chelan, Grant and Douglas counties), US fisheries agencies (NOAA-Fisheries, US Fish and Wildlife Service), Bonneville Power Administration, and Columbia River Tribes (Colville, Yakama, Umatilla), define management obligations for US power producers upstream of Hanford Reach to help achieve these conservation goals. These agreements include the 1979 Vernita Bar Settlement Agreement, the 1987 Rock Island Settlement Agreement (amended 1993; now consolidated into the Mid-Columbia Habitat Conservation Plan), and the 2004 Hanford Reach Fall Chinook Protection Program Agreement (Harnish et al. 2014, NOAA-NMFS 2002; WDFW 2006).

Along the mainstem of the Columbia, seven US power producing dams are located upstream of Hanford Reach. In order, moving upstream, these include Priest Rapids, Wanapum, Rock Island, Rocky Reach, Wells, Chief Joseph and Grand Coulee. Chief Joseph and Grand Coulee are US Bureau of Reclamation and US Army Corps of Engineers projects, while the five dams downstream of Chief Joseph are operated by county-owned Public Utility

Districts (USEIA 2018). Collectively all seven dams can produce up to 112 terawatt hours of electricity during the March to July period, but on average about 22% of that capacity is actually generated over the period due to natural flow limits, electricity demand, and trade-offs with other interests such as flood management and fish conservation (USEIA 2018). Irrigation diversions occur primarily from Franklin D. Roosevelt Lake, which was formed by Grand Coulee Dam and services the Columbia Basin Project – the largest agricultural land creation project in the US, irrigating approximately 2,700 km$_2$ of previously arid cropland and supporting a wide range of crop types sold both domestically and internationally (Ortolano and Cushing 2000). Regional irrigation demand rises in March and peaks in July before declining from August to October (WDE 2011).

3.3. Materials and methods

3.3.1. Decision analysis framework

Decision analysis explicitly considers uncertainty in the selection of management alternatives using six core steps: (1) specify management objectives, (2) identify alternative management actions, (3) identify uncertain states of nature, (4) assign probabilities to these states of nature, (5) calculate expected values for each management action given the uncertain states of nature, and (6) rank management options (Robb and Peterman 1998). We used the following steps to apply decision analysis in this study (details of the methods for each step are provided in subsequent sections):

Parameterization and multi-attribute utility estimation

1. Parameterize a) egg-to-pre-smolt, b) hydropower production, and c) irrigation diversion relationships with regulated flows using Bayesian regression (generate 15,000 draws from the joint Bayes posteriors for each valued component)

2. Forecast the number of returning adult Chinook at equilibrium using the survival forecasts from step 1 as inputs to a Ricker population model. Results from this step are used in step 4 as salmon conservation utility.

3. For hydropower production and irrigation, use the relationships from step 1 to forecast utility for hydropower production in gigawatt hours (GWh), and irrigation diversions in million acre-feet (MAF)

4. Normalize the utility forecasts for salmon conservation, hydropower production and irrigation diversions to a common scale (0 to 1) and compute the sum of the normalized forecasts (salmon conservation + hydropower + irrigation) to obtain 15,000 multi-attribute utility curves. The maximum point of each curve represents optimal multi-attribute utility and the median of these optimums is the expected optimal multi-attribute utility.

Assessment of different prioritization strategies

5. Assign a range of priority weight combinations across the three valued components to forecast multi-attribute utilities under each combination (e.g., 0.35 / 0.60 / 0.05 for salmon conservation, hydropower production, and irrigation diversions respectively; 160 combinations in total x 15,000).

6. Bin multi-attribute utility forecasts (2.4 million in total) into ‘prioritization categories’, such that combinations more heavily weighted toward salmon conservation, hydropower or irrigation respectively are binned together and those that are more evenly balanced are binned into a ‘balanced’ prioritization category. Each prioritization category can be characterized as a separate management ‘philosophy’ that encompasses a range of potential trade-offs but still prioritizes a single valued component (balanced category excepted).

7. Determine the median optimal flow within each prioritization category, where optimal flow is defined as the regulated flow at maximum multi-attribute utility

8. Evaluate median optimal flow results relative to historical performance, and determine flow augmentation that would have been needed to achieve these optimal flows

9. For optimal flows, forecast resulting benefits for salmon conservation (# returning adults), hydropower production (GWh), and irrigation diversions (MAF)

Multi-criteria assessment of flow augmentation alternatives

10. Subsample 1,000 parameter sets from each valued component's joint Bayes posterior and repeat steps 2-6

11. For the years 1993-2008, forecast incremental benefits of 10 flow augmentation alternatives (1, 2, 3… 10 MAF) relative to a no-augmentation base case for salmon conservation (# of returning adults), hydropower production (GWh), and irrigation diversions (MAF)

12. Apply a set of decision criteria to identify the top flow augmentation alternatives under each prioritization category (see Section 3.4.4 for a description of criteria)

Management options for the valued components include a balanced approach and imbalanced prioritization of either salmon, hydropower, or irrigation, as well as different March-July flow augmentation alternatives ranging from 0-10 MAF. Uncertain states of nature are captured using a combination of Bayesian regression and sensitivity analyses to test the effects of different model parameters. The following sections explain the derivation and treatment of model input data, utility estimation methods for each of the three valued components (salmon, hydropower, irrigation), the multi-attribute utility estimation method used to identify optimal flows, the application of flow augmentation alternatives, and our approach to examining uncertainty in our results.

3.3.2. Input data

We selected the March to July time period for input data for the following reasons:

1) to capture the period where fall Chinook pre-smolt survival is most affected by regulated flow volumes, based on a preliminary assessment of survival and flow data, personal communications with Pacific Northwest National Laboratory (PNNL) staff (Brian

Bellgraph and Ryan Harnish email correspondence, September 30, 2014), and Table D.1 in Harnish et al. (2012, p. D-3), and

2) to include the NPUA flow augmentation period, which is typically May to July. This time horizon reflects the possibility that benefits from flow augmentation could begin as early as March, although managers may be constrained in the use of augmented flows under status quo operating rules.

Daily average regulated and ‘natural’ flows (Figure 3.2a,b) at Priest Rapids Dam are from Bonneville Power Administration’s 2010 Level Modified Streamflow study in cubic feet per second (cfs) – the former represent actual gauge observations, while the latter are the closest publicly available approximations of Columbia River flows in the absence of dams and represent unregulated flows adjusted to account for the fact that irrigation diversion and evaporation would still occur without dams in place (BPA 2010). From the Bonneville Power Administration study, we also acquired daily irrigation diversions (Figure 3.2e) between Grand Coulee and Priest Rapids in cfs. For all seven dams in this stretch of the mainstem, monthly power generation (Figure 3.2d) in megawatt hours (MWh) is from USEIA (2018). We summed BPA flows and irrigation diversions from 44 years between 1953-2008, and power generation data from 19 of those years between 1979-2000 to get total March to July amounts converted to million-acre feet (MAF) and gigawatt hours (GWh) respectively. While power generation data are available from USEIA from 1970, full capacity was not installed between the Canada-US border and Hanford Reach until 1979.

We calculated annual Chinook egg-to-pre-smolt survival (Figure 3.3c) using outputs for the same 44 years (1953-2008) from the Pacific Northwest National Laboratory’s (PNNL) HierARCHY model (Bellgraph and Perkins 2012). HierARCHY simulations return the annual population remaining in Hanford Reach, number of juveniles that migrated from the reach, and the total number of eggs laid per year. We divided the sum of population and migrants by total eggs to obtain annual egg-to-pre-smolt survival rates. Figure 3.2 shows frequency distributions for all input data.

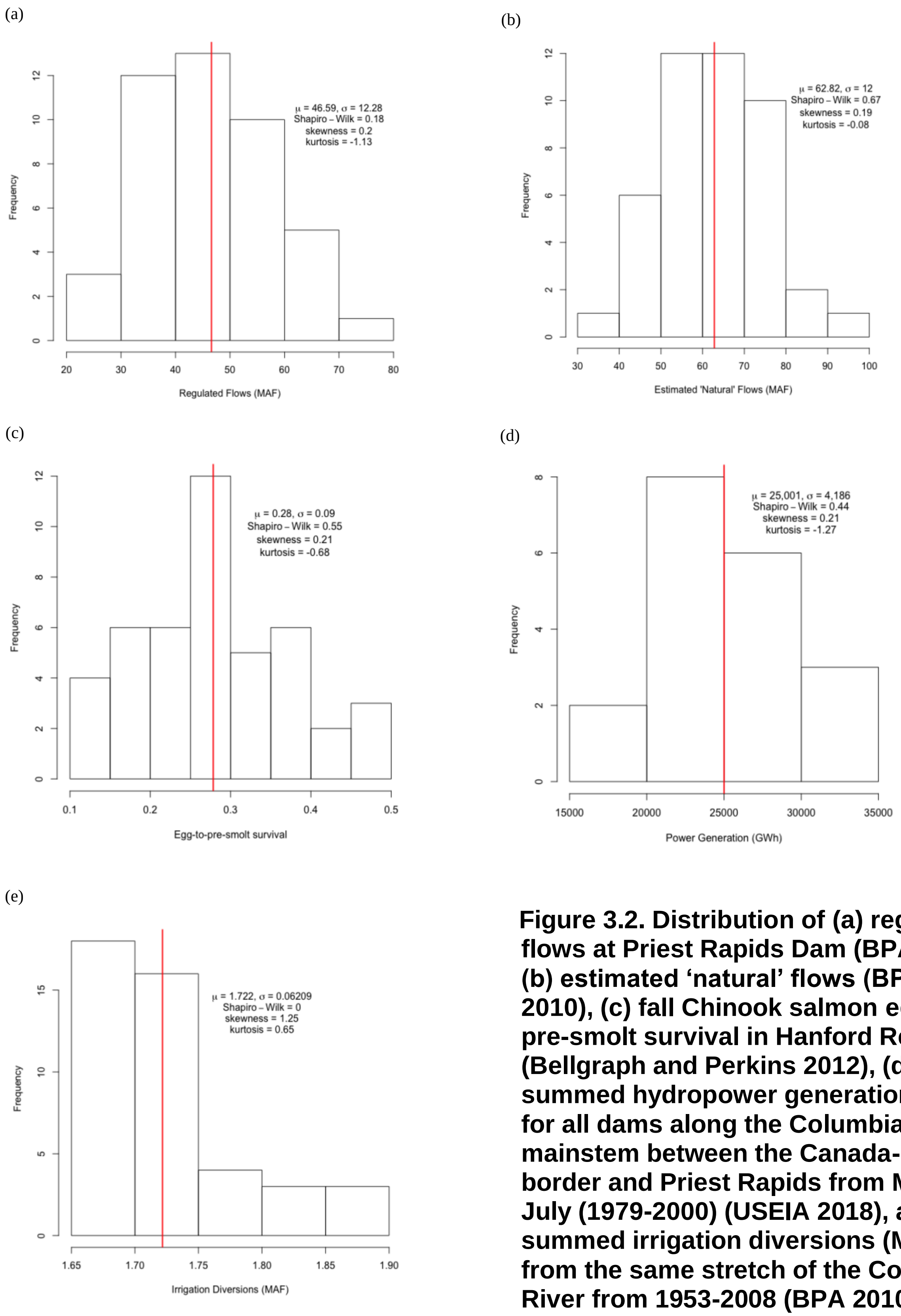

Figure 3.2. Distribution of (a) regulated flows at Priest Rapids Dam (BPA 2010), (b) estimated 'natural' flows (BPA 2010), (c) fall Chinook salmon egg-to-pre-smolt survival in Hanford Reach (Bellgraph and Perkins 2012), (d) summed hydropower generation (GWh) for all dams along the Columbia River mainstem between the Canada-US border and Priest Rapids from March to July (1979-2000) (USEIA 2018), and (e) summed irrigation diversions (MAF) from the same stretch of the Columbia River from 1953-2008 (BPA 2010).

3.3.3. Utility forecasts

Salmon Utility

Using a variation of the Ricker stock-recruit model (Ricker 1975, Ricker 1954) that links changes in regulated flows at Priest Rapids Dam with adult escapement to Hanford Reach, we define salmon utility as the expected number of returning adult fall Chinook at equilibrium abundance, or carrying capacity (*K*).[15] The modelling procedure for salmon utility is composed of three main steps: (1) predict pre-smolt survival rates given regulated flows using the available input data shown in Figures 3.2a and 3.2c to develop a functional relationship, (2) predict the pre-smolt population at equilibrium using a variation of the Ricker model, and (3) estimate smolt-to-adult survival (including fisheries exploitation) and adult escapement given predicted pre-smolt populations.

To account for uncertainty in the egg-to-pre-smolt relationship with flow, we developed the egg-to-pre-smolt survival model using Bayesian regression with a quadratic functional form and uninformative, normally distributed priors (Eq. B.4, Appendix B). We chose a functional form with one linear and one quadratic term based on preliminary tests of linear and quadratic forms, where the latter were assessed with and without a linear modifier. To make detecting a survival-flow relationship easier (compare the raw data points in Figure 3.4b and Figure 3.4a) and to account for the potential influence of the unregulated flow regime, we performed our regression on log transformed survival data that are also transformed by ‘natural’ flows (*Qnat*) (Eq. B.3, Appendix B). We then back-transformed the outputs using the inverse log (Eq. B.5, Appendix B) and the relationship between regulated flows (*Qreg*) and *Qnat* defined by the equation shown in Figure 3.4 (also Eq. B.2, Appendix B). Upon back-transformation, only our chosen quadratic form with the linear modifier provided biologically plausible results. Figure 3.5(b) shows the full range of models with median, 95% and 50% credibility intervals resulting from 15,000 Bayesian

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[15] *Equilibrium is the abundance at which a population is in balance such that it does not increase or decrease from generation to generation (c.f. Haak 2000; Vandermeer and Goldberg 2013). For salmon populations, equilibrium abundances tend toward carrying capacity (K), or the maximum individuals the environment can support. This attraction to K is driven by both density-dependent (compensatory and depensatory) and density-independent causes of mortality (Ricker 1954). Equilibrium abundances can change due to new environmental conditions that affect K (e.g., flow volumes). In the Ricker model, equilibrium abundance is non-linear with respect to K.*

results. A separate frequentist regression determined an r_2 of 0.57 on the expected curve prior to back-transformation.

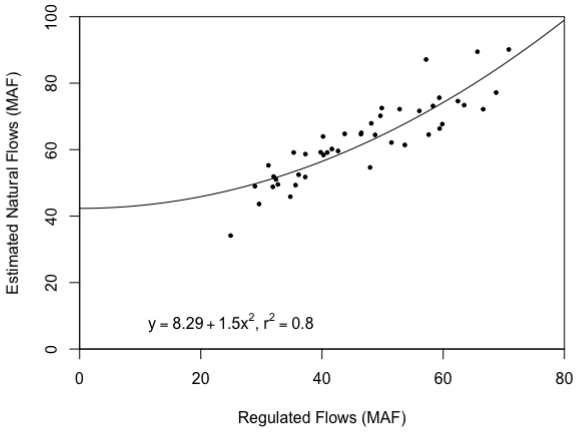

Figure 3.3. Functional relationship between estimated natural flows (Qnat) and regulated flows (Qreg). R-squared = 0.80.

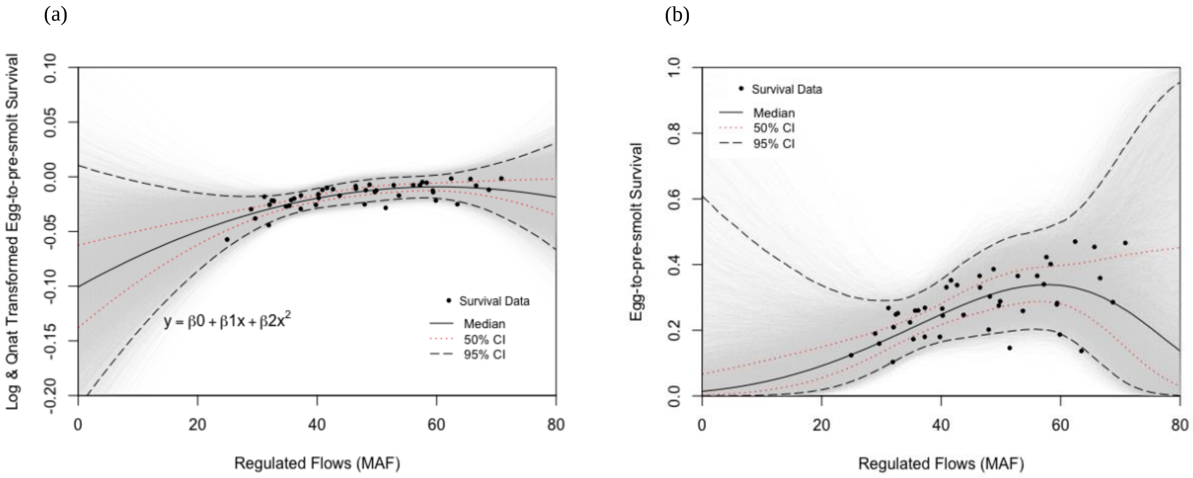

Figure 3.4. Bayesian regression results with median and credibility intervals (95%, 50%) for (a) transformed and (b) back-transformed egg-to-pre-smolt survival vs. regulated flows in Hanford Reach (n=15,000). Frequentist r-squared for expected curve prior to back-transformation = 0.57.

Next, we used the pre-smolt survival rates from the full suite of Bayesian models as inputs to a variation of the Ricker model to simulate the equilibrium pre-fishery recruits from the Hanford Reach population across the range of possible survival-flow models (Eq. B.6, Appendix B) (Cooper 2008; Ricker 1975; Ricker 1954). The Ricker model has been used previously for stock-recruit analysis of Columbia River fall-Chinook and provided the best fit to the Hanford Reach population when compared to Beverton-Holt and Smooth Hockey Stick models (Harnish et al. 2014). We obtained egg-to-adult density dependence and maximum egg-to-adult survival parameters for the Ricker model (b = -1.078e-08, a = 0.00451228) from a PNNL study conducted for Grant County Public Utility District (Ryan Harnish, PNNL, pers. comm., March 31, 2014). The fecundity parameter value is based on the age-3 estimates used by HierARCHY ($\bar{f}$= 3811 eggs/female). Preliminary investigation revealed relatively high model sensitivity to the Ricker a parameter, so we conducted sensitivity analyses of final multi-attribute utility results across a range of a values as well as b and $\bar{f}$ parameters (Appendix C). Using the base parameters, the expected number of pre-fishery recruits at equilibrium for regulated flows between 40 and 70 MAF (the majority of observed regulated flows fall in this range – see Figure 3.2) is approximately 150,000 fish (Figure 3.5(a)).

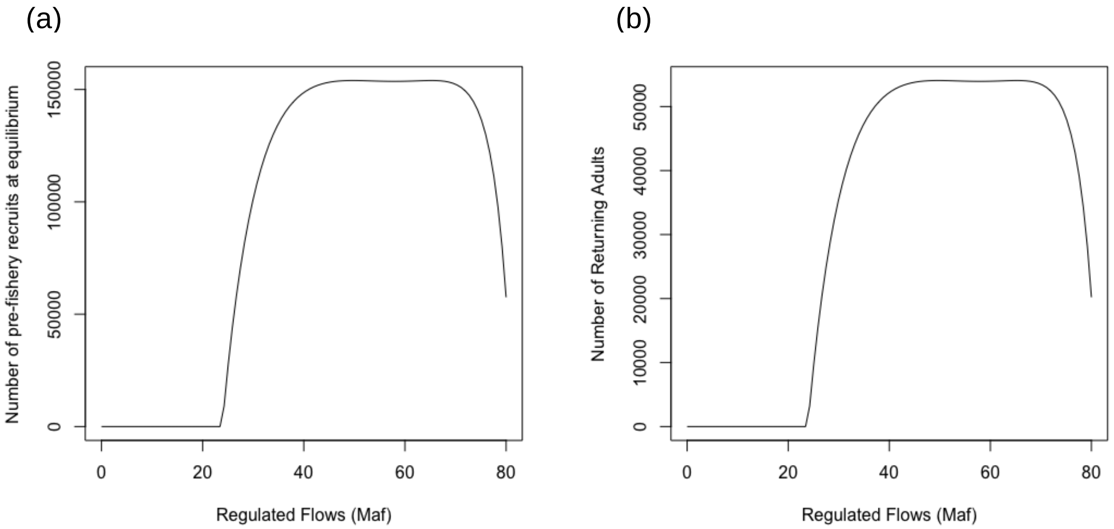

Figure 3.5. (a) Number of pre-fishery recruits to the Hanford Reach Chinook salmon population at equilibrium vs. regulated flows at Priest Rapids Dam (median Bayesian results), and (b) number of adult Chinook salmon returning to Hanford Reach (escapement).

Lastly, we estimated adult escapement by adjusting equilibrium pre-fishery recruits to account for ocean survival (*oc*) at a rate of 0.8 (Ryan Harnish, PNNL, pers. comm., December 30, 2014), average ocean (*h1*), downriver (*h2*) and upriver (*h3*) proportional harvest rates (0.1640, 0.2165, and 0.0689 respectively) (ODFW, WDFW 2002), and finally an inter-dam survival rate (*int*) of 0.759 (Harnish et al. 2014) (Eq. B.7, Appendix B). Again using the base parameters, for regulated flows between 40 and 70 MAF the expected number of adult fall Chinook returning to Hanford Reach at equilibrium is approximately 50,000 fish (Figure 3.5(b)). These escapement numbers are also roughly consistent with those reported by Hillborn and Walters (1992) and Hoffarth (2010), where, respectively, the estimated escapement of age-3 adult equivalents from 1975-2004 was ~44,000 adults, and the average adult escapement from 1975-2010 was ~41,000 adults (Harnish et al. 2012). Harnish et al. also report a maximum estimate of ~53,000 spawners in Hanford Reach prior to implementation of the Vernita Bar Settlement Agreement (VBSA) (Brood Year 1975-1988), and ~40,000 spawners post-VBSA (Brood Year 1989-2004). We normalized the equilibrium values from 0 to 1 to represent utility from salmon given regulated flows. Note that this approach to estimating utility does not consider possible differences in utility between wild and hatchery raised fish. Two hatcheries contribute to Hanford Reach fall Chinook salmon escapement – Priest Rapids and Ringold Springs hatcheries. The average proportion of hatchery-origin fall Chinook salmon that spawned in Hanford Reach from 1975 through 2009 was 8.4% (Harnish et al. 2014).

Hydropower production utility

We calculated utility from hydropower production as the sum of power generated from March to July by all seven dams upstream of Hanford reach to the Canadian border, normalized from 0 to 1. Similar to the pre-smolt survival model, we use a Bayesian regression model with a quadratic functional form and normally distributed, uninformative priors (Eq. B.8, Appendix 3.B). Unlike the survival model, the hydropower model does not utilize a *Qnat* transformation. The dams are designed specifically to produce consistent power to meet electricity demand regardless of natural flows, so transforming by natural flows results in a relatively flat curve (i.e., the dams are doing their job, so the relationship with Qnat transformed flows is essentially a straight line – hydropower production remains constant). Figure 3.6 shows the full range of hydropower-flow models with median, 95% and 50% credibility intervals resulting from 15,000 Bayesian parameter outputs. A separate frequentist regression determined an r_2 of 0.96 on the expected curve.

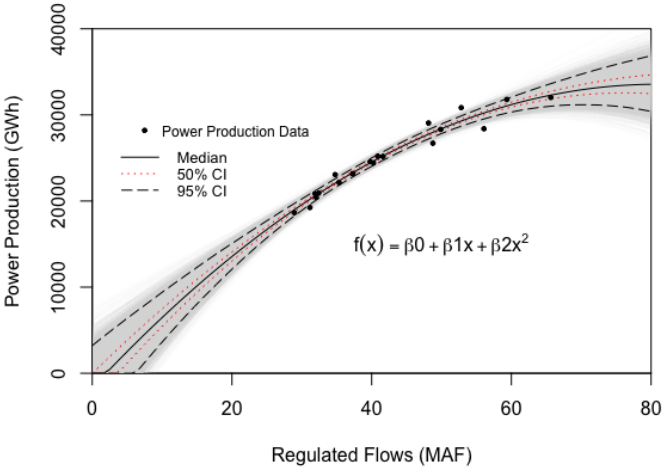

Figure 3.6. Relationship between power production (GWh) and regulated flows (MAF) at Priest Rapids Dam. Bayesian regression results are shown (n=15,000) with median and credibility intervals (95%, 50%. Frequentist r-squared for expected curve = 0.96

Irrigation diversion utility

We define utility from irrigation diversions as the normalized (0 to 1) sum of diverted flow volumes from March to July from the portion of the Columbia River from and including Franklin D. Roosevelt Lake (the main source of irrigation diversions) downstream to Priest Rapids Dam. Untransformed irrigation diversions do not have a detectable relationship with regulated flows since the latter are intended to supply a relatively consistent level of diversions year-to-year, so transforming the data by Qnat is useful in this case because it permits detection of a relationship by accounting for the incremental difference between diversions under regulated and unregulated conditions, thereby capturing the effect of annual variations in natural inflows. As expected, Qnat adjusted irrigation diversions decline during wetter years (Figure 3.7(a)), but once backtransformed remain relatively constant, reflecting the fact that the annual volume of diversions from the mainstem between March and September is kept fairly uniform by the regulated system (Figure 3.7(b)). Given this relationship, we expected comparatively minor trade-offs for irrigation. As with the other two valued components, we used a Bayesian regression model with a quadratic functional form and normally distributed, uninformative priors (Eq. B.9, Appendix 3.B). We found that a quadratic function with no linear modifier performed best during preliminary frequentist trials, with an r_2 of 0.74 on the expected curve. Figure 3.7(b) shows the full range of back-transformed (Eq. B.10, Appendix 3.B) irrigation-flow models with median, 95% and 50% credibility intervals resulting from 15,000 Bayesian parameter outputs.

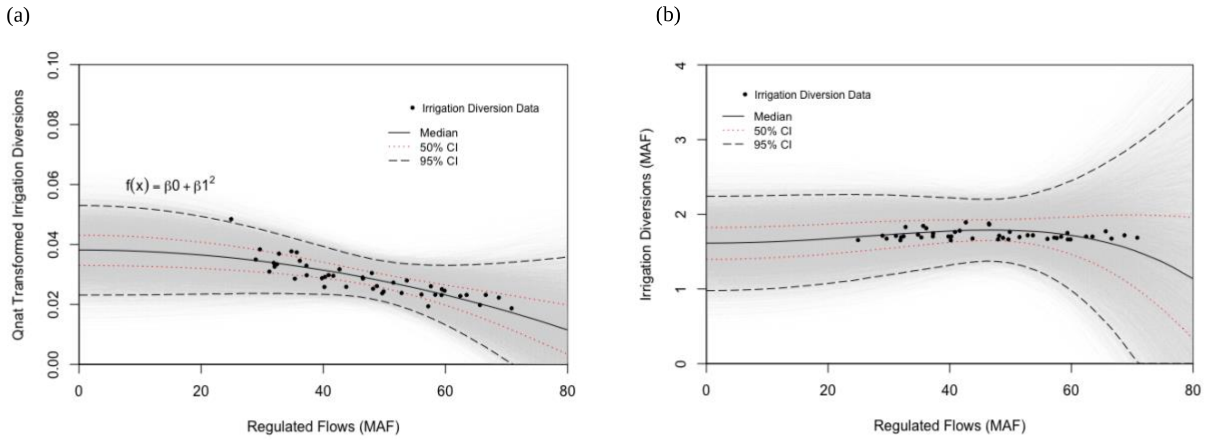

Figure 3.7. Bayesian regression results with median and credibility intervals (95%, 50%) for transformed (a) and backtransformed (b) irrigation diversions (MAF) vs. regulated flows (MAF) at Priest Rapids Dam (n=15,000). Frequentist r-squared for expected curve in figure (a) = 0.74.

3.3.4. Multi-attribute utility under different management priorities

We calculated multi-attribute utility as the sum of the normalized utility results across all three valued components (Eqs. B.11, B.12, B.13, Appendix 3.B) with weights applied to each individual utility curve to reflect a range of priority levels managers might place on each of salmon conservation, hydropower production and irrigation, respectively (i.e., a 'linear value model' Eq. B.14, Appendix 3.B). Multi-attribute utility normalizes individual utility outputs from each valued component to a common scale to simplify decision-making (Wheeler et al. 1998). Because the three utility curves are not in opposition to one another, there is a possibility of equifinality (i.e. multiple maximums). Due to the depensatory effects of density dependence, this is particularly possible in scenarios where salmon conservation is heavily prioritized, producing a slightly bimodal curve. However, in this case both hydropower and irrigation curves are unimodal, and depensatory effects are relatively small, which means that unless salmon conservation is prioritized one hundred percent, the other curves will offset depensation and a unique maximum will be available under each weighting scheme. To ensure a unique maximum in every case, and to rule out implausible prioritization schemes, we excluded all weight combinations that placed a priority of one hundred percent on any single valued component. We identified a total of 160 possible weight combinations where the total summed weight across all valued components was always equal to 1 with unique weights varying from 0.05-0.95 in increments of 0.05 (e.g., 0.35 / 0.60 / 0.05 for salmon, hydropower, and irrigation respectively), and one weight set representing perfect balance (i.e.,$0.\overline{33}$ / $0.\overline{33}$ / $0.\overline{33}$). We applied all possible weight combinations to each of the 15,000 normalized curves from each valued component's Bayesian outputs to acquire a distribution of weighted multi-attribute utility under all prioritization schemes. We then split these results into 'prioritization categories' (salmon, hydropower, irrigation, balanced), where multi-attribute utility outputs were assigned to a category if the difference in weighting factors for a given valued component was greater than or equal to 0.2 relative to other valued components. If the difference was less than 0.2, we categorized the weighting scheme as 'balanced'. For example, a weighting scheme such as 0.35 / 0.60 / 0.05 for salmon, hydropower and irrigation respectively would be assigned to the hydropower priority category, while a weighting scheme such as 0.35 / 0.35 / 0.30 would be assigned to the balanced priority category (i.e., the weights are relatively similar for each valued component). To better understand the impact of balanced versus imbalanced prioritization schemes on multi-attribute utility outcomes, we also created a 'Trade-off Balance Index', which is the normalized (0 to 1) product of the weights assigned to each valued component such that a highly imbalanced weighting scheme like 0.05 / 0.90 / 0.05 would be close to 0 while a more balanced weighting scheme would be close to 1 (see Figure 3.9).

3.3.5. Optimal flow, historical performance, and flow augmentation alternatives

Optimal flow is defined as the regulated flow volume at maximum multi-attribute utility (Eq. B.15, Appendix 3.B). We calculated this value for all weight/model combinations (2.4 million in total) and used the same procedure described above to split results into prioritization categories. Using a frequentist version of the model, Figure 3.8 illustrates example outputs for different prioritization extremes. We used median optimal flow values from the weight/model combination outputs to assess historic performance across the 44 study years for both regulated and unregulated flows. Under each prioritization category for years with sufficient unregulated flows but insufficient regulated flows, we also calculated the median, minimum and maximum flow augmentation values that would have been needed historically to meet optimal flows. After multi-attribute utility values and optimal flows were estimated for each weight combination, we used the optimal flow results and each valued component's relationship with flows to convert the utility value back to individual unit values for ease of interpretation.

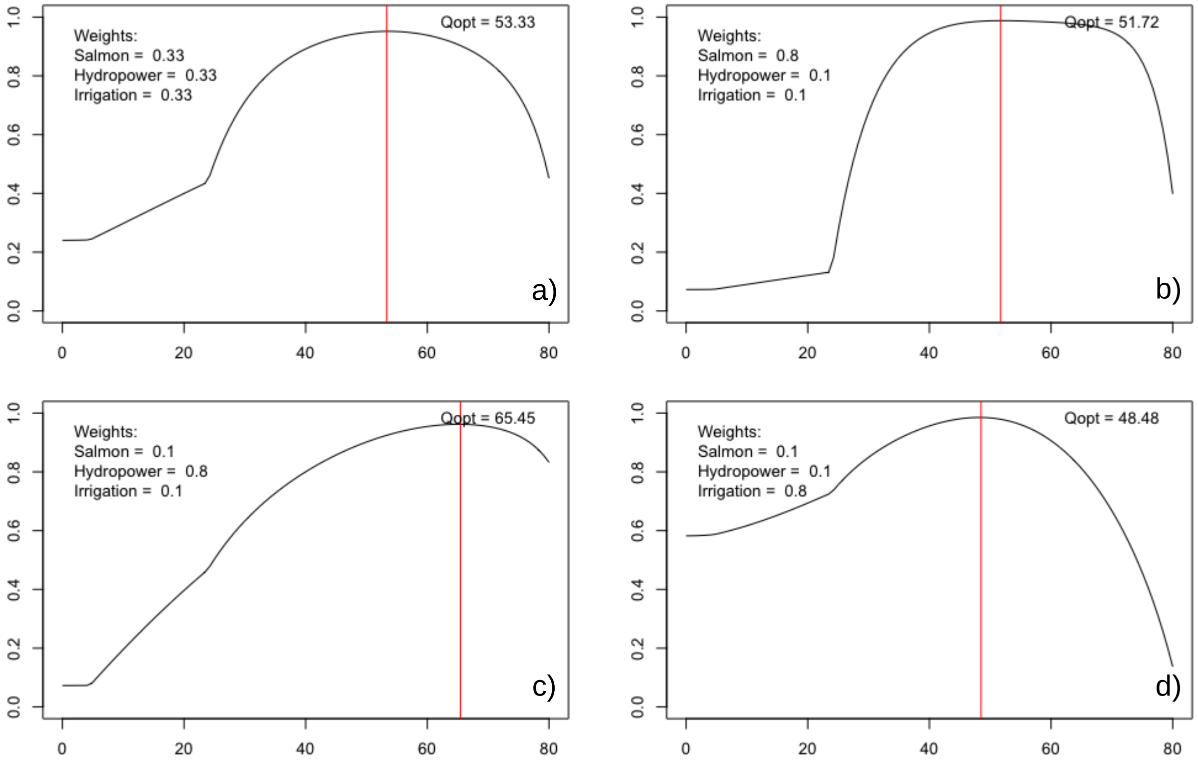

Figure 3.8. Example multi-attribute utility curves with optimal regulated flows indicated (red line) for (a) perfectly balanced weighting across the three valued components, and high prioritization of (b) salmon conservation, (c) hydropower priority, and (d) irrigation diversions.

Finally, we randomly sampled 1,000 models from each valued component's Bayesian model set (N=15,000) and for each prioritization category we generated a subset of all data to include only years after the first Non-Power Uses Agreement was implemented (1995-2008). We then calculated predicted benefits from different flow augmentation alternatives. We considered ten augmentation volumes from 1-10 MAF above the current augmentation level of 1 MAF and summed all years that would have benefitted in terms of the additional flow volume's effect on multi-attribute utility. These results represent years where multi-attribute utility improvements are *in addition* to that already achieved by existing flow augmentation efforts *if* the given prioritization category was the preferred management approach across those years.

Similarly, we calculated cumulative incremental net benefits over the twelve years to salmon, hydropower and irrigation under each augmentation alternative and used these values to identify the best flow augmentation scenario depending on prioritization preferences and based on the following criteria: 1) the lowest flow augmentation volume (Criterion 1), 2) the highest total net incremental benefit (Criterion 2), and 3) the most even distribution of benefits across all three valued components (Criterion 3). For each of the three criteria we developed a normalized index value and summed these using different weights to get a final score depending on how each criterion was prioritized.

3.3.6. Uncertainty

The methods described above rely on a Bayesian approach to model uncertainty about the true relationship between each of the three valued components and regulated flows. Using Bayesian outputs, we report credibility intervals associated with our results in Table 3.1 and Table 3.2. However, relying on historic valued component and flow observations as indicators of future responses assumes a level of stationarity that is unrealistic given climate change projections for the region (Miles et al. 2000, Mantua et al. 2010, Hamlet 2011, Rupp et al. 2016, Rajagopalan et al. 2018). To better understand these uncertainties, for each of the three valued components we selected the five Bayesian curves representing the median, and upper/lower 95% and 50% credibility intervals and, for each curve, simulated 60 years of new ‘observed’ data given four different coefficients of variation ranging from 0.1-0.4 (Eqs. B.16, B.17, Appendix 3.B). For each of the five Bayesian curves, these steps resulted in four 60-year datasets (one for each *cv* value, twenty simulated datasets in total). In Appendix 3.C, Appendix 3.D, and Appendix 3.E we provide a graphical representation of these sensitivity results, which permits an assessment of how each of the three utility~flow relationships are affected by uncertainty.

Uncertainty also exists regarding the fish population model parameters, which are not included in the Bayesian component ($a, b, \bar{f}, h1, h2, h3, int, oc$). For each of these parameters, we performed additional sensitivity analyses using ±20% of each parameter value as new inputs and holding all other parameters constant (sixteen model runs). We report the impact of these results on optimal flows, multi-attribute utility, feasibility, and required flow augmentation in Appendix 3.F.

3.4. Results

3.4.1. Optimal flows and effects on multi-attribute utility of different prioritization alternatives

Our results suggest an optimal March-July flow volume in Hanford Reach ranging from 50.10 to 63.84 MAF depending on which valued component is prioritized (nearly a 14 MAF difference across management priorities) (Table 3.1). For example, a median optimal hydropower production of 31,839 GWh[16] (hydropower priority) would require a median optimal flow of 63.84 MAF in Hanford Reach from March to July. To achieve a median optimal salmon conservation benefit of 53,942 returning adults (salmon priority), a median optimal flow of 56.57 MAF would be needed.

Table 3.1. Effect of different prioritization schemes on optimal flows and maximum benefits from salmon conservation, hydropower production and irrigation diversion March – July (n=465,000 for all priority categories except Balanced: n=195,000). Median and 95% credibility intervals are shown.

	Optimal total regulated flow Mar-Jul (MAF)		**Equilibrium Chinook salmon** (# adults)		**Hydropower production** (GWh)		**Irrigation diversion** (MAF)	
*Priority**	*median*	*95% CI*	*median*	*95% CI*	*median*	*95% CI*	*median*	*95% CI*
Salmon	56.57	39.60 80.00**	53,942	49,939 54,068	30,365	24,385 34,281	1.751	1.066 2.746
Hydropower	63.84	53.33 80.00**	52,701	0 54065	31,839	29,538 35,437	1.619	0.744 3.174
Irrigation	50.10	33.13 80.00**	52,446	0 54064	28,648	21,579 35,256	1.908	1.431 3.459
Balanced	55.76	42.83 80.00**	53,427	44,850 54,067	30,140	25,927 34,590	1.810	1.294 3.015

**For each valued component, priority is assigned if the difference in weighting factors is greater than or equal to 0.2 relative to other valued components. If the difference is less than 0.2, the weighting scheme is categorized as balanced.*

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[16] All valued component unit-results are calculated from the multi-attribute utility values

***Regulated flows are limited to the maximum of the product between natural flows and the ratio of regulated to natural flows ($max(Qnat \times Qreg/Qnat)$), rounded up to the nearest ten.*

Optimal flow volumes vary widely within the 95% credibility interval. The upper and lower bounds for median optimal flows under each prioritization category are across all weight combinations. Under salmon prioritization, for example, upper and lower 95% CI results are selected from all 31 weight combinations from the extreme (e.g. 0.90/0.05/0.05), to the less extreme (e.g. 0.55/0.25/0.20) applied to all 15,000 Bayesian outputs (n=465,000). Uncertainty in optimal flows is therefore a function of uncertainty in the 'true' sub-model as well as the range of possible levels of trade-off with other valued components. We limit the upper 95% CI to 80 MAF to exclude physically implausible credibility intervals.

For individual valued components, the difference in maximum values between highest and lowest median results across all prioritization categories is 1,496 adult salmon, 3,191 GWh of power generation, and 0.289 MAF of irrigation diversions annually (Table 3.1). For the balanced prioritization category, the difference from the maximum for each valued component is relatively small at 515 adult salmon, 1,699 GWh of power generation, and 0.098 MAF of irrigation diversions (Table 3.1). Results are particularly uncertain for salmon under hydropower and irrigation prioritization categories, which show a lower 95% credibility bound of 0 adults.

The sub-model most sensitive to simulated uncertainty in flows is the egg-to-pre-smolt~Qreg survival relationship. Visual assessment of plots shown in Appendix 3.C through Appendix 3.E show that the hydropower~Qreg and irrigation~Qreg relationships are more sensitive at the higher end of the Qreg range (Appendix 3.D and Appendix 3.E, see 'Cv=0.4' columns), while the salmon survival sub-model is more sensitive in the middle range (Appendix 3.C, see 'Cv=0.4' column) where regulated flows most frequently occur historically (see Figure 3.2).

We also tested for uncertainty in the location and functional form of each sub-model using the upper/lower 50% credibility intervals of each valued component's single-attribute utility outputs (see Figure 3.4, Figure 3.6, and Figure 3.7 and Appendix 3.C through Appendix 3.E). Using the output data corresponding to these credibility intervals, we generated new results reported in Appendix 3.F. Optimal flows are most sensitive to either a downward shift in the egg-to-pre-smolt~Qreg relationship, or an upward shift in the irrigation~Qreg relationship, resulting in a 6.5 MAF decrease, or a 5.7 MAF increase in optimal flows respectively. Irrigation and hydropower are most sensitive to upward or downward shifts in the irrigation~Qreg relationship, either decreasing with the former or increasing with the latter. Salmon conservation utility is most sensitive to changes in the hydropower~Qreg relationship, with shifts in either direction resulting in an increase.

This increase in salmon conservation benefits (1,606 fish) is small compared to the potential effects of uncertainty in the Ricker stock-recruit model's parameter values. Appendix 3.F shows the effects of a ±20% change in each of these parameters (all other parameters held constant). Compared to the base case, a ±20% change in the sub-model's parameter values would either increase the number of returning adults by ~600-19,000 or decrease this number by ~600-24,000 depending on which parameter is varied. The model is most sensitive to changes in the ocean survival rate (oc) (increases or decreases), followed by decreases in the Ricker density dependence parameter (b), and changes in the downriver ($h2$) and ocean ($h1$) harvest rates. With these sensitivities acknowledged, to simplify subsequent analyses, we use only the base data, functional forms and sub-model parameters.

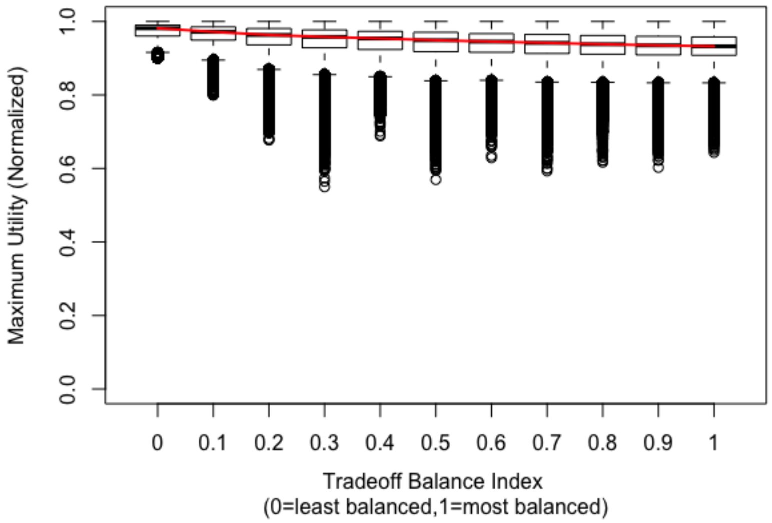

Figure 3.9. Effect on maximum multi-attribute utility of 'trade-off balance' across the three valued components. The Trade-off Balance Index is the normalized product of weights assigned to each component (e.g. a highly imbalanced weighting scheme such as 0.05 / 0.90 / 0.05 for salmon, hydropower and irrigation respectively would be close to 0 while a more balanced weighting scheme such as 0.35 / 0.35 / 0.30 would be close to 1). The red line indicates the median value across all box and whisker plots.

Figure 3.9 applies a Trade-off Balance Index to show that as prioritization of each valued component becomes increasingly balanced, maximum multi-attribute utility declines slightly. The Index is the normalized product of weights assigned to each component. For example, a highly imbalanced weighting scheme such as 0.05 / 0.90 / 0.05 for salmon, hydropower and irrigation respectively would have an Index value close to 0 while a more balanced weighting scheme such as 0.35 / 0.35 / 0.30 would be close to 1. Certainty in the results is greater near the imbalanced end of the scale, indicating that prioritization of a single valued component may provide slightly greater protection against uncertain multi-attribute utility outcomes.

3.4.2. Historical performance

The median flow augmentation required to achieve optimum flow during years that were physically capable of meeting optimal flows ranges from 9.23 to 10.66 MAF depending on the management priority (Table 3.2). For a balanced priority across all three valued components, the optimum flow volume (55.76 MAF) would have been physically possible during 73% of historical years but was only actually met during 30% of those years. Meeting optimal flow under the irrigation management priority is the most feasible historically, with 84% of years physically capable of meeting the 50.10 MAF target, and 36% of those years actually meeting that target. Accomplishing the same under a hydropower management priority is the most difficult, with 50% of years physically capable of meeting the 63.84 MAF optimum and only 9% of those years actually meeting that optimum. Optimizing under a salmon conservation priority would require 56.57 MAF, which was possible 70% of the time but only achieved 27% of the time.

Table 3.2. Historic performance for optimal flows at Priest Rapids Dam March – July (1953-2008) under different prioritization assumptions, and, for years with sufficient natural flows, flow augmentation needed to meet optimal regulated flow volumes

Priority	**Optimal flow (median)** (MAF)	**Years met or surpassed by Qnat** (n=44)	**Years met or surpassed by Qreg**	**Augmentation of Qreg needed to achieve optimal flow*** **median** (min, max)
Salmon	56.57	70% (31)	27% (12)	10.13 (0.5,21.23)
Hydropower	63.84	50% (22)	9% (4)	9.40 (0.37,23.66)
Irrigation	50.10	84% (37)	36% (16)	9.23 (0.23,18.93)
Balanced	55.76	70% (31)	30% (13)	10.66 (2.08,20.42)

**For years with sufficient natural flows but insufficient regulated flows to meet optimal flow*

3.4.3. Benefits from flow augmentation alternatives

Using a sub-sample of 1,000 parameter sets from each valued component's joint Bayes posterior, Table 3.3 reports results for a range of flow augmentation alternatives from 1-10 MAF to illustrate benefits associated with sub-optimal flow augmentation alternatives under each prioritization category. We report results for each valued component as the incremental benefit accrued over a twelve year period from 1995-2008 (i.e., after onset of NPUA implementation) relative to the base case of zero additional flow augmentation (above the 1 MAF annual augmentation currently provided). Over the twelve year period, meeting any of these flow augmentation targets would have been physically feasible in terms of available natural flows, but the targets were not necessarily met by regulated flows which are designed to adhere to a range of operating constraints including flood control. Based on median results (n=1,000) under all prioritization categories, most flow years from 1995-2008 would have benefitted across all three valued components from smaller increments of additional flow augmentation than those needed to reach optimal flows. For example, over the twelve years under the salmon prioritization category, an additional flow augmentation volume of 2 MAF annually would have achieved a cumulative 6,328 more adult Chinook salmon compared to a 0 MAF augmentation scenario, while also providing improved benefits for hydropower and irrigation (see scenario ID 2 in Table 3.3).

Table 3.3. Benefits from flow augmentation alternatives (1-10 MAF) for 12 years after the onset of NPUA implementation (1995-2008) (i.e, augmentation of historic regulated flows that include the 1MAF of augmentation when utilized). The proportion of years with sufficient unregulated flows is shown (100% in all cases), as is the proportion of years that would have benefited from increases to regulated flows. Valued component results are the median net incremental benefit for each valued component over the twelve-year period relative to zero additional flow augmentation over the same period (n=1000).

ID	**Augmentation (MAF)**	*Years with sufficient unregulated flows*	*Years that would have benefitted*	*Annual incremental benefit relative to zero flow augmentation case* (median, n=1000)		
		1995-2008 (median) (n=12)		**Salmon** (# adults)	**Hydropower** (GWh)	**Irrigation** (MAF)
	Salmon Conservation Priority					
1	1	100% (12)	83% (10)	3,620	880	0.002
2	2	100% (12)	83% (10)	6,328	1,423	0.004
3	3	100% (12)	83% (10)	8,177	1,586	(0.001)
4	4	100% (12)	83% (10)	9,399	1,392	(0.012)
5	5	100% (12)	83% (10)	10,281	1,066	(0.024)
6	6	100% (12)	83% (10)	10,507	625	(0.03)
7	7	100% (12)	83% (10)	10,286	181	(0.051)
8	8	100% (12)	83% (10)	9,495	(222)	(0.074)
9	9	100% (12)	75% (9)	8,520	(810)	(0.11)
10	10	100% (12)	75% (9)	7,059	(1,262)	(0.153)

ID	**Augmentation (MAF)**	*Years with sufficient unregulated flows*	*Years that would have benefitted*	*Annual incremental benefit relative to zero flow augmentation case* (median, n=1000)		
		1995-2008 (median) (n=12)		**Salmon** (# adults)	**Hydropower** (GWh)	**Irrigation** (MAF)
	Hydropower Production Priority					
11	1	100% (12)	92% (11)	2,447	2,997	0.004
12	2	100% (12)	92% (11)	4,886	5,726	0.012
13	3	100% (12)	92% (11)	6,933	8,201	0.018
14	4	100% (12)	92% (11)	8,710	10,432	0.015
15	5	100% (12)	92% (11)	10,327	12,376	0.016
16	6	100% (12)	92% (11)	11,787	14,166	0.01
17	7	100% (12)	92% (11)	13,243	15,760	0.003
18	8	100% (12)	83% (10)	14,446	17,182	0.003
19	9	100% (12)	83% (10)	15,482	18,369	(0.006)
20	10	100% (12)	83% (10)	16,448	19,460	(0.012)

	Augmentation (MAF)	*Years with sufficient unregulated flows*	*Years that would have benefitted*	*Annual incremental net benefit relative to zero flow augmentation case* (median, n=1000)		
		1995-2008 (median) (n=12)		**Salmon** (# adults)	**Hydropower** (GWh)	**Irrigation** (MAF)
ID	*Irrigation Diversion Priority*					
21	1	100% (12)	83% (10)	1,352	1,213	0.118
22	2	100% (12)	75% (9)	2,418	2,472	0.212
23	3	100% (12)	75% (9)	3,438	3,785	0.271
24	4	100% (12)	75% (9)	4,038	5,072	0.305
25	5	100% (12)	75% (9)	4,810	6,287	0.308
26	6	100% (12)	75% (9)	4,973	7,633	0.296
27	7	100% (12)	75% (9)	5,099	8,996	0.266
28	8	100% (12)	75% (9)	4,752	10,380	0.220
29	9	100% (12)	75% (9)	4,395	11,688	0.136
30	10	100% (12)	58% (7)	4,426	12,935	0.055

	Augmentation (MAF)	*Years with sufficient unregulated flows*	*Years that would have benefitted*	*Annual incremental net benefit relative to zero flow augmentation case* (median, n=1000)		
		1995-2008 (median) (n=12)		**Salmon** (# adults)	**Hydropower** (GWh)	**Irrigation** (MAF)
ID	*Balanced Priority*					
31	1	100% (12)	83% (10)	1,823	1,509	0.029
32	2	100% (12)	83% (10)	3,363	2,629	0.061
33	3	100% (12)	83% (10)	4,359	3,298	0.086
34	4	100% (12)	83% (10)	5,322	3,515	0.098
35	5	100% (12)	83% (10)	6,269	3,491	0.098
36	6	100% (12)	83% (10)	6,558	3,161	0.099
37	7	100% (12)	83% (10)	6,816	2,773	0.093
38	8	100% (12)	83% (10)	6,612	2,219	0.073
39	9	100% (12)	83% (10)	6,302	1,539	0.051
40	10	100% (12)	75% (9)	6,100	859	0.022

3.4.4. Multi-criteria assessment of management alternatives

Each prioritization/augmentation combination comes with different trade-offs in terms of a) volume of additional flow augmentation required (Criterion 1), b) total additional multi-attribute utility generated (Criterion 2), and c) evenness of the benefits distribution across the three valued components (Criterion 3)[17]. Table 3.4 shows results after applying different weights to normalized indices from these three criteria to select the top three prioritization/augmentation combinations given different emphases on each criterion (e.g., weights of 0.8 / 0.1 / 0.1 for Criteria 1-3 respectively represent a priority placed on Criterion 1 while weights of 0.1 / 0.8 / 0.1 represent a priority placed on Criterion 2). If all criteria are equally weighted or if the highest multi-attribute utility (Criterion 2) is viewed as most important, either the salmon or balanced prioritization categories combined with 3-5 MAF of additional flow augmentation would have provided the best multi-attribute utility outcomes over the 1995-2008 flow years. If the least additional flow augmentation (Criterion 1) is the priority, then irrigation, salmon or balanced prioritization combined with 1 MAF of additional flow augmentation would be the best choice.

Table 3.4. Top three prioritization/augmentation combinations given different emphases placed on Criteria 1-3.

ID	Prioritiz-ation Category	Addt'l Flow Augmentation (MAF)	Increased benefits (Years)	Salmon (# adults)	Hydropower (GWh)	Irrigation (MAF)
Equally Weighted Criteria						
4	Salmon	4	83% (10)	9399	1392	(0.012)
35	Balanced	5	83% (10)	6269	3491	0.098
3	Salmon	3	83% (10)	8177	1586	(0.001)
Priority on Least Additional Flow Augmentation (Criterion 1)						
21	Irrigation	1	83% (10)	1352	1213	0.118
31	Balanced	1	83% (10)	1823	1509	0.029

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[17] We determined evenness by computing the average of the utility differences between all pairwise combinations of valued components within each prioritization category, and then normalizing the results across each prioritization category's set of ten flow augmentation alternatives. Higher normalized values represent more evenly distributed utilities across the three valued components.

ID	Prioritiz-ation Category	Addt'l Flow Augmentation (MAF)	Increased benefits (Years)	Salmon (# adults)	Hydropower (GWh)	Irrigation (MAF)
1	Salmon	1	83% (10)	3620	880	0.002
Priority on Highest Multi-attribute Utility (Criterion 2)						
4	Salmon	4	83% (10)	9399	1392	(0.012)
35	Balanced	5	83% (10)	6269	3491	0.098
3	Salmon	3	83% (10)	8177	1586	(0.001)
Priority on Most Evenly Balanced across Valued Components (Criterion 3)						
4	Salmon	4	83% (10)	9399	1392	(0.012)
35	Balanced	5	83% (10)	16799	20042	0.015
16	Hydropower	6	92% (11)	11787	14166	0.010

3.5. Discussion

Overall, our results indicate that potential salmon conservation, hydropower production, and irrigation benefits have not been fully exploited in the Columbia River between Grand Coulee Dam and Hanford Reach during the period from March through July each year. Under almost any prioritization category, achieving optimal flows in Hanford Reach would improve upon historic average utility values for each individual valued component. The optimal March-July flow volume in the Reach ranges from 50.10 to 63.84 MAF depending on which valued component is prioritized. Across all prioritization categories, median results for optimal utility translate to over 10,000 more fish annually (a 31-35% increase)[18], 3,650-6,800 GWh more hydropower (a 15-27% increase)[19], and 0.103 MAF less irrigation diversions (a 6% *decrease* – hydropower prioritization category only), or 0.029-0.186 more irrigation diversions (a 2-11% *increase* – all other prioritization categories). [20]

Proportionally, trade-offs between hydropower and irrigation are greater than those between hydropower and salmon conservation (Table 3.1). Irrigation benefits drop

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[18] Compared to the average estimated escapement of ~40,000 returning adults reported by Harnish et al. (2012)

[19] Compared to the 1979-2008 observed average of ~25,000 GWh (see Figure 3.2)

[20] Compared to the 1953-2008 average of ~1.7 MAF (see Figure 3.2)

by 15% (0.289 MAF) if hydropower is prioritized rather than irrigation, and hydropower benefits drop by 10% (3,191 GWh) if irrigation is prioritized rather than hydropower. Meanwhile salmon conservation benefits drop by only 2.5% (1241 adults) if hydropower is prioritized rather than salmon conservation and hydropower benefits drop by only 4.5% (1474 GWh) if the reverse is true. Comparing the maximum and minimum median results for each valued component (Table 3.1) also suggests that hydropower and irrigation have more to lose (proportionally) than salmon conservation if they are not prioritized (2.8% / 10% / 15% for salmon conservation, hydropower, and irrigation respectively).

We acknowledge that these proportional differences do not reflect market values or other types of value that may influence the importance of a particular valued component to decision-makers. For example, based on an estimated net welfare value of between $22.34-$34.35 per salmon (2013 USD, Morton et al. 2017; and see Chapter 2), an approximate net value of $27.65 per MWh of hydropower produced (2001 USD, Hamlet et al. 2002; FCRPS 2017),[21] and net benefits of between $11.5-$43.7 per acre-foot of irrigation diversions (2002 USD, Huppert et al. 2004), scenario ID 35 (see Table 3.3) would provide approximately $150-240 thousand in additional net economic welfare from salmon conservation, $96.5 million in additional net benefits from hydropower, and $1.54-$5.84 million in additional net benefits from irrigation diversions.[22] As shown in Table 3.1 and discussed in Section 3.3.4, our models allow for the possibility that decision makers may not assign relative importance to the valued components solely on the basis of market value. We account for such ‘values differences’ by assessing a wide range of priority weights applied to each valued component.[23]

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[21] We calculated net hydropower sales using gross sales of $25/MWh (2001 USD) reported in Hamlet et al. (2002) and averaged total costs of generation across Grand Coulee and Chief Joseph generating facilities of $7.54/MWh (2017 USD) reported in FCRPS (2017)

[22] Incremental benefits accumulated over twelve years, not discounted; all values adjusted to 2018 USD using the US GDP Implicit Price Deflator (FRED Economic Data 2019)

[23] If net economic welfare based on market values were the only prioritization measure of importance to decision makers, using the low-end values noted above for fish conservation and irrigation, the weights would be 0.36 / 0.45 / 0.19 for salmon conservation, hydropower, and irrigation respectively, and using the high-end values they would be 0.33 / 0.26 / 0.41. Resulting optimal flows would be 58.99 MAF for the first set of weights (# of returning adults = 53,565,

Optimal flows under a given prioritization category may not always be physically achievable. For all prioritization categories, Median optimal flows are higher than historical average regulated flows of 46.59 MAF from March-July, and, in the case of hydropower prioritization are also higher than historical average natural flows of 62.82 MAF (see Figure 3.2). Achieving optimal regulated flows under hydropower prioritization would have been impossible 50% of the time due to insufficient natural flows. For the remaining years, only 9% of regulated flows actually achieved or surpassed the optimum (see Table 3.2). The ability to physically achieve optimal flows is considerably higher for other prioritization categories (e.g. 84% of years for irrigation priority), although in all cases these optimums are still only realized by historical regulated flows less than 40% of the time. Historical regulated flows were most successful at meeting or surpassing optimal flows for irrigation and balanced prioritization strategies.[24] Other factors such as flood management, managing for optimal timing of flows for hydropower outside the March-July period, and US commitments under the Columbia River Treaty all have significant implications for the feasibility of optimizing regulated flows in Hanford Reach.

While different management priorities are associated with varying degrees of feasibility, differences in benefits across the four prioritization categories are relatively small and the benefits may even improve upon historical averages (Table 3.1). This finding suggests that optimizing for one of the more feasible priority categories (i.e., salmon conservation, irrigation, or balanced) would still result in fairly similar, possibly improved, benefits across all three valued components, a result reinforced by the trade-off index outcomes shown in Figure 3.9. For example, from a fish conservation perspective, since the wide 95% credibility intervals for salmon conservation under irrigation or hydropower prioritization suggest much higher uncertainty (Table 3.1), and since the balanced approach is associated with greater uncertainty in overall multi-attribute utility compared to prioritization of a single valued component (Figure 3.9), the salmon conservation priority category would be the most desirable management philosophy. In addition, achieving optimal flows under this prioritization approach would

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hydropower GWh = 31,089, diversions MAF = 1.70), or 53.33 MAF for the second set of weights (# of returning adults = 53,459, hydropower GWh = 29,473, diversions MAF = 0.938).

[24] Note that surpassing optimum would not maximize multi-attribute utility, but the capacity to do so shows that achieving optimum is physically possible

result in *improved* benefits from hydropower and irrigation compared to historical averages (+5,364 GWh, +0.029 MAF) during the March to July period.

An inability for the US to meet perfectly optimal flows due to physical constraints or prioritization of other values (e.g. flood management, timing of hydropower demand outside the March to July period) does not mean benefits cannot be achieved from lower flow augmentation volumes. For years where optimal flows were achievable but not realized, the average flow augmentation needed to reach optimal flows ranges from 9.23 – 10.66 MAF – substantially higher than the 1 MAF currently available under the Non-Power Uses Agreements (NPUAs) with Canada. Since meeting optimal regulated flows under any prioritization category has relatively low probability given historical operating practices, we suggest two main options for the US: (1) adjust existing US-based operations to permit higher flow volumes through Hanford Reach during the March to July period, or (2) maintain existing US-based operations and negotiate for additional flow augmentation from Canada. In this study, we focus on the latter option and assess if smaller augmentation volumes are worthwhile in terms of multi-attribute utility improvements. Our model suggests that, under all prioritization categories over a twelve-year period, improvements across all three valued components are possible from such smaller flow augmentation volumes (Table 3.3). We identify the best of these alternatives using a multi-criteria index based on: a) lowest flow augmentation required, b) highest multi-attribute utility achieved, and c) most even distribution of benefits across the three valued components (Table 3.4). If all criteria are equally weighted, pursuing either a balanced prioritization strategy or one that emphasizes salmon conservation along with 3-5 MAF of additional flow augmentation annually would best meet these three criteria, but if the US were primarily concerned with minimizing additional flow augmentation (criterion (a)), negotiating an additional 1 MAF under an irrigation, balanced, or salmon conservation priority would be the best approach.

3.6. Conclusion

In this study we assessed the potential benefits to salmon conservation, hydropower production, and agricultural irrigation from optimizing flows in Hanford Reach across these three valued components. Results suggest that optimal flows from March through July are rarely achieved in the Reach and that more benefit could be realized across all three valued components than has been the case historically. We also show that balancing multiple valued components rather than prioritizing a single valued component results in relatively minor losses in optimal outcomes. If optimal flows under a balanced prioritization scheme are sought, additional flow augmentation beyond what is available via existing sub-agreements would achieve benefits during 83% of years. While 6 MAF annually would maximize incremental benefit, an additional 1 MAF would also generate improvements across all three valued components. Obviously, the availability of optimal flows or even sub-optimal augmentation volumes depends on year-to-year hydrologic conditions and operating constraints imposed by flood management needs, the timing of hydropower demand, Canadian hydropower interests, and recreation and navigation objectives on both sides of the border. However, the fact that sub-optimal flow augmentation can also provide incremental benefits across all three valued components suggests that the US may wish to pursue negotiations with Canada for additional deliveries of water between March-July. While the annually negotiated NPUAs are responsive relative to more fixed agreements, we recommend adjusting the current practice of 1 MAF of augmentation to a range of volumes or an agreed-upon proportion of available storage. This approach would be more adaptive given uncertainty about future flow conditions. Revising the Columbia River Treaty to explicitly include ecosystem services like salmon conservation as a shared benefit would also align with this strategy.

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Appendix 3.A. Model notation and parameter estimates

Parameter	Units	Value	Source
Model inputs			
Total Priest Rapids Mar-Jul 'natural' flow volume, $Qnat$	MAF		BPA (2010)
Total Priest Rapids Mar-Jul regulated flow volume, $Qreg$	MAF		BPA (2010)
Hanford Reach fall Chinook egg-to-pre-smolt survival, S	rate		this study using Bellgraph and Perkins (2012)
Hydropower generation Mar-Jul, P	GWh		USEIA (2018)
Irrigation diversions Mar-Jul, I	MAF		BPA (2010)
Natural flow ~ Regulated flow			
Total Priest Rapids Mar-Jul regulated flow volume, $Qreg$	MAF	0-80	this study
Intercept, $\beta0_Q$		8.29	this study
Quadratic term, $\beta1_Q$		1.5	this study
Egg-to-pre-smolt survival ~ Regulated flow (Bayesian regression)			
Total Priest Rapids Mar-Jul regulated flow volume, $Qreg$	MAF	0-80	this study
Intercept, $\beta0_{es}$		0.1012 (median)	this study
Linear term, $\beta1_{es}$		0.00304 (median)	this study
Quadratic term, $\beta2_{es}$		-0.00003 (median)	this study
Bayesian error term, τ			this study
Standard deviation of error, σ			this study
Population estimation			
Equilibrium pre-smolts			
Ricker maximum egg-to-adult survival rate, a	adults/egg	0.00451228	pers. comm., Ryan Harnish (PNNL) (March 31, 2014)
Ricker density dependence parameter, b		-1.078e-8	pers. comm., Ryan Harnish (PNNL) (March 31, 2014)
Average female fall Chinook fecundity, $\overline{f}$	pre-smolts/egg	3811	this study, Bellgraph and Perkins (2012)
Adult escapement at equilibrium			
Natural ocean survival, oc	rate	0.8	pers. comm., Ryan Harnish (PNNL) (December 30, 2014)
Inter-dam survival (upstream), int	rate	0.759	Harnish et al. (2012)
Ocean harvest mortality, $h1$	rate	0.14	this study using ODFW, WDFW (2002)
Downriver harvest mortality, $h2$	rate	0.18	this study using ODFW, WDFW (2002)
Upriver harvest mortality, $h3$	rate	0.18	this study using ODFW, WDFW (2002)
Hydropower production ~ Regulated flow (Bayesian regression)			

Parameter	Units	Value	Source
Total Priest Rapids Mar-Jul regulated flow, Q_{reg}	MAF	0-80	this study
Intercept, $\beta 0_P$		-4349.88 (median)	this study
Linear term, $\beta 1_P$		990.05 (median)	this study
Quadratic term, $\beta 2_P$		-6.65 (median)	this study
Error term, τ			this study
Standard deviation of error, σ			this study
Irrigation diversion ~ Regulated flow (Bayesian regression)			
Total Priest Rapids Mar-Jul regulated flow, $Qreg$	MAF	0-80	this study
Intercept, $\beta 0_I$		0.0479 (median)	this study
Quadratic term, $\beta 1_I$		-0.00042 (median)	this study
Error term, τ			this study
Standard deviation of error, σ			this study
Multi-attribute utility weighting			
$\boldsymbol{n}$th weight on salmon conservation, hydropower, and irrigation utility, w_n		0.05-0.95 by 0.05, $0.\overline{33}$ (22 possible weights)	this study
Observations			
Total Priest Rapids Mar-Jul ‘natural’ flow volume, $Qnat$	MAF		
Egg-to-pre-smolt survival from Bayesian regression, Ses	rate		
Pre-smolt equilibrium population, Seq	# pre-smolts		
Pre-smolt-to-adult survival (escapement), Ssa	# adults		
Optimal total Mar-Jul Priest Rapids regulated flow, $Qopt$	MAF		
Estimated multi-attribute utility, U'	normalized (0,1)		
Estimated salmon conservation utility, U_s'	normalized (0,1)		
Estimated hydropower utility, U_p'	normalized (0,1)		
Estimated irrigation utility, U_i'	normalized (0,1)		
Simulated observations for sensitivity analyses (Ses, P, or I), Obs_{sim_i}			

Appendix 3.B. Model equations

Index

Parameters

B.1
$$\Theta = \{a, b, \beta 0_{Q,es,P,I}, \beta 1_{Q,es,P,I}, \beta 2_{es,P}, cv, \varepsilon, \overline{f}, h1, h2, h3, int, oc, \sigma, \tau, w_n\}$$

Natural flow ~ Regulated flow

B.2
$$Qnat = \beta 0_Q + \beta 1_Q (Qreg^2)$$

Pre-smolt survival ~ Regulated flow (Bayesian)

B.3
$$qnat\_logitSes = {\log \left({}^{S}\!/\!_{(1-S)} \right)} \Big/ {}_{Qnat}$$

B.4
$$qnatSes = \frac{e^{\beta 0_{es} + \beta 1_{es}(Qreg) + \beta 2_{es}(Qreg^2)}}{\left(1 + \ e^{\beta 0_{es} + \beta 1_{es}(Qreg) + \beta 2_{es}(Qreg^2)}\right)}$$

$$\theta 1_i, \theta 2_i, \theta 3_i \sim N(0{,}0.00001);\ i = 15{,}000{,}000;\ burnin = 7{,}500{,}000, thin = 3{,}000$$

$$\tau_i \sim Gamma(0.01{,}0.01);\ \sigma_i = {}^{1}\!\Big/\!_{\sqrt{\tau_i}}$$

B.5
$$Ses_i = \ qnatSes_i \cdot \left(\beta 0_Q + \beta 1_Q (Qreg^2)\right)$$

Equilibrium population estimation

B.6
$$Seq_i = 2 \cdot log \left(\frac{2/a \cdot Ses_i \cdot \overline{f}}{b \cdot Ses_i \cdot \overline{f}} \right)$$

B.7
$$Ssa_i = Seq_i \cdot oc \cdot int \cdot (1 - h1) \cdot (1 - h2) \cdot (1 - h3)$$

Hydropower production ~ Regulated flow (Bayesian)

B.8
$$P = \beta 0_P + \beta 1_P (Qreg) + \beta 2_P (Qreg^2)$$

$$\theta 1_i, \theta 2_i, \theta 3_i \sim N(0{,}0.00001);\ i = 15{,}000{,}000;\ burnin = 7{,}500{,}000, thin = 3{,}000$$

$$\tau_i \sim Gamma(0.01{,}0.01);\ \sigma_i = {}^{1}\!\Big/\!_{\sqrt{\tau_i}}$$

Irrigation diversion ~ Regulated flow (Bayesian)

B.9
$$qnatI = \ {}^{I}\!/\!_{Qnat} \ \ ; \ \ qnatI = \beta 0_I + \beta 1_I (Qreg^2)$$

$$\theta 1_i, \theta 2_i \sim N(0{,}0.00001);\ i = 15{,}000{,}000;\ burnin = 7{,}500{,}000, thin = 3{,}000$$

$$\tau_i \sim Gamma(0.01{,}0.01);\ \sigma_i = {}^{1}\!\Big/\!_{\sqrt{\tau_i}}$$

B.10
$$I_i = qnatI_i \cdot \left(\beta 0_Q + \beta 1_Q (Qreg^2)\right)$$

Salmon utility

B.11
$$U\_s_i = {}^{Ssa_i - \min(Ssa)} \Big/ {}_{\max(Ssa) - \min(Ssa)}$$

Hydropower utility

B.12
$$U\_p_i = {}^{P_i - \min(P)} \Big/ {}_{\max(P) - \min(P)}$$

Irrigation utility

B.13 $$U\_i_i = {I_i - \min(I)} \Big/ {\max(I) - \min(I)}$$

Multi-attribute utility

B.14 $$U_i = w_n \cdot U\_s_i + (1 - w_n) \cdot U\_p_i + (1 - w_n) \cdot U\_i_i$$

Optimal regulated flow

B.15 $$Qopt_i = \underset{Qreg}{\operatorname{argmax}} U_i(Qreg)$$

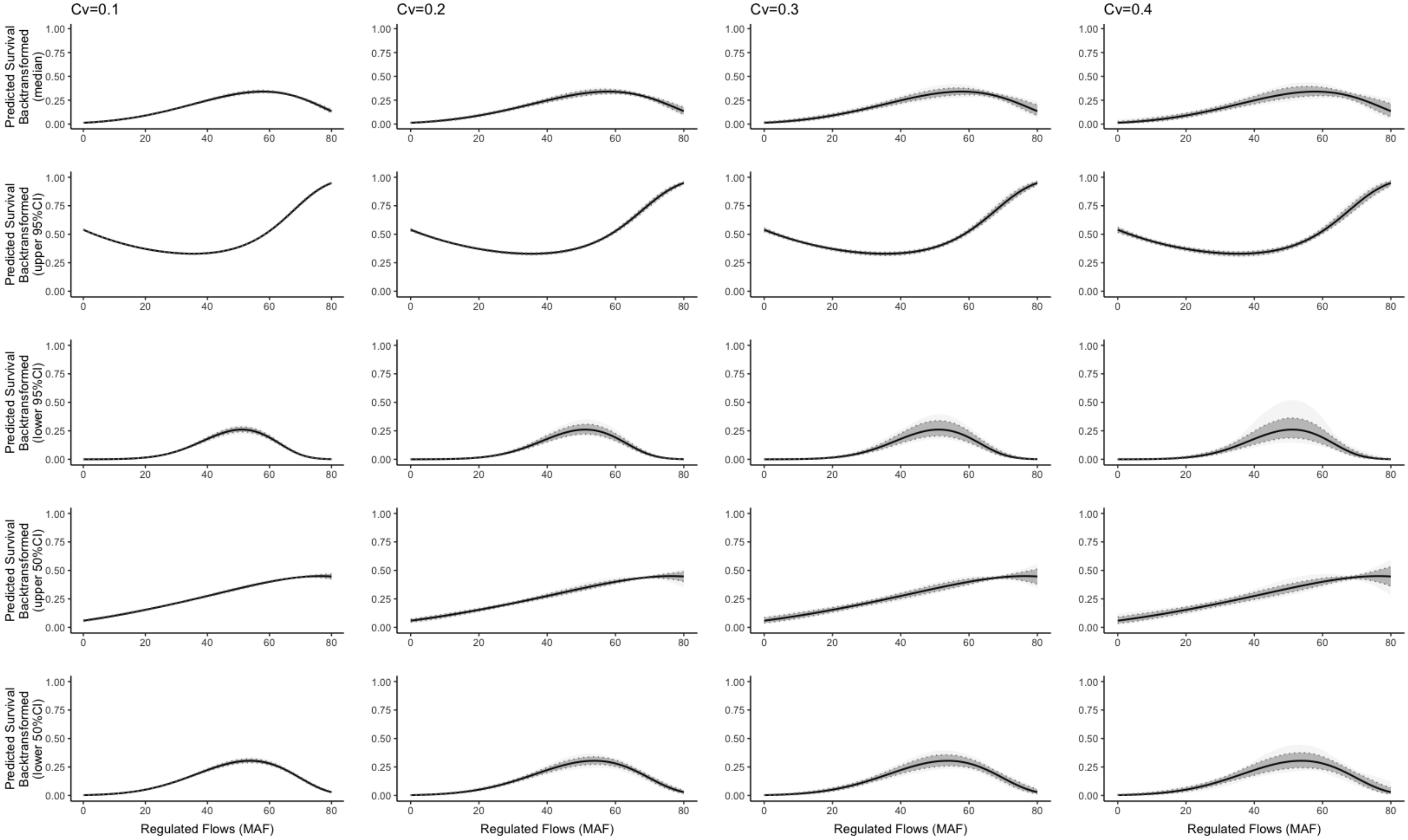
Sensitivity analyses

B.16 $$\varepsilon_{S_i} = e^{cv_S \cdot \varepsilon_i - \frac{cv_S{}^2}{2}}$$

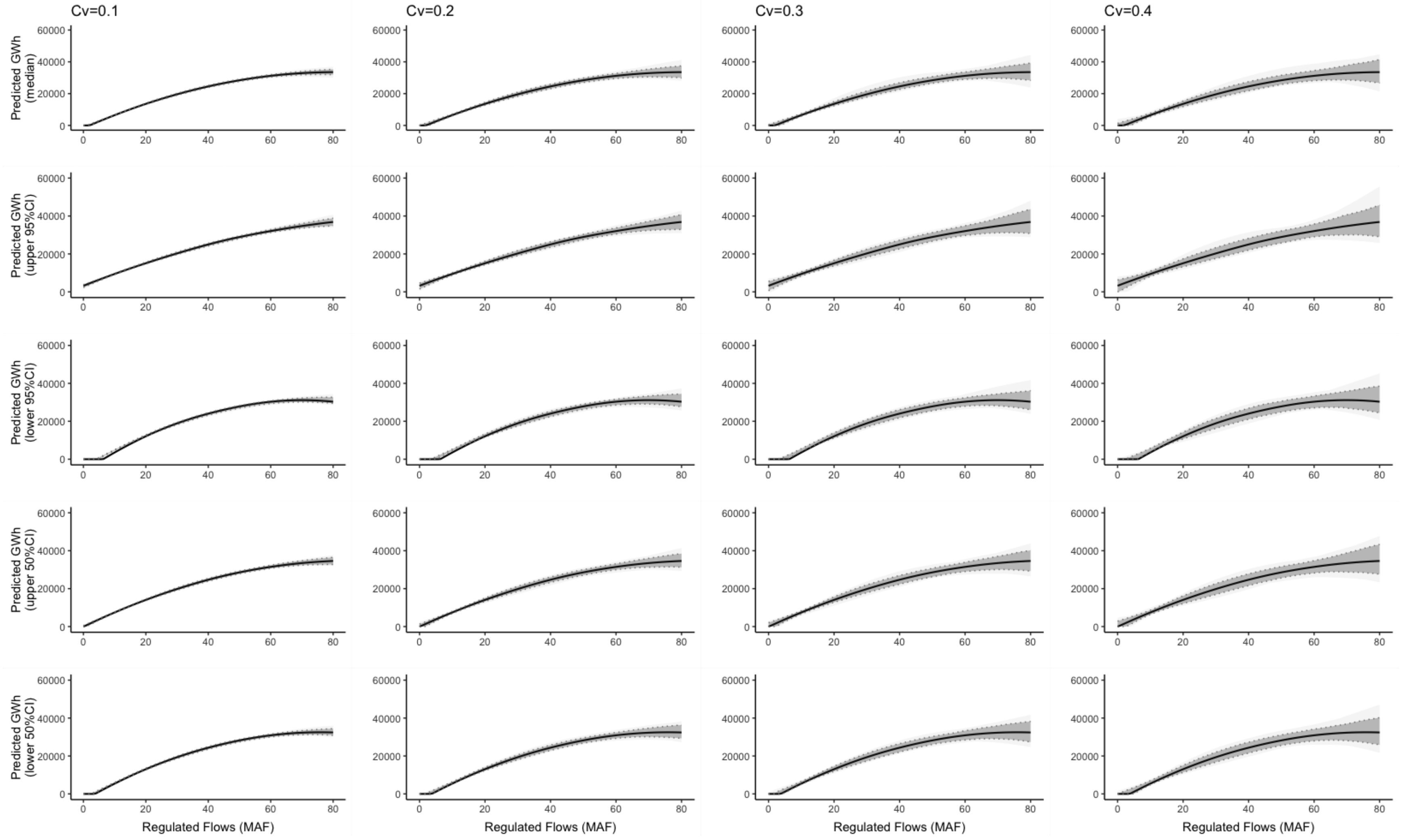
B.17 $$\varepsilon_{P\ or\ I_i} = cv_{P\ or\ I} \cdot \varepsilon_i - \frac{cv_{P\ or\ I}{}^2}{2}$$

B.18 $$Obs_{sim_i} = S, P\ or\ I_i \cdot \varepsilon_{S,P\ or\ I_i}$$

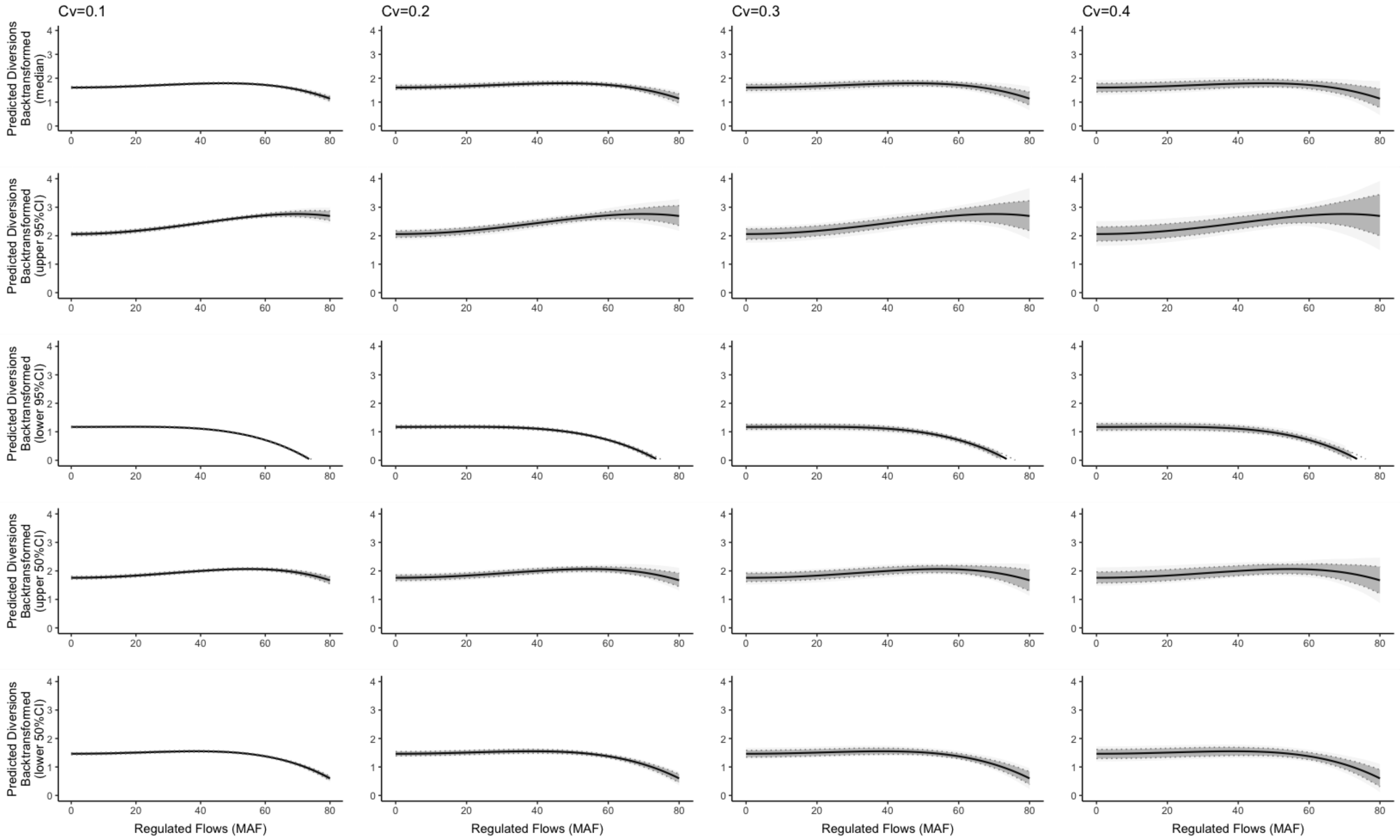
Appendix 3.C. Chinook egg-to-pre-smolt survival model with uncertainty in the ‘true’ model and simulated Qreg under different uncertainty assumptions (Cv)



Appendix 3.D. Hydropower production model with uncertainty in the ‘true’ model and simulated Qreg under different uncertainty assumptions (Cv)



Appendix 3.E. Irrigation diversion model with uncertainty in the ‘true’ model and simulated Qreg under different uncertainty assumptions (Cv)



Appendix 3.F. Optimal flows and utility outcomes with uncertainty in the ‘true’ utility models for salmon, hydropower and irrigation*

Sensitivity results (all other models held constant)								Differences from base case					
Priority	base	loSalmon	upSalmon	loHydro	upHydro	loIrrig	upIrrig	loSalmon	upSalmon	loHydro	upHydro	loIrrig	upIrrig
	Optimal regulated flow (MAF)												
Salmon	56.57	50.1	54.14	52.53	52.53	58.18	50.91	-6.47	-2.43	-4.04	-4.04	1.61	-5.66
Hydropower	63.84	62.22	60.61	63.84	63.03	63.84	63.03	-1.62	-3.23	0	-0.81	0	-0.81
Irrigation	50.10	48.48	49.29	49.29	49.29	55.76	44.44	-1.62	-0.81	-0.81	-0.81	5.66	-5.66
Balanced	55.76	52.53	54.14	54.14	53.33	58.18	50.91	-3.23	-1.62	-1.62	-2.43	2.42	-4.85
	Salmon (# returning adults)												
Salmon	53942	53943	54012	54048	54048	53961	54048	1	70	106	106	19	106
Hydropower	52701	52534	53559	53961	53961	54006	53961	-167	858	1260	1260	1305	1260
Irrigation	52446	54028	53917	54052	54052	53961	53685	1582	1471	1606	1606	1515	1239
Balanced	53427	53745	54026	53994	54012	53943	54061	318	599	567	585	516	634
	Hydropower (GWh)												
Salmon	30365	28376	29634	29355	28900	30721	28641	-1989	-731	-1010	-1465	356	-1724
Hydropower	31839	31637	31291	32380	31378	31955	31800	-202	-548	541	-461	116	-39
Irrigation	28648	27825	28104	28276	27882	30090	26327	-823	-544	-372	-766	1442	-2321
Balanced	30140	29151	29634	29859	29135	30721	28641	-989	-506	-281	-1005	581	-1499
	Irrigation (MAF)												
Salmon	1.751	1.778	1.733	1.755	1.755	2.036	1.477	0.027	-0.018	0.004	0.004	0.285	-0.274
Hydropower	1.619	1.503	1.567	1.43	1.468	1.854	1.16	-0.116	-0.052	-0.189	-0.151	0.235	-0.459
Irrigation	1.908	1.785	1.782	1.782	1.782	2.062	1.538	-0.123	-0.126	-0.126	-0.126	0.154	-0.37
Balanced	1.810	1.755	1.733	1.733	1.745	2.036	1.477	-0.055	-0.077	-0.077	-0.065	0.226	-0.333

*Based on upper (up) and lower (lo) 50% Bayesian credibility intervals for each valued component

Appendix 3.G. Chinook salmon stock-recruit (pre-smolt to returning adult) model results with varying parameter values*

Sensitivity Scenario	Returning adults at maximum multi-attribute utility	Change in returning adults
base	53,427	
a -20%	42,194	(11,233)
a +20%	63,922	10,495
b -20%	66,833	13,406
b +20%	44,550	(8,877)
f -20%	52,779	10,585
f +20	53,258	(10,664)
oc -20	42,768	(24,065)
oc +20	64,168	19,618
int -20	42,772	(10,007)
int +20	64,141	10,883
hoc -20	55,191	12,423
hoc +20	51,713	(12,455)
hdr -20	55,807	13,035
hdr +20	51,113	(13,028)
hur -20	55,808	617
hur +20	51,135	(578)

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Chapter 4. The adaptive capacity of the Columbia River Treaty for fish conservation

This chapter is from the draft manuscript titled "Freshwater treaties and species conservation: The Libby Dam incident and the adaptive capacity of the Columbia River Treaty", co-authored by C Morton and M Rutherford, which will be submitted to the journal Policy Sciences. I authored the majority of the text and exclusively completed and authored the data analysis, tables and figures.

Abstract

This study applies incident analysis to assess the Canada-US Columbia River Treaty's (CRT) adaptive capacity to respond to evolving species conservation needs, despite the fact that the terms of the treaty do not explicitly include species conservation. We analyze the discourses and normative expectations of politically relevant groups regarding an international conflict over management of Libby Dam in Montana, and the efforts of the US to conserve an endangered species of sturgeon affected by water flows from the dam. We found four distinct discourse coalitions that formed around the issue, each with their own interpretation of the problem, normative expectations about how it should be addressed, and power to shape the agenda. We show how the parties found operating flexibility within status quo operations under the CRT to enable additional flow releases for sturgeon, but in the process further consolidated decision-making authority for species conservation issues in the hands of the CRT implementing agencies. This consolidation of authority strengthened the agencies' ability to constrain and close decision-making processes regarding species conservation and demoted what are arguably more value-neutral dispute-resolution mechanisms formally available under the agreement. Our assessment of the dispute reveals several persistent problems for species-at-risk in the basin including, a) insufficient flexibility in the operating regime, b) a limited definition of shared 'benefits', and c) asymmetrical conservation laws on either side of the border. The incident also highlights how domestic conservation laws can directly impinge upon an international treaty. The US was willing to adjust the priority of its own hydropower interests to accommodate sturgeon conservation because it was

obliged to do so according to its own domestic laws. Other revealed solutions include improved operating techniques for the hydro-system, the creation of a transboundary river basin organization, using payments for ecosystem services, and constitutive changes to the treaty.

4.1. Introduction

Transboundary freshwater treaties are important for biodiversity conservation efforts because they govern the shared use of waters in major lakes and river basins covering over forty percent of the earth's land surface (OSU 2012, Brels, Coates and Loures 2009). Unfortunately, most of these treaties do not directly address species conservation, focusing instead on values such as hydropower, irrigation, infrastructure, flood management and navigation. Of the small number of international agreements that do contain commitments concerning potentially affected species (OSU 2012), most relate to utilitarian goals such as sustaining fish stocks for harvest rather than broader environmental goals like conserving biodiversity and protecting species at risk. Recognizing the importance of this gap, the parties to the Convention on Biological Diversity included bi- and multi-lateral freshwater treaties in their 2008 recommendation to strengthen existing international environmental agreements as a means to implement the Convention's conservation goals (Convention on Biological Diversity 2008; Belbin and VanderZwaag 2016).

In contrast to international agreements, domestic laws and policies dealing with species conservation within nation-states have often advanced at a faster pace (e.g., the Endangered Species Act in the United States). As a result, the policy context for species conservation in transboundary freshwater systems is often complex, with fragmented and sometimes contradictory prescriptions spanning international and domestic arenas (national and sub-national) (Belbin and VanderZwaag 2016). When a state's water-management commitments at the international level conflict with its conservation commitments at the domestic level, the political and environmental trade-offs can challenge the capacity of water sharing institutions to adapt. Since freshwater treaties often lack built-in expiry dates or have long revision cycles (e.g., 60 years), it may not be practical to rely solely on renegotiation and amendment to address these problems.

Referring to the capacity of social-ecological systems to respond to unanticipated changes, Young (2017) stresses the importance of adaptive capacity in modern international institutional arrangements. Although he focuses on the risk of abrupt, non-linear and sometimes irreversible changes that arise in these complex systems, there is also a need for international institutional arrangements to adapt to societal goals and value demands that evolve more slowly over time. Adaptive capacity may be built into the explicit wording of a treaty (the prescription), but it may also be found in the social and decision making processes through which the treaty is interpreted, invoked and applied.

Reisman (1981) characterizes international lawmaking as a process of communication, involving three "communication streams": policy content, authority signal (indicating that the source of the prescription has the appropriate authority), and control intention (showing that the prescription will be enforced) (see Lasswell 1971; Clark 2002; Land 2013-2014). "It is the coordination of these three message flows—policy content, authority signal and control intention—that indicates prescription or, in popular parlance, that makes law" (Reisman 1981, p.111). Accordingly, knowledge of "the existence and content of the expectations of politically relevant individuals and groups" is essential to an understanding of international norms (Reisman 1981, p.113). The formal norms (policy content) specified in written texts such as treaties and exchanges of diplomatic notes may not match the expectations about norms that will actually apply in practice (Reisman 1988; Koh 2007). Reisman and Willard (1988) call such normative expectations "the law that really counts in world politics."

Institutional scholars make a similar distinction between "rules-in-form" and "working rules" or "rules-in-use", where the latter may reflect interpretations of the former, sometimes held as unwritten beliefs or assumptions (Ostrom 1999; Cole 2017). These interpretations exist along a continuum from perfect alignment to no clear relation to the associated formal rules (Cole 2017). Interpretations of rules often differ across groups, and the claims and counterclaims of these groups influence institutional responses to changes in the social-ecological context.

Applying these insights to transboundary freshwater treaties, increasing these agreements' adaptive capacity for species conservation may require 'opening up' shared freshwater institutions to be shaped to varying degrees by domestic conservation laws and policies, as well as by evolving international and domestic conservation goals. The extent to which treaty-based institutional arrangements can open in this way depends in large part on the set of relevant influential actors and their expectations about what the words of the treaty mean, and, notwithstanding the formal text, what the norms are that should apply. For example, if conservation values clash with the priorities and expectations of influential actors, treaty arrangements that appear to be comparatively flexible (e.g., those with low formal specificity) may nevertheless exclude these values in practice. Alternatively, a seemingly rigid treaty on paper may be quite open to conservation values in practice if the expectations of influential actors about rules-in-use that govern acceptable behaviour are aligned with those values. Domestic conservation laws and policies play a significant role, as they reflect expectations about appropriate conservation norms, but also shape expectations (domestically and internationally) over time. As Nagtzaam (2009, p.35) states, “the environmental norms of conservation and preservation were born at the domestic level.”

Disagreements between states often bring to the surface expectations about norms that may otherwise be difficult to detect (Reisman and Willard 1988). Accordingly, one useful approach for assessing normative expectations is to analyze the behaviour and discourse of participants during incidents of international conflict (Reisman and Willard 1988). In the interest of supporting more adaptive water treaties, and to better understand what can be expected of these institutions as species conservation needs change, in this paper we use the incident analysis approach to study an international conflict that arose as a result of efforts to conserve an endangered species in a river governed by the Columbia River Treaty between Canada and the United States (CRT, or the ‘Treaty’). Using this single incident as our unit of analysis, we apply quantitative discourse analysis to identify the major discourse coalitions that became evident during the dispute and the expectations of these groups about applicable norms.

The conflict we examine is the Libby Dam dispute, an international incident involving efforts in the US to conserve Kootenai River white sturgeon (*Acipenser transmontanus*), a fish listed as endangered under the US Endangered Species Act (ESA). Our research addresses five main questions:

1. How do discourses and normative expectations differ across politically relevant groups regarding species conservation under a transboundary

freshwater treaty that does not explicitly deal with species conservation?

2. What norms held by politically relevant groups were not apparent prior to the Libby Dam incident and what happened to these norms as a result of the dispute?

3. How can domestic conservation laws affect interpretation, invocation and application of formal treaty text?

4. What is the capacity of a transboundary freshwater treaty that does not explicitly deal with species conservation to adapt to external pressures for change regarding species conservation?

5. What alternative strategies are revealed by the Libby Dam incident that may be of use in future similar situations involving Canada and the US and in other international settings?

Like many other international freshwater agreements, the Columbia River Treaty is silent on the topic of species conservation despite having significant implications for a variety of terrestrial and aquatic species, including species-at-risk (Bankes 2004; Belbin and VanderZwaag 2016). In the more than five decades since its ratification the two parties have easily resolved numerous minor disagreements about various issues. The only major conflict to-date was triggered by US efforts to protect the endangered Kootenai white sturgeon. Referred to as the ‘Libby Dam dispute’, this disagreement stands out, having escalated to a refusal by the parties to sign-off on operating plans and formal exchanges of diplomatic notes between the two countries. The dispute’s resolution, the Libby Coordination Agreement, provides guidance about adaptive capacity and the possibility of modernizing the Treaty for better integration of fish conservation values. However, the conflict also illustrates the rigidity of transboundary water institutions and their capacity to maintain or consolidate the power of dominant interest groups in ways that will likely be challenged by future conservation needs.

Following a brief overview of incident analysis, we examine the broader social context of the Libby Dam dispute, its ecological setting, and the historical background that shaped its management institutions and the general policy landscape. Next, we apply quantitative discourse analysis to identify the major discourse coalitions that emerged during the dispute. We then examine the normative expectations revealed by the dispute, the challenges to those normative expectations raised during the dispute, and the effects of the challenges on normative outcomes. Finally, we discuss implications for the future integration of conservation values into the Columbia River Treaty.

4.2. Analysis of environmental incidents

As originally formulated, incident analysis is a method that can be used to investigate the “normative expectations of those who are politically effective in the world community” (Reisman 1988, p. 4). An incident can be defined as a conflict among international actors that “created, clarified, or changed the expectations of elites regarding international norms” (Reisman 1988, p.29). The basic premise of incident analysis is that during an incident the statements and actions of elites can reveal and sometimes reconfigure the legal norms that will actually be invoked and applied, and that these norms may be hidden from traditional analysis of formal written rules (Reisman and Willard 1988).

Early examples of incident analysis appraised international conflicts concerning the military, trade, human rights, illegal immigration, and extraterritorial jurisdiction (Reisman and Willard 1988). Steps in a typical analysis include: 1) description of the facts, 2) identification of relevant norms, 3) description of the parties’ claims and counterclaims about the issue, and 4) appraisal of the outcomes with particular attention to future normative implications (Willard 1984).

More recently, policy scientists have applied the incident analysis approach to study domestic incidents involving species conservation and environmental management. Examples include conflicts over the officially sanctioned euthanization of a grizzly bear captured in Grand Teton National Park, Wyoming (Cromley 2000), the removal of two cougars from popular recreation areas in Arizona (Mattson and Clark 2012), the unauthorized killing of a grizzly bear by elk hunters in Grand Teton National Park (Vernon, Bischoff-Mattson, and Clark 2015), water allocation in the Murray Darling River Basin in Australia (Bischoff-Mattson and Lynch 2016), and a polar-bear inflicted human injury in northern Manitoba, Canada (Schmidt and Clark 2018). Unlike their international counterparts, these domestic studies assessed reactions of interested or affected domestic actors rather than onlooking states, and used qualitative and quantitative discourse analysis to evaluate actors' claims, counterclaims, and broader perspectives about norms of appropriate behaviour.

As an indicator of the normative expectations of powerful actors, the Libby Dam dispute is well suited to incident analysis. Moreover, because the dispute straddled international and domestic arenas, it offers an opportunity to apply the method in a new way that draws on both streams of incident analysis. The dispute was a significant international conflict for Canada and the US, but unlike the original incident analysis cases, it did not raise a substantial response from other states on the international stage. On the other hand, the disagreement did spark a period of heated discourse among state and non-state actors on both sides of the Canada-US border. Like the domestic applications of incident analysis, discourses among these actors clarified and influenced normative expectations about the international and domestic rules applicable to fish conservation in the context of this freshwater treaty.

Consistent with all prior applications of incident analysis, our analytical approach is grounded in Lasswell's (1971) broad formulation of the policy process: "people seeking values through institutions using resources". Our focus is primarily on institutions, understood here in the broad sense of repeated patterns of behavior that become embedded in configurations of power (Clark and Rutherford 2005). We treat norms in the international relations sense, as shared expectations about appropriate collective behavior (Hofferberth and Weber 2015; Finnemore and Sikkink 1998; Keck and Sikkink 1998; Keck and Sikkink 1999). Aligning with constructivist views of international relations, we forego purely state-level explanations of international events in favour of a multi-level analysis that includes domestic actors such as corporations, NGOs, Indigenous groups and sub-national governments (Nagtzaam 2009; Young 1999). This approach is also consistent with legal scholars who promote the study of 'transnational law' as "a hybrid body of law that transcends old dichotomies between international and domestic law" (Koh 2007).

The most recent applications of incident analysis (Mattson and Clark 2012; Vernon, Bischoff-Mattson and Clark 2015; Bischoff-Mattson and Lynch 2016; Schmidt and Clark 2018) have used quantitative discourse analysis (Titscher et al. 2000; Phillips and Hardy 2002) to evaluate documents (e.g. news articles) and interview transcripts expressing the perspectives of participants in, and observers of, the incident. The discourse analytic approach permits an appraisal of the normative expectations of relevant actors by identifying discrete ‘problem discourses’—consisting of statements about problems, facts and solutions—and the coalitions of actors associated with these discourses (Mattson and Clark 2012; Vernon, Bischoff-Mattson, and Clark 2015). Discourses about problems are tightly linked to norms because they reveal expectations of actors about what is considered right and wrong, and “who gets what, when, how” (Lasswell 1936; and see Vernon, Bischoff-Mattson, and Clark 2015). Thus, the study of problem discourses can significantly aid in understanding how and why norms surface and potentially change during disputes.

4.3. Kootenai River White Sturgeon and The Libby Dam Dispute

The Libby Dam dispute originated with a declining population of white sturgeon in an American segment of the Kootenai River (“Kootenay” in Canada). The river is a major tributary of the Columbia River that flows south from the Canadian Rockies into the State of Montana and then north again into Canada, where it empties into the Columbia River’s mainstem near Castlegar, British Columbia (Figure 4.1). Libby Dam is on the US section of the Kootenai River, and is unique as the only instance under the Treaty where Canada is affected by the upstream dam operations of the US instead of the reverse.

White sturgeon in the Kootenai River have been landlocked by natural obstructions since the last ice-age (approximately 10,000 years), and are now a genetically distinct sub-population of the normally anadromous species (Scott and Crossman 1973). Instead of migrating to brackish waters, the fish complete their life cycle in a 190 km section of the river below the Libby Dam (Paragamian, Beamesderfer, and Ireland 2005). Spawning areas extend to just upstream of Bonners Ferry, Idaho in the US, and the downstream range extends to Kootenay Lake, British Columbia. The population was once a major food source with significant cultural and religious value for Indigenous people in the region (Belbin and VanderZwaag 2016).

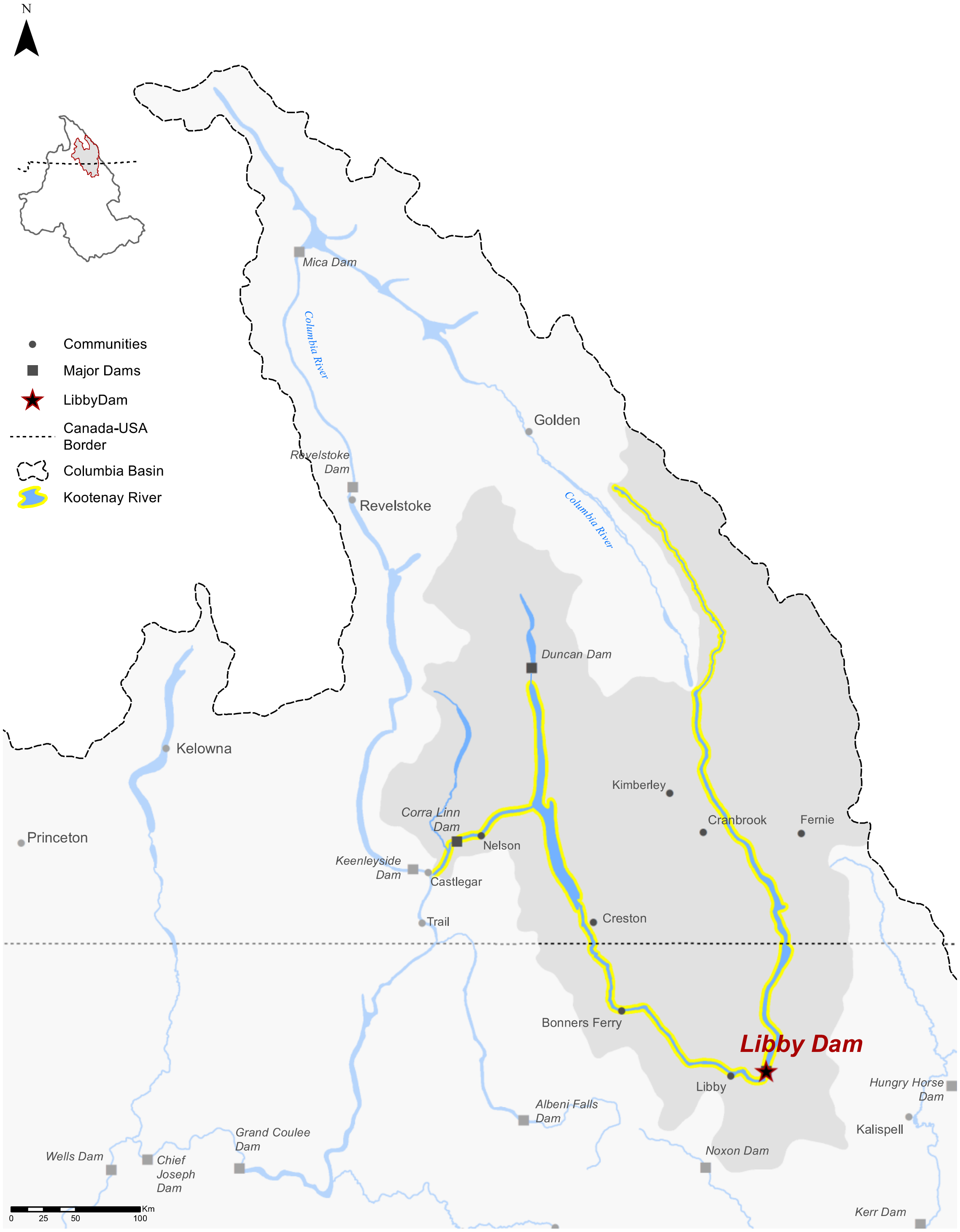

Figure 4.1. Libby Dam on the Kootenay River

After Libby Dam was constructed and operations commenced in early 1975 the population of white sturgeon went into full decline, and within a decade exhibited almost no recruitment[25] of new individuals (Paragamian 2012; Paragamian, Kruse, and Wakkinen 2001). In the early 1990s, biologists on both sides of the border concluded that the abundance of sturgeon juveniles was too low to sustain the population. In 1994, the US listed Kootenai white sturgeon as endangered under Section 4 of the Endangered Species Act (ESA). Direct causes of the decline are thought to include post-dam reductions in spring flows, reduced water-scouring of coarse substrate needed for egg deposition and rearing downstream from the dam, decreased downstream productivity due to sediment capture behind the dam, and shifts in winter and summer stream temperatures (Paragamian 2012; Paragamian et al. 2009; Paragamian, Kruse, and Wakkinen 2001; Duke et al. 1999). The fish also appear to be unable or unwilling to move from historic spawning ranges to more suitable nursery and rearing habitat elsewhere in the river (McDonald et al. 2010; Barton 2004; Kock, Congleton, and Anders 2006; Duke et al. 1999).

To appreciate the nature of the Libby dispute it is necessary to understand some background information about the CRT and the associated institutional arrangements for managing the dams in the Columbia River Basin governed by the Treaty. Ratified in 1964, the CRT is an acclaimed example of transboundary water cooperation due to its 50/50 split of hydropower benefits between the two countries, which exemplifies international water law's equitable utilization principle (Ketchum and Barroso 2006; Paisley 2002). Core features of the Treaty include a) the construction of four dams, two on the Columbia River in Canada (Mica and Keenleyside dams), one on the Duncan River in Canada (Duncan Dam), and one on the Kootenai River in the US (Libby Dam), b) flood management provided to the US by Canada using Treaty dams and reservoirs, the first 60 years of which were paid for in advance by the US in a single lump sum payment that helped finance construction of the Canadian dams, c) the Canadian Entitlement, which is Canada's annual share of US hydropower benefits resulting from construction and operation of the Treaty dams, d) establishment of three agencies as the Canadian and US 'Entities' empowered to implement the Treaty (BC Hydro in Canada, and jointly, Bonneville Power Administration and the US Army Corps of Engineers in the

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[25] *The number of juvenile sturgeon surviving to maturity*

US)[26], f) the annual negotiation and agreement on an Assured Operating Plan (AOP) six years in advance of the actual operating year to which it applies, and a Detailed Operating Plan (DOP) for the upcoming year (Canada, United States of America, 1964). Under the Treaty, various Non-power Uses Agreements (NPUAs) have also been signed annually since the 1990s to accommodate different interests, including fish conservation (British Columbia, 2013).

In 1995, a Biological Opinion (BiOp) was issued by the US Fish and Wildlife Service under the ESA requiring the US Army Corps of Engineers (USACE) to spill water at Libby Dam to more closely mimic natural flows for sturgeon (USFWS 1999). Combined with habitat enhancement and conservation aquaculture, sturgeon experts felt at the time that this action would restore wild spawning, rearing, and recruitment within a relatively short time-span (Paragamian 2012). The USACE began implementing this spill for sturgeon (the "sturgeon spill") in the same year the BiOp was issued, without first securing Canada's agreement (Ketchum and Barroso 2006).

The timing of the sturgeon spill affected Canada's ability to optimize hydropower production at its dams downstream, resulting in economic losses and prompting Canada to object formally under the Treaty, initiating the Libby Dam dispute (Ketchum and Barroso 2006). The disagreement escalated to exchanges of diplomatic notes, mobilization of lawyers on both sides of the border, and discussions about the possibility of referring the dispute to the Canada-USA International Joint Commission (IJC) and the International Court of Justice (ICJ) as potential dispute resolution mechanisms. The 'solution' to the dispute, the Libby Coordination Agreement (LCA), was formally agreed to by the parties in 2000. The LCA allows Canada to manage Treaty-storage across its reservoirs in a manner not previously permitted under the Treaty in order to self-compensate for losses from US sturgeon operations (Ketchum and Barroso 2006). The two countries still officially disagree about Treaty interpretation, so the LCA represents a compromise that is paradoxically emblematic of both the CRT's capacity to adapt to changing conservation values, and its inability to do so.

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[26] After Treaty ratification, the Province of BC was included as part of the Canadian Entity for purposes of administration of the Canadian Entitlement.

4.4. Historical context

Declining fish populations were a concern in the Columbia River well before the CRT was negotiated, but at that time hydropower and flood control benefits superseded this concern (Blumm 1980). A pre-Treaty cost-benefit assessment was commissioned by the US and Canada in 1944 (completed by the IJC in 1959) that was to include wetland, fish, and wildlife conservation values along with other benefits and costs (Canada, United States of America 1964). These environmental values were ultimately excluded from consideration on the grounds that there was “no urgent need” and that any such benefits (or costs) “would be so small in comparison to power and flood management values” that further study was not required (Canada, United States of America 1964). The IJC studies did, however, contemplate that future water needs might shift the primary roles for Treaty-based water storage, a sentiment ambiguously reflected in the last clause of the Treaty’s preamble, which states that “cooperative measures for hydroelectric power generation and flood control . . . will make possible other benefits as well” (Canada, United States of America 1964).

The Libby Dam’s completion in 1973 coincided with the year the US Endangered Species Act came into force. The US’s increased domestic legal and regulatory obligations for fish conservation prompted a minor ‘pre-Libby dispute’ with Canada in the late 1970s and early 1980s (Swainson 1979). The position of the US at that time was that operations of Libby for fish conservation were permissible if specified in the Treaty’s jointly produced Assured Operating Plans (AOPs), and that Article VII (4) of the Treaty, which permits agreed-upon modification of shared hydropower benefits, should be interpreted as allowing reductions in payments to the Canadian Entitlement if Treaty-water was used by the US for non-power purposes (Blumm 1980). Canada disagreed with the American interpretation, arguing that it directly contradicted key parts of the Treaty and missed the agreement’s defining cooperative context of shared hydropower benefits (Bankes 1996). In the late 1980s, the Entities referred this disagreement to the Treaty’s Permanent Engineering Board (PEB), a jointly managed body sometimes called upon to aid in resolving minor Treaty-based disputes of a technical nature. The PEB ruled in favour of Canada’s interpretation and from that point forward the US was free to conduct operations for fish conservation, but only if these operations did not affect the Canadian Entitlement. In 1988, the two countries signed an agreement adopting the

PEB's interpretation (Canadian Entity representative, interview, April 16, 2013). This formalization set a clear normative expectation that the use of cross-border flows to meet US fish conservation obligations was permissible as long as it had no negative consequences for Canada's economic benefits under the Treaty.

Over the next five years (after 1988), shared water relations became somewhat strained between Canada and the US. The North American Free Trade Agreement (NAFTA) between Canada, the US and Mexico was signed in 1992 and some Canadian stakeholders asserted that its terms potentially eroded Canadian control over its water resources (Barlow and Clarke 2002). Since some of the CRT's sub-agreements occur between BC Hydro and Bonneville Power Administration, they qualified as commercial agreements potentially governed by NAFTA. Politicians in BC drew parallels between American uses of Columbia River flows for fish conservation and bulk water exports from Canada to the US (Legislative Assembly of British Columbia 1995a). While the Libby dispute was escalating, the province of BC was also enacting the 1996 Water Protection Act banning bulk water exports from the province (Legislative Assembly of British Columbia 1995a).

Also illustrative of strained hydro-politics was BC's public condemnation of Bonneville Power Administration (BPA). At the onset of the Treaty, BC had agreed to accept the first thirty years of the Canadian Entitlement in a lump sum payment, an arrangement that was supposed to revert to annual payments beginning in 1998. In preparation for the commencement of annual payments, BC and BPA signed a Memorandum of Understanding (MOU) in 1994 about the format of payment and receipt over the next thirty years. The MOU specified an advance partial payment of more than $180 million (1995 USD), the anticipation of which allowed BC to balance its entire 1994 provincial budget (Legislative Assembly of British Columbia 1995b). However, wholesale power prices in the Pacific Northwest dropped in the early 1990s, resulting for BPA in a twenty-five percent decrease in demand as customers shifted to cheaper power suppliers (USGAO 2004). In 1995 BPA backed out of the MOU citing a drop in the short-term market value of hydroelectric capacity. This move placed the BC government in a difficult position with its electorate and tarnished BPA's Treaty-based and commercial relationship with the province. The issue prompted heated debate in the BC Legislature that culminated in the Legislative Assembly's[27] formal condemnation of BPA by a near unanimous vote of 51 yeas to 1 nay (Legislative Assembly of British Columbia 1995c).

Bonneville Power Administration's reversal was almost certainly influenced by the threat of litigation from interest groups in the US against BPA related to the US Endangered Species Act (ESA). From 1992 to 2005 thirteen Columbia Basin fish populations were listed under the Act as threatened or endangered (USFWS 2014), triggering a long series of lawsuits from US conservation groups and development interests. The cases eventually culminated in a pro-environmental reading of the ESA that required US 'action agencies' to consult with the National Marine Fisheries Service (NMFS) or US Fish and Wildlife Service (USFWS) prior to any action that could affect listed aquatic species or critical habitat (see 50 C.F.R §402.14(a) (2009)). Under the ESA, the NMFS or USFWS were then required to issue a Biological Opinion (BiOp) stating whether the action was likely to jeopardize the continued existence of the species, and, if so, to recommend alternative actions (see 16 U.S.C. §§1536(a)(4), (a)(2), (b) (2006); 50 C.F.R. §402.02 (2012), 402.14 (2009)). The action agency (in this case BPA and the USACE) was then required to adjust its proposed operations in accordance with the BiOp. In 1994, two separate notices of intent to sue issued by the State of Oregon and Northwest Environmental Defense Center targeted potential management implications of BPA's MOU with the BC government (Canada 1995) and claimed BiOps should have been prepared prior to Canada-US agreement on any AOPs or DOPs. This growing influence of the ESA offers some context underpinning the US's motivation to unilaterally alter flows at Libby dam for sturgeon conservation.

4.5. Methods

The fact that the Libby Dam dispute played out without extensive media coverage or a high public profile precluded us from relying solely on newspaper content or media interviews and necessitated gathering primary and secondary data from multiple types of sources (see Table 4.3 for a summary of sources). The PEB granted us

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[27] *The British Columbia Parliament's deliberative assembly, composed of elected Members of the Legislated Assembly (MLAs) who represent their electoral districts ('ridings') throughout the province.*

access to a substantial collection of archival documents including diplomatic exchanges of notes, e-mail communications, legal appraisals, draft reports, and the record of decision for the Libby Coordination Agreement produced from 1994 to 2000. Other data sources gathered via comprehensive web-based searches of publicly available databases (e.g., Google and government databases) included four US Federal Register reports (1994-2001), one US Congressional Report (1997), 12 Hansard records of British Columbia Legislative Assembly debates (1995-2003), one record of a Canadian House of Commons debate (1993), one speech from a Canadian federal Member of Parliament (1999), one speech from the Governor of Oregon (1999), and 31 articles (1994-2003) from MacLean's Magazine, The Vancouver Sun, The Times Colonist, The Cranbrook Daily Townsman, The Lewiston Morning Tribune, The Seattle Post-Intelligencer, The Spokesman Review, The Columbian, and The Missoulian. We performed exhaustive database searches using keyword combinations such as "Libby Dam", "Libby AND dispute", "Libby AND sturgeon". Where search capabilities were unavailable (e.g., legislative debates) we downloaded documents for the 1993-2003 period and searched each document individually. We also requested article searches from local museums or libraries in Cranbrook (BC), Kalispell (BC), Helena (Montana), and Coeur d'Alene (Idaho) which surfaced two 1999 articles unavailable online from the Cranbrook Daily Townsman.

In addition, we used 18 academic or technical papers (1996-2012), and transcripts from nine interviews of key informants conducted by the lead author from March to June 2013. Interview participants included representatives of the Canadian Entity (2), the US Entity (1), a Canadian First Nation (1), a US Tribe (1), the BC provincial government (1), a Canadian river basin organization (1), a US river basin organization (1), and a US state conservation agency (1) (descriptions intentionally generic to protect participant anonymity). All interviews were semi-structured and, for historical context, focused on the period leading up to the incident through to the signing of the Libby Coordination Agreement (~1985 – 2000). To our knowledge, these source materials represent the most comprehensive library of information about the Libby Dam dispute available anywhere.

With the exception of the interviews and academic papers, these sources were all produced from 1993 to 2003, which is the period we define as the 'incident'. We extend the temporal bounds of the incident three years beyond the 2000 signing of the

LCA to capture some ongoing commentary from three newspaper articles in 2001, one newspaper article in 2003, one academic article about the effects of Libby Dam on sturgeon published in 2002, one BC Legislative Assembly Debate in 2003, and one CRT technical document published by UNESCO in 2003.

We also included post-incident sources (academic articles published and interviews conducted after 2003) in our analysis because some key participant groups were absent from contemporaneous coverage of the dispute process, and we were only able to include their views through retrospective assessments. Bischoff-Mattson and Lynch (2016) acknowledge such missing perspectives as an issue in their analysis, which relied solely on contemporaneous textual sources. Additionally, the recollections of interviewees and the post-incident articles provided a window on the positions of actors and the normative outcomes of the dispute with a level of detail unavailable in any of the other documentation. To be transparent about potential bias (e.g., recall bias) for post-incident content, we highlight any results that are not confirmed by the contemporaneous data.

Adapting methods established by Mattson and Clark (2012) and Vernon et al. (2015), we reviewed all source material to obtain four categories of information: (1) the participant group to which statements were attributed, (2) statements about problems related to Libby Dam operations and management, (3) factual statements related to the Libby dispute and its social context, and (4) statements advocating solutions to problems.

We attributed all statements to corresponding participant groups and classified them as either problem, fact, or solution statements. Consistent with recommended methods for subjective contextual analysis of texts (Titscher et al. 2000), we summarized the statements to distill the essence of their communication (e.g., a paragraph-long solution statement from a participant might be summarized as “The US government should permit state representation in decision-making related to Libby Dam’s sturgeon operations”) and then grouped similar statements into statement types (e.g., “Improve state representation in decision making”) (Mattson and Clark 2012). We categorized statements by participant group according to the affiliation or societal role of the individual(s) to whom the statement was attributed (e.g. federal government, reporter, ENGO, First Nations) (Table 4.1). We then recorded the frequencies with which different participant groups made each type of problem, fact and solution statement in a matrix with statement types as rows and participant groups as columns. Frequencies were converted to binary presence-absence data (1 = occurrence, 0 = non-occurrence) for cluster analysis. We interpreted combined clusters of problem, fact and solution statement types as distinct problem discourses. 'Problem discourses' are thus composed of collections of statements by actors about problems – claims about "discrepancies between actual and desired states of affairs", facts – "assertions about the state of the world", and solutions – "alternatives to address an identified problem" (Vernon, Bischoff-Mattson, and Clark 2015, p. 68). This approach is consistent with research about the ways people define problems, in which all three components are part of a single discourse (Weiss 1989).

Table 4.1. Actor Group Codes and Descriptions

Code	Description
BC_CAN_pol	Canadian federal and BC provincial politicians (independent or opposition)*
BCGV	BC provincial government
CANGV	Canadian federal government
CONS-can	Canadian provincial and federal conservation agencies
CONS-us	US state and federal conservation agencies
ENGO	US environmental non-governmental organizations
ENT-can	Canadian Columbia River Treaty Entity (BC Hydro)
ENT-us	US Columbia River Treaty Entity (BPA, USACE)
LEGL-can	Canadian legal scholar (Bankes)
LEGL-us	US legal scholar (Blumm)
RBO-can	Canadian River Basin Organization (Columbia Basin Trust)
RBO-us	US River Basin Organization (Northwest Power and Conservation Council)
RPTR-can	Canadian newspaper reporter
RPTR-us	US newspaper reporter
TRIB-can	Ktunaxa First Nation
TRIB-us	Kootenai Tribe of Idaho
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGV-ct_st	US county and state government
USGV-fed	US federal government

*No statements from independent or opposition politicians were available from US sources

We detected separate discourses associated with coalitions of participant groups ('discourse coalitions') using automated cluster analysis in R with the vegdist (Oksanen et al. 2018) and hclust functions (R Core Team 2017). We used hierarchical agglomerative clustering, applying a Jaccard transformation and Ward's (1963) method to cluster problem, fact and solution statement types based on their co-occurrences across participant groups. We inspected initial outputs to detect coding errors and re-coded where appropriate before running a final cluster analysis. Within a discourse, we interpreted the top contributing participant groups to all combined statement types as that discourse's 'primary discourse coalition' (PDC). We identified the PDC by adding the proportional contributions from individual participant groups to all problem, fact, and solution statements in order from greatest to least until a 50% threshold was achieved. We included all participants above this 50% threshold in the PDC.

We also identified norms revealed during the dispute and their status at the onset, during, and after the dispute was resolved. To do so, we followed methods suggested by Willard (1984): a) survey trends in the broader surrounding context, b) expand time parameters of the survey beyond the incident itself, c) identify norms through the lens of a) and b), and d) only provide a final specification of relevant norms after assessing participant groups' statements of fact. We established baseline norms from historical contextual assessment of earlier events concerning the CRT that were factually similar or closely related to the incident (summarized in the preceding sections) (Willard 1984), then compared these with norms expressed during and after the incident in our source materials. We verified expressed norms by cross-checking across all seven types of data sources (see Table 4.3). We classified the status of norms as established or not yet revealed at the onset of the dispute, challenged or unchallenged during the dispute, and changed or unchanged post-dispute.

4.6. Results

4.6.1. Claims and Counterclaims

The broad claim made by Canada at the onset of the Libby dispute was that the USACE's operation of Libby Dam for sturgeon conservation contravened the Treaty and that the US was responsible for any losses to Canada caused by the operation. Canada argued that the USACE's unilateral action violated consultation and coordination requirements of the Treaty and resulted in annual economic losses in the range of \$3.6-4.2 million (1995 USD) from foregone Canadian power production resulting from upstream sturgeon operations at Libby. As a separate issue, in response to US claims Canada also reminded the US of the earlier PEB decision that US use of Treaty-based water for fish conservation must be authorized six years in advance by an approved AOP and could not reduce the Canadian Entitlement.

Table 4.2. Summary of Canadian and American legal claims

Canadian Claims

1. The US's unilateral action breached Article V of the Protocol Agreement to the Treaty. When Paragraph V is read in conjunction with Article XIV (2)a & d, and Article XII(5), it places a duty on the Entities to consult and coordinate Libby operations with Canadian plants to ensure Canada obtains the benefits contemplated by Article XII(2) and XII(4) and/or incurs no damages.
2. The timing of additional spill for sturgeon caused a loss of power generating capacity at Canadian downstream dams. Estimated annual losses ranged from 1995 CDN$ 4.9-5.8 million (USD 3.6-4.2 million*).
3. Article VIII (4) obligated the US to optimize flows for power generation, and, read in the context of the entire Treaty, prohibits a retrospective determination of the Canadian Entitlement (i.e. no adjustments for fish conservation after the Assured Operating Plan (AOP)).
4. The Treaty established no obligation to provide flows for US fish conservation. Canada acknowledged the endangered status of the Kootenai White sturgeon population but objected to the US's solution.
5. The US was not limited to power and flood management uses of Libby storage per Articles XII (1, 2, 5), but this does not mean it was free to operate Libby outside these uses without consequence.

American Claims

1. The US's unilateral action was consistent with Article XII (1) of the Treaty, which states that the purpose of Libby Dam is for flood management *and other purposes* in the US.
2. Article VIII (4) of the Treaty implied a reduction of the Canadian Entitlement was permissible when water is spilled for non-power purposes.
3. The US was not obligated to compensate Canada for downstream power losses caused by changes in timing/volume of Libby flows.
4. US obligations under the ESA superseded its obligations under the Treaty's operating plans (both AOP & DOP).
5. The duty imposed on the US by the Treaty was merely to consult, not to reach agreement about implementation of spill for sturgeon.

**Calculated using the annual average Canada-US exchange rate for 1995 (0.728802). Sources: this study*

The US countered that the Treaty always envisioned other uses for Libby Dam and that the US Entity did inform Canada of its intention to change Libby flows, but that Canada misconstrued the Treaty as requiring not only consultation but also agreement. Further, since the additional water spilled at Libby was for non-power purposes, the US felt it should be subtracted from the Canadian Entitlement (re-opening the earlier disagreement resolved by the PEB). This latter claim hinged on the assertion that the Entitlement is technically a 50% share of additional power production enabled by the Treaty and was not intended to incorporate other values such as fish conservation. Additionally, the US took the position that its domestic ESA obligations superseded its Treaty obligations and that it should not be held accountable for Canadian foregone power benefits.

4.6.2. Problem Discourses

In total, 107 unique sources supplied 1,913 individual statements about problems, facts and solutions related to the Libby Dam dispute (Table 4.3).

Table 4.3. Summary of problem, fact and solution statements by source type

Source Type	No. Sources	Problems	Facts	Solutions	TOTAL
Academic articles	12	44	245	53	**342**
Diplomatic notes	10	47	131	38	**216**
Government hearings & debates	32	90	192	33	**315**
Interviews	9	96	349	86	**531**
Legal, policy & technical reports	6	13	31	32	**76**
Letters & speeches	7	25	22	18	**65**
Newspaper articles	31	146	142	80	**368**
TOTAL	**107**	**461**	**1112**	**340**	**1913**

A majority of statements were factual assertions (58%), followed by problem statements (24%), and solution statements (18%). In order of statement frequency, interviews, newspaper articles, academic articles, and government hearings and debates were the largest contributors. Within the 1,913 individual statements, we identified 36 different types of problem statements, 62 different types of factual assertions, and 25 different types of solution statements. Cluster analysis then identified four problem discourses.

Based on themes observed in each discourse cluster, we named these problem discourses: (1) Treaty Violation, (2) Unrepresented Interests, (3) Sturgeon at Risk, and (4) Treaty Misinterpretation. We summarize results for each problem discourse and its associated coalition of participant groups in two separate tables for each problem discourse (Table 4.4 to Table 4.11). The first table lists statement types associated with the discourse and the second table provides the number and proportion of statement types for problem, fact and solution categories. For the latter tables, participant groups shown in bold are the overall “Primary Discourse Coalition” (PDC). The “total loading of PDC” (final row) is determined by adding the proportional contributions from individual participant groups in order from greatest to least until a 50% threshold is achieved. All participants above this 50% threshold in the ALL column are included in the PDC. Disaggregated results for problem, fact, and solution categories are shown to illustrate where non-PDC groups made meaningful contributions to each category despite not being included in the PDC. We characterize each problem discourse further in the Discussion sections.

Table 4.4. Problem Discourse 1: Treaty Violation - summary of statement types

Primary Discourse Coalition: ENT-can (17%); CANGV (15%); BCGV (14%); LEGL-can (13%)

Statements about Problems

- Canadian hydropower and revenue losses, leading to higher rates for ratepayers
- Increasing electricity demand and inefficient energy use
- Inability to proceed with Treaty implementation
- No resolution regarding Treaty interpretation
- Risk to water sovereignty (Canada)
- The US Entity is untrustworthy
- Treaty violation
- Unilateral nature of US Entity's actions for sturgeon
- US is incorrectly interpreting the Treaty
- Over-prioritization of fish conservation (US)

Post-incident sources only:

- Escalation of dispute to federal level (US and Canada)
- Climate change

Statements about Facts

- BC-Canada interests are strongly aligned
- Canada supports sturgeon conservation
- Fish conservation is important, values have shifted since the CRT was signed
- Libby operations for sturgeon negatively impact ecosystems around the reservoirs & wetlands
- Libby operations for sturgeon result in Canadian power losses
- Procedural facts* about the Libby Coordination Agreement
- Procedural facts* about the Libby dispute process
- The BC government formally condemned the US Entity
- The correct interpretation of the Treaty is that it is meant to prioritize power and flood management benefits
- The Treaty is an agreement for hydropower and flood management, not fish conservation
- The US is in breach of Treaty obligations
- There is a lot of scientific uncertainty about what sturgeon need to recover
- Canada benefits from Libby Dam and is entitled to these benefits
- Canada incurred costs from Libby construction
- The US benefits from Libby Dam

Post-incident sources only:

- The Entities have always worked well together

Statements about Solutions

- Canada US communication and cooperation (Libby dispute)
- Compensate Canada for foregone power benefits
- Elevate issue to federal level to spur US action (Canada)
- Empower Entities to negotiate a settlement
- Formal dispute resolution per Treaty (IJC, ICJ)
- LCA provisions permitting agreement
- Align ESA and Treaty obligations domestically (US)
- US to cease pursuing unilateral actions in future
- Use the Treaty to force US to change Libby sturgeon operations or provide compensation
- Non-cooperation (Canada to operate as it wishes without an AOP, terminate Non-Treaty Storage Agreements)
- Improve LCA to permit adjustment proportional to changing losses over time

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*Procedural facts refer to factual statements about administrative or implementation details (e.g., “The Libby Coordination agreement is an Entity agreement, not an agreement between Canada and the US” or “The Libby dispute included exchanges of diplomatic notes”

Table 4.5. Problem Discourse 1: Treaty Violation – number and proportion of statement types by participant group for problem, fact and solution categories

	ALL		Problem		Fact		Solution	
Group	*n*	%	*n*	%	*n*	%	*n*	%
BC_CAN_pol	0	0.0%	0	0.0%	0	0.0%	0	0.0%
BCGV	21	**14.0%**	7	**17.5%**	9	**12.9%**	5	**12.5%**
CANGV	22	**14.7%**	7	**17.5%**	9	**12.9%**	6	**15.0%**
CONS-can	0	0.0%	0	0.0%	0	0.0%	0	0.0%
CONS-us	4	2.7%	0	0.0%	4	5.7%	0	0.0%
ENGO	1	0.7%	0	0.0%	1	1.4%	0	0.0%
ENT-can	26	**17.3%**	8	**20.0%**	10	**14.3%**	8	**20.0%**
ENT-us	8	5.3%	2	5.0%	3	4.3%	3	7.5%
LEGL-can	19	**12.7%**	4	10.0%	10	**14.3%**	5	**12.5%**
LEGL-us	6	4.0%	1	2.5%	1	1.4%	4	10.0%
RBO-can	7	4.7%	2	5.0%	3	4.3%	2	5.0%
RBO-us	7	4.7%	0	0.0%	3	4.3%	4	10.0%
RPTR-can	11	7.3%	5	12.5%	6	8.6%	0	0.0%
RPTR-us	2	1.3%	0	0.0%	2	2.9%	0	0.0%
TRIB-can	3	2.0%	1	2.5%	2	2.9%	0	0.0%
TRIB-us	1	0.7%	1	2.5%	0	0.0%	0	0.0%
UNESCO	7	4.7%	1	2.5%	3	4.3%	3	7.5%
USGV-ct_st	1	0.7%	0	0.0%	1	1.4%	0	0.0%
USGV-fed	4	2.7%	1	2.5%	3	4.3%	0	0.0%
Total Statements	150		40		70		40	
Total Loading of PDC		**58.7%**		**55.0%**		**54.3%**		**60.0%**

Table 4.6. Problem Discourse 2: Unrepresented Interests – summary of statement types

Primary Discourse Coalition: TRIB-us (21%); RBO-us (13%); TRIB-can (13%); CONS-us (15%)

Statements about Problems

- Adverse effects on resident fish, habitat, and ecosystems of system-wide Libby operation for flood management and salmon conservation
- Adverse impacts of Libby operations on human health (dust) and water supply
- Lack of flexibility in flood management rules
- Lack of stakeholder, state and tribal government representation in LCA
- Lack of understanding of Libby sturgeon operations (US and Canada)
- Uncertainty, lack of evidence, about sturgeon needs for recovery
- Violation of tribal rights to fish
- Out-dated Treaty (not representative of current values)

Post-incident sources only:

- BC Hydro is more interested in profit than fish conservation
- Incorrect sturgeon operations at Libby (not as originally designed and implemented by the USACE due to ESA interference)
- Loss of sturgeon is cultural, subsistence and spiritual loss to tribes

Statements about Facts

- Facts about sturgeon conservation efforts other than Libby operations
- Libby operations for sturgeon increase flood risk
- Libby operations for sturgeon negatively affect residents around the reservoirs
- Other fish species are negatively impacted by Libby Dam
- Sturgeon are culturally and spiritually important to Indigenous people, who also have special fishing rights
- The Libby Coordination Agreement is not representative of all affected interests
- Libby operations for sturgeon negatively impact recreation and tourism
- Recreation and tourism interests are important
- Libby operations for system flood management and salmon negatively impact resident fish

Post-incident sources only:

- Canada and BC Hydro do not care about US fish conservation
- Kootenai Tribe of Idaho benefits from Libby Dam
- The Libby Coordination Agreement was a Canadian concession to secure the Entitlement
- The Libby Dispute was just a money grab by BC Hydro
- Tribal interests on both sides of the border were more aligned with sturgeon conservation than with BC Hydro's claims
- The LCA outcome was explained by BC Hydro to local residents

Statements about Solutions

- More inclusive of stakeholders, state and tribal governments and their interests
- Relax flood management rules

Post-incident sources only:

- Treaty revision to include environmental values

Table 4.7. Problem Discourse 2: Unrepresented Interests – number and proportion of statement types by participant group for problem, fact and solution categories

	ALL		**Problem**		**Fact**		**Solution**	
Group	*n*	%	*n*	%	*n*	%	*n*	%
BC_CAN_pol	3	3.5%	2	6.7%	0	0.0%	1	6.7%
BCGV	0	0.0%	0	0.0%	0	0.0%	0	0.0%
CANGV	1	1.2%	0	0.0%	1	2.3%	0	0.0%
CONS-can	1	1.2%	0	0.0%	1	2.3%	0	0.0%
CONS-us	13	**15.1%**	5	**16.7%**	7	**15.9%**	1	6.7%
ENGO	0	0.0%	0	0.0%	0	0.0%	0	0.0%
ENT-can	4	4.7%	1	3.3%	2	4.5%	1	6.7%
ENT-us	3	3.5%	0	0.0%	2	4.5%	1	6.7%
LEGL-can†	2	2.3%	0	0.0%	0	0.0%	2	**13.3%**
LEGL-us	0	0.0%	0	0.0%	0	0.0%	0	0.0%
RBO-can†	9	10.5%	2	6.7%	6	**13.6%**	1	6.7%
RBO-us	11	**12.8%**	6	**20.0%**	3	6.8%	2	**13.3%**
RPTR-can	1	1.2%	0	0.0%	1	2.3%	0	0.0%
RPTR-us	8	9.3%	3	10.0%	4	9.1%	1	6.7%
TRIB-can	11	**12.8%**	3	10.0%	6	**13.6%**	2	**13.3%**
TRIB-us	18	**20.9%**	6	**20.0%**	10	**22.7%**	2	**13.3%**
UNESCO	0	0.0%	0	0.0%	0	0.0%	0	0.0%
USGV-ct_st	4	4.7%	2	6.7%	1	2.3%	1	6.7%
USGV-fed	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Total Statements	86		30		44		15	
Total Loading of PDC		**61.6%**		**56.7%**		**65.9%**		**53.3%**

†Participant groups not included in the final PDC but still a primary contributor for at least one, problem, fact or solution category

Table 4.8. Problem Discourse 3: Sturgeon at Risk – summary of statement types

Primary Discourse Coalition: CONS-us (18%); RPTR-us (12%); ENGO (11%); LEGL-can (9%)

Statements about Problems

- Adverse impacts of Libby Dam on sturgeon
- Construction and operation of Libby Dam
- Declining and at-risk sturgeon population
- Different fish conservation laws, regulations, priorities in Canada and the US (esp. sturgeon)
- Lack of funding for fish and wildlife conservation
- Lack of prioritization of fish (incl. sturgeon) conservation
- Other causes of sturgeon decline
- Violation of ESA

Statements about Facts

- Actions performed by the US Entity under the Treaty are at risk of litigation under ESA (e.g., signing AOPs and DOPs)
- Canada benefits from Libby operations for sturgeon
- Canada was aware of upcoming sturgeon listing
- Facts about how Libby Dam is used for downstream salmon conservation
- Facts about what sturgeon need for recovery
- General descriptive facts about Kootenai sturgeon characteristics and life-cycle
- Libby Dam construction and operation are responsible for sturgeon decline
- Libby operations for sturgeon have positive impacts on the species
- Not enough is being done for sturgeon conservation (violation of ESA)
- Other factors contributed to sturgeon decline (not just Libby Dam)
- Procedural facts about Libby Dam construction and operation (pre-sturgeon operations) (e.g., onset of construction)
- Procedural facts about Treaty implementation (e.g., rules for creating AOPs and DOPs)
- Separate agreements can be used for fish conservation
- Sturgeon populations are declining
- The impacts of Libby operations for sturgeon on sturgeon recruitment are unclear
- There was tension between DFO and the Canadian Entity (BC Hydro) over Canada's position on Libby sturgeon operations
- Treaty flows from Arrow and Kootenay Lake were modified for Canadian fish conservation (prior to Libby)

Post-incident sources only:

- If Libby operations for sturgeon were conducted as originally designed and implemented by the USACE (and collaborators) they would not cause increased flood risk
- Canada's reaction to sturgeon operations at Libby was surprising because they also considered the species to be at risk

Statements about Solutions

- Altered Libby operations for sturgeon conservation
- Canada US cooperation (sturgeon conservation)
- Compensation for increased flood damages to farms from sturgeon operations (US)
- Decommission Libby Dam
- Sturgeon hatchery
- Relax flood management rules

Post-incident sources only:

- Improve communication and understanding about VarQ

• Establish a new RBO with more power to address power and conservation trade-offs than NPPC • Legal action (ESA violation) • Return to originally intended sturgeon operations	• Return to originally intended sturgeon operations (sturgeon tiered flows, integrated rule curves w/VarQ as implemented by USACE starting ~2001)

Table 4.9. Problem Discourse 3: Sturgeon at Risk – number and proportion of statement types by participant group for problem, fact and solution categories

	ALL		**Problem**		**Fact**		**Solution**	
Group	*n*	%	*n*	%	*n*	%	*n*	%
BC_CAN_pol	0	0.0%	0	0.0%	0	0.0%	0	0.0%
BCGV	2	1.4%	0	0.0%	1	1.2%	1	5.6%
CANGV	3	2.1%	0	0.0%	3	3.6%	0	0.0%
CONS-can	6	4.3%	1	2.6%	4	4.8%	1	5.6%
CONS-us	26	**18.4%**	7	**17.9%**	14	**16.7%**	5	**27.8%**
ENGO	16	**11.3%**	5	**12.8%**	9	**10.7%**	2	11.1%
ENT-can†	11	7.8%	1	2.6%	10	**11.9%**	0	0.0%
ENT-us	5	3.5%	1	2.6%	4	4.8%	0	0.0%
LEGL-can	13	**9.2%**	4	**10.3%**	9	**10.7%**	0	0.0%
LEGL-us	4	2.8%	0	0.0%	4	4.8%	0	0.0%
RBO-can	2	1.4%	0	0.0%	2	2.4%	0	0.0%
RBO-us	2	1.4%	0	0.0%	2	2.4%	0	0.0%
RPTR-can	6	4.3%	2	5.1%	3	3.6%	1	5.6%
RPTR-us	17	**12.1%**	6	**15.4%**	7	8.3%	4	**22.2%**
TRIB-can	4	2.8%	2	5.1%	2	2.4%	0	0.0%
TRIB-us†	9	6.4%	4	**10.3%**	3	3.6%	2	11.1%
UNESCO	1	0.7%	1	2.6%	0	0.0%	0	0.0%
USGV-ct_st	7	5.0%	2	5.1%	3	3.6%	2	11.1%
USGV-fed	7	5.0%	3	7.7%	4	4.8%	0	0.0%
Total Statements	141		39		84		18	
Total Loading of PDC		**51.1%**		**66.7%**		**50.0%**		**50.0%**

†Participant groups not included in the final PDC but still a primary contributor for at least one, problem, fact or solution category

Table 4.10. Problem Discourse 4: Treaty Misinterpretation – Summary of Statement Types

Primary Discourse Coalition: ENT-us (36%); USGV-fed (14%)

Statements about Problems

- Canada is incorrectly interpreting the Treaty
- Difficult to identify best sturgeon operation at Libby
- Treaty is ambiguous
- US hydropower losses from LCA, leading to higher rates for ratepayers
- Difficult to manage trade-off between power optimization and fish conservation

Statements about Facts

- The ability to operate Columbia River dams was at risk due to the Libby dispute
- The LCA is non-optimal for power production
- The Treaty can be interpreted in more than one way
- US power benefits from Libby are relatively small
- The correct interpretation of the Treaty is that it permits use of Treaty flows for fish conservation
- The ESA supersedes the Treaty (US)
- The Treaty can be interpreted as inclusive of fish conservation
- Canada's claims are not substantiated
- Escalation of the Libby dispute to the federal level did not aid in its resolution

Post-incident sources only:

- The Treaty (and LCA) is an internationally observed example of transboundary water cooperation
- The US incurs minor costs from the LCA

Statements about Solutions

- More sturgeon science
- Agree to interpret Treaty as inclusive of fish conservation

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Table 4.11. Problem Discourse 4: Treaty Misinterpretation – number and proportion of statement types by participant group for problem, fact and solution categories

	ALL		**Problem**		**Fact**		**Solution**	
Group	*n*	%	*n*	%	*n*	%	*n*	%
BC_CAN_pol	0	0.0%	0	0.0%	0	0.0%	0	0.0%
BCGV	0	0.0%	0	0.0%	0	0.0%	1	20.0%
CANGV	0	0.0%	0	0.0%	1	3.4%	0	0.0%
CONS-can	0	0.0%	0	0.0%	0	0.0%	0	0.0%
CONS-us	0	0.0%	0	0.0%	1	3.4%	0	0.0%
ENGO	0	0.0%	0	0.0%	0	0.0%	0	0.0%
ENT-can†	5	22.7%	0	0.0%	6	**20.7%**	0	0.0%
ENT-us	11	**50.0%**	5	**62.5%**	8	**27.6%**	2	**40.0%**
LEGL-can	1	4.5%	0	0.0%	1	3.4%	0	0.0%
LEGL-us	0	0.0%	0	0.0%	4	13.8%	0	0.0%
RBO-can	0	0.0%	0	0.0%	0	0.0%	0	0.0%
RBO-us	0	0.0%	1	12.5%	0	0.0%	1	20.0%
RPTR-can	0	0.0%	0	0.0%	0	0.0%	0	0.0%
RPTR-us	0	0.0%	0	0.0%	0	0.0%	0	0.0%
TRIB-can	0	0.0%	0	0.0%	1	3.4%	0	0.0%
TRIB-us	1	4.5%	1	12.5%	1	3.4%	0	0.0%
UNESCO	1	4.5%	0	0.0%	1	3.4%	1	20.0%
USGV-ct_st	0	0.0%	0	0.0%	0	0.0%	0	0.0%
USGV-fed†	3	13.6%	1	12.5%	5	**17.2%**	0	0.0%
Total Statements	22		8		29		5	
Total Loading of PDC		**50.0%**		**62.5%**		**65.5%**		**40.0%**

†Participant groups not included in the final PDC but still a primary contributor for at least one, problem, fact or solution category

4.6.3. Revealed Norms and Outcomes

We identify seven key norms revealed during the Libby dispute at both the international and domestic levels. Table 4.12 summarizes the status of these norms at the onset, during, and after the incident, and lists problem discourses that either supported norms discernable at the onset of the incident or desired normative change. Of the seven norms, four were already established and discernible at the dispute's onset. Norms that were not discernable prior to the dispute in the source materials for this study include those related to dispute resolution mechanisms and representation (3, 4 and 5 in Table 4.12). Of these, two were revealed only retrospectively in post-incident sources (4 and 5).

We distinguish two types of norms: “Treaty institutional norms,” which are expectations about how the Treaty should be interpreted and applied in practice, and “domestic legal norms”, which are expectations about how domestic conservation laws should be interpreted and applied in practice, including with respect to any obligations that conflict with an international treaty.

Treaty institutional norms include a) the expectation that Canadian Treaty flows may be used for US fish conservation without Canadian prior approval, b) that US fish conservation using Treaty flows may not result in Canadian economic losses, c) that responsibility for dispute resolution should be retained by the Entities, and, d) that in resolving conservation related disputes, it is not necessary to include affected parties from outside the main Treaty-based institutional arrangements (e.g. conservation agencies, ENGOs, First Nations and Tribes).

Domestic legal norms include the requirement to protect Kootenai white sturgeon under the ESA, and the expectation of both Canada and the US that although it is to be avoided, breaching an international Treaty may be acceptable to satisfy domestic laws.

Table 4.12. Summary of revealed norms, their change in status, and association with discourses supporting or challenging the norms

	Status			Problem discourses supporting or challenging the norm	
Revealed norms	Onset	During	After	Status quo	Change
Treaty Institutional Norms (International Level)					
1. Canadian Treaty flows may be used for US fish conservation efforts without Canadian prior approval	Established	Not challenged	Unchanged	Treaty Violation; Treaty Mis-interpretation	Not Applicable
2. US fish conservation efforts using Treaty flows must not result in Canadian economic losses	Established	Challenged	Unchanged	Treaty Violation	Treaty Mis-interpretation; Un-represented Interests; Sturgeon at Risk
3. Difficult conservation-related disputes (or any such disputes) should be referred to higher level dispute resolution mechanisms (e.g., federal, IJC, ICJ)	Established	Challenged	Changed	None	Treaty Violation; Treaty Mis-interpretation
4. Consultation with the conservation experts, agencies and ENGOs is unnecessary to resolve conservation-based Treaty disputes	Not revealed	Revealed and not challenged	Unchanged	Treaty Violation; Treaty Mis-interpretation	Unrepresented Interests
5. Consultation with First Nations/Native American governments is unnecessary to resolve conservation-based Treaty disputes	Not revealed	Revealed and not challenged	Unchanged	Treaty Violation; Treaty Mis-interpretation	Unrepresented Interests
Domestic Legal Norms (Domestic Level)					
6. ESA listed endangered species require protection	Established	Not challenged	Unchanged	Treaty Mis-interpretation; Un-represented Interests; Sturgeon at Risk	Not Applicable

	Status			**Problem discourses supporting or challenging the norm**	
Revealed norms	Onset	During	After	Status quo	Change
7. To satisfy domestic conservation laws, breach of an international Treaty may be acceptable domestically	Established	Not challenged	Unchanged	Treaty Violation; Treaty Mis-interpretation	Not Applicable

4.7. Discussion

In this section we return to the five questions raised in the introductory section (Section 4.1) and discuss our findings with respect to each question.

1. How do discourses and normative expectations differ across politically relevant groups regarding species conservation under the CRT?

While we observe general agreement across the four discourse coalitions about the need to protect Kootenai white sturgeon, the groups differ in their normative expectations about how that protection should be approached under the terms of the Treaty. These expectations range from a low prioritization of fish conservation relative to power and flood management values (Treaty Violation) to expectations that the Treaty's norms include fish conservation values (Sturgeon at Risk). We also observe disagreement about how and by whom decisions should be made (discussed under Question 2). Each problem discourse is characterized below.

Problem Discourse 1 – Treaty Violation

The first cluster of participants are focused on problems related to a perceived US violation of the Treaty and failure to meet Canadian interests (Table 4.4). The primary discourse coalition (PDC) for this set of problems, facts and solutions is composed of BC Hydro (as the Canadian Entity), the BC provincial government, the Canadian federal government and Canadian legal scholars (Table 4.5). The problem discourse is concerned with the trustworthiness of the US Entity, risks to Canadian water sovereignty, and the unilateral nature of the US's sturgeon operations at Libby Dam. While the importance of sturgeon conservation is acknowledged, that goal is secondary to protecting Canadian economic benefits from hydropower production. Knowledge gaps, such as scientific uncertainty about causal linkages between US sturgeon operations and improvements in sturgeon recruitment, are also highlighted. As stated by one interview participant, “I'm not aware of any evidence that this operation has led to recruitment of young sturgeon” (Canadian Entity representative, interview, April 16, 2013). Solutions favoured by this group do not preclude US sturgeon conservation operations, but they do demand compensation to Canada for any economic losses arising from reduced capacity to produce hydropower. This problem discourse also demands an end to unilateral operational decisions by the US and that the US work domestically to align the Treaty and the Endangered Species Act so as to avoid similar disputes in the future.

Problem Discourse 2 – Unrepresented Interests

Participants in this cluster were not part of the main Treaty-based institutional arrangements and are concerned primarily with a lack of representation for stakeholders, and state and Indigenous governments negatively affected by the loss of sturgeon and by Libby Dam operations (Table 4.6). The PDC for this problem discourse is composed of US Tribes, US state and federal conservation agencies, the US river basin organization (Northwest Power and Conservation Council), and Canadian First Nations (Table 4.7). Interview statements from US Tribe and Canadian First Nation representatives suggest that these groups view themselves as more closely aligned with one another and with Canadian and US sturgeon conservation interests than with the Canadian Entity. While not part of the PDC, the Canadian river basin organization (Columbia Basin Trust) aligns with a relatively large portion of the factual assertions for this discourse (6 of 15 statement types), which is not surprising considering the organization's mandate to ensure representation of community-based interests in the region.

This problem discourse views the Treaty as outdated and unrepresentative of modern values. Of primary concern are impacts of Libby Dam operations to human health from increased airborne dust due to reservoir drawdowns, protection of the water supply, recreation, tourism, resident fish species (including sturgeon), and tribal fishing rights. Members of the PDC view BC Hydro with distrust, citing a perceived profit motive and lack of concern for local interests, tribal interests, and fish conservation. One interviewee stated, "the way it played out it seemed primarily driven by Hydro's economic interests" (First Nation representative, interview, June 11, 2013). Another participant echoed this sentiment:

> I am, I guess, remaining hopeful that the BC First Nations and British Columbians in general will basically tell BC Hydro, which will give us the ability on the US side to tell US Army Corps of Engineers and Bonneville

> Power Administration - stop this damn bickering about how much money you think you should get and let's focus on actually governing this system in a way that benefits both of our countries (Native American Tribe representative, interview, May 23, 2013).

Favoured solutions include constitutive changes to the Treaty that incorporate environmental values, as well as greater representation of multiple interest groups in Treaty-related decision-making processes like the LCA. As stated by a First Nations representative:

> We think there needs to be co-management over Libby and the scope of that management and the context of that management needs to be expanded to explicitly include ecosystems and I think there was a missed opportunity to get to that point ten or more years ago with the LCA (interview, June 11, 2013).

Problem Discourse 3 – Sturgeon at Risk

The Sturgeon at Risk cluster's main focus is protection of the declining white sturgeon population in the Kootenay River downstream of Libby Dam (Table 4.8). Like the Unrepresented Interests cluster, this discourse coalition existed outside the main Treaty-based institutional arrangements. It is comprised primarily of US state and federal conservation agencies, US reporters, ENGOs, and Canadian legal scholars (Table 4.9). While not included in the PDC, statements attributable to US Tribes align with four of eight problem statement types, and those attributable to the Canadian Entity (BC Hydro) align with ten of 19 fact statement types. This latter finding reinforces that the Canadian Entity did not take issue with the facts of sturgeon decline, but viewed protection of hydropower benefits and economic return as more important.

Causes of sturgeon decline are viewed as including US violation of the ESA (i.e. lack of action and funding for sturgeon protection), adverse impacts to sturgeon from Libby Dam operations, other adverse impacts from historic diking and levee construction, and differences between Canada-US fish conservation laws and priorities.

Further, sturgeon, and other species such as burbot and bull trout, spend parts of their life cycles on both sides of the border and “people need to be continuously reminded” of this dynamic (US state conservation agency representative, interview, April 24, 2013). In collaboration with US states, ENGOs in this PDC harnessed procedural facts about the Treaty, the ESA, and sturgeon biology to construct a legal case against the US for failing to protect the fish. Some participants expressed surprise about Canada’s reaction to US sturgeon operations, citing that Canada knew the operations were pending, and precedents existed where sub-agreements accommodated fish conservation on both sides of the border. Inconsistences in the Canadian position are highlighted due to tensions between the Canadian federal Department of Fisheries and Oceans (DFO) (which supported sturgeon conservation) and BC Hydro (which was more focused on hydropower production):

> …there was some tension there between...Department of Fisheries and Oceans, on our side, because they were taking the sort of moral stand on restoring the Kootenay. So we were somewhat in tension with them in the sense that we were saying to the US, you shouldn't be allowed to operate like this for sturgeon (Canadian Entity representative, interview, April 16, 2013).

Potential solutions identified by participants in this PDC include legal action to enforce improved Libby operations for sturgeon, cross-border cooperation for sturgeon conservation, and construction of a sturgeon hatchery. As with the Unrepresented Interests PDC (see Table 4.6), this cluster is also supportive of more responsive flood management rules (i.e., ‘variable flow’ or VarQ, discussed below) combined with compensation to those impacted by any increased flood damage (e.g., farmers).

Problem Discourse 4 – Treaty Misinterpretation

This cluster’s main participants are affiliated with either the US Entity (BPA and USACE) or the US federal government (Table 4.11). The problem discourse focuses on Canadian misinterpretation of the Treaty (Table 4.10). However, statements attributable to the Canadian Entity align with more than twenty percent of the factual statement types for this discourse (6 of 29), suggesting that the Canadian Entity agreed with several of the facts asserted by the US.

The Treaty Misinterpretation discourse emphasizes problems on two fronts: (1) ESA obligations to protect sturgeon, and (2) disagreement with Canada about Treaty interpretation. The US Entity notes challenging tradeoffs between hydropower optimization and fish conservation, which contributed to the difficulty in identifying the best operational strategy at Libby Dam for sturgeon conservation. Ambiguities in the Treaty are cited to illustrate that Canada arrived at an erroneous interpretation and that sturgeon operations are permissible without any obligation to compensate Canada. For the US, the Treaty is viewed as subordinate to the ESA, and more sturgeon science is seen as the main solution to help the Entity meet its ESA obligations. To resolve the Libby dispute, Canadian agreement to interpret the Treaty as inclusive of fish conservation is this PDC's favoured solution.

2. What norms held by politically relevant groups were not apparent prior to the Libby Dam incident and what happened to these norms as a result of the dispute?

Returning to Reisman's and Willard's (1988) “law that really counts”, the Libby dispute revealed several normative expectations about the treaty, conservation, participation in decision making, and dispute resolution. Some of these expectations were apparent at the dispute's onset and were either unchallenged, challenged and changed, or challenged and not changed. Some norms were also not discernable in our source materials prior to the dispute, so the incident helped surface these norms and their status during and after the dispute (Table 4.12).

Focusing first on these latter norms, the incident showed that the expectation of the Entities is that representation of Indigenous governments, communities, and conservation agencies from outside the Treaty-based institutional arrangements is unnecessary to resolve disputes related to species conservation issues (4 and 5 in Table 4.12). BC Hydro did consult with First Nations and affected communities in Canada, and at least one First Nation stated their support for sturgeon conservation operations at Libby, but these groups had no real power over outcomes. We found no evidence that the Entities' normative expectations regarding representation were challenged during the dispute. However, one First Nations representative indicated they would have "pushed much harder" if the resolution moved away from what was viewed as "a fisheries-beneficial outcome" (interview, June 11, 2013), suggesting the Canadian Entity may have faced a greater domestic challenge if it had pressed to discontinue sturgeon conservation flows. In the US, conservation agencies (US Fish and Wildlife Service, Montana Fish and Wildlife, Idaho Department of Fish and Game), ENGOs, and Tribes had significantly more legal leverage backed by the ESA but were not afforded a seat at the decision-making table for the Libby dispute.

The CRT-based institution remained a closed forum. While this norm is fully consistent with historic interpretations of the formal content of the Treaty, the dispute brought into clearer view the implications for species conservation by revealing how the Entities can constrain and close decision-making processes under the Treaty by excluding affected parties like Indigenous governments and conservation agencies, despite these groups being directly interested in and affected by its impacts and having specialized knowledge about the affected species. This finding raises questions about the "success" of transboundary cooperation and the continued legitimacy of status quo institutional arrangements given evolving conservation needs in Canada and the US.

The incident also showed how both countries were reluctant to use the main formal Treaty mechanisms for dispute resolution (i.e., IJC mediation, tribunal, or ICJ-based litigation) due to uncertain outcomes and potentially large investments of time and money (Canadian Entity representative, interview, April 16, 2013; US Entity representative, interview, May 23, 2013). US reluctance may have also stemmed from the fact that the legal question at stake could pit international treaty law against the domestic Endangered Species Act. One Canadian interviewee described the Treaty's formal dispute resolution mechanisms as "disillusioning," contributing to the realization that "we weren't going to make much progress if we got into the diplomatic arena" (Canadian Entity representative, interview, April 16, 2013). Because the two governments could not agree, Canada was unwilling to sign-off on Detailed Operating Plans and that became a critical problem. After the expiration of the remaining Assured Operating Plans that were signed with a six-year lead time, the stalemate would place the Entities in the untenable situation of having no viable operating plan for the Treaty-based components of the Columbia River system. The following quote from one interviewee captures the resulting pressure that dam operators felt:

> I have to get you an agreement about what we're gonna do on Saturday and that immediacy, the fact that you've got a huge machine [the Columbia River] that you're operating jointly and have to operate it or it runs into default, I mean it's going to be chaos essentially. It means that I can negotiate like hell for the next five years about how many angels are on the pin, but Saturday I've got to know what to do to change the operation (Canadian Entity representative, interview, April 16, 2013).

Ultimately, with none of the Treaty's formal dispute resolution options being attractive to Canada or the US, the Entities were empowered by their respective governments to collaboratively develop a solution. This decision did not contravene the terms of the Treaty, which states that the two governments can agree on an alternative dispute resolution procedure via an exchange of notes (Article XVI (6)), but it did reveal normative expectations of the Entities and the two governments about the usefulness of the agreement's traditional dispute resolution mechanisms. One participant stated, "I think it's actually set up a bit of a model for resolution of other disputes" (Canadian Entity representative, interview, March 4, 2013). Additionally, representatives from other countries such as Brazil, Norway, Sudan and Thailand as well as other North American river basins have looked to the Treaty and the LCA as "a good example of how water agreements can work and how even difficult stuff like this can be resolved" (Canadian Entity representative, interview, March 4, 2013).

One previously established norm visible at the dispute's onset was challenged: US fish conservation efforts must not result in Canadian economic losses (1 in Table 4.12), an expectation that was supported by the PEB's 1988 ruling about the Canadian Entitlement. The Treaty Violation discourse (i.e. primarily Canadian federal and provincial governments and BC Hydro) supported the previously PEB-decreed norm, while the Treaty Misinterpretation discourse (primarily the US Entity) challenged the norm unsuccessfully. The LCA more firmly integrated fish conservation into the operational fabric of the Treaty, but only to the extent that the hydropower production benefits to Canada remain unaltered. The Entities essentially found flexibility within the existing treaty arrangements to allow the status quo norm to remain intact while still addressing conservation values.

The three remaining norms were unchallenged and thus remained unchanged after the Libby dispute. Once Treaty water crosses the border, the US is still permitted to use these flows for any purpose it wishes including fish conservation, no challenges were made to the ESA, and both countries retain a domestic legal option to breach an international Treaty to satisfy domestic conservation laws. On this latter point, both Canadian and American courts have held that it is permissible to breach an international water treaty to satisfy a domestic conservation statute as long as the treaty is not yet incorporated into domestic law (as is the case in both countries with the Columbia River Treaty) (Bankes and Cosens 2012). However, the breach would still be a violation of the country's international obligations, including its obligations under the United Nations' Vienna Convention on the Law of Treaties[28] (Aust 2013). Therefore, both countries typically endeavor to interpret domestic statutes consistently with international legal obligations to avoid conflict (Bankes and Cosens 2012).

3. How did domestic conservation laws affect interpretation, invocation and application of the CRT's formal text?

While normative expectations regarding fish conservation did not change significantly as a result of the Libby dispute, the incident nevertheless revealed the potential for domestic conservation rules to be used by external actors to directly impinge upon the Treaty status quo. The Sturgeon at Risk discourse coalition was backed by powerful ESA legislation and thus succeeded in breaching the internal-

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[28] Canada is party to the Vienna Convention while the US is not. However, based on the assessment of Bankes and Cosens (2012), if the Libby dispute had escalated to the ICJ, this point would likely have been moot since, as early as 1997, the court began establishing much of the Vienna Convention's content as a codification of customary international law and therefore binding even to non-parties. Furthermore, on other occasions prior to the dispute the US indicated that it regarded the Convention as binding (Anon. legal advice to Canada, 1995).

external divide between American CRT policy participants, a breach that led directly to the Libby dispute. This came as a surprise to some:

> …the importance of the Endangered Species Act in the US was quite a shock …I mean we've got an operating system here that is highly technical being run by a Judge [Judge James A. Redden] that has no technical experience at all. You want to surprise me? That surprised me…I was surprised that they were operating that way. I had no inkling that that was going to happen. I mean until they operated for them I didn't know there were sturgeon in Kootenay Lake below Libby (Canadian Entity representative, interview, April 16, 2013).

Meanwhile, one Canadian interviewee was surprised at BC Hydro’s resistance:

> The second thing that was surprising to me was that BC Hydro seemed to take such a strong view that this was simply about financial impact and that other values didn't have much bearing (anonymous interview, June 11, 2013).

These two contrasting views are emblematic of the key difference between the Treaty Violation problem discourse and the other three problem discourses, each of which support sturgeon conservation regardless of any economic impact to Canada. The Entities clearly still retain more control over the agenda, but the Libby dispute revealed that the Treaty-based institutional arrangements may need to adapt to keep pace with domestic conservation laws or face further, more frequent challenges to that control. Over the last two decades, American conservation interests backed by the ESA have increasingly succeeded in inserting conservation values into US Columbia River operations, and current Treaty negotiations (at time of writing) are expected to deliver a revised agreement by 2024 that better reflects environmental values on both sides of the border (British Columbia 2014, US Entity 2013).

4. What is the capacity of the CRT to adapt to external pressures for change regarding species conservation?

Incident analysis of the Libby dispute revealed a key limitation of the Treaty's adaptive capacity with respect to species conservation. The CRT was designed from the outset to optimize hydropower revenues and minimize flood risk. While the Treaty permits an element of flexibility to accommodate other uses through supplementary agreements, these adjustments only occur within the constraints of agreed-upon operations that first optimize for hydropower and flood management. Diversions from this standard on either side of the border will necessarily result in economic losses and this disincentive contributes to the Treaty's rigidity regarding protection of transboundary species-at-risk.

The most important normative shift illuminated by the dispute occurred asymmetrically – only the US was willing to adjust the priority of its own hydropower interests to accommodate conservation of a transboundary species-at-risk because it was obliged to do so according to its own domestic laws. Canada had no such obligation and was unwilling to accept these losses without compensation. Without formal changes to the Treaty or new normative interpretations of the agreement, future conservation goals may only be achievable in a consistent way across the border to the extent both parties agree, or are both bound by domestic laws, to accept hydropower revenue losses or more flexible flood management rules. As one interviewee stated, "In a sense it's a shame that it had to come down to the US fisheries law forcing it, but maybe in this case that was the only way for this to happen" (Canadian Entity representative, interview March 4, 2013).

Another key outcome of the dispute, the departure from existing norms about Treaty-based dispute resolution, also has implications for the Treaty's adaptive capacity. Originally, the Canadian Entity viewed escalation of the dispute to the federal level as a solution to prompt US action (see Table 4.4), but ultimately this action deterred timely resolution of the disagreement because the two governments were distrustful of the formalized CRT dispute resolution options at this level (e.g., IJC, tribunal, ICJ), viewing them as impractical. This reaction suggests these mechanisms are, or have become, unsuitable to meet the needs of the parties. As already noted, Article XVI (6) permits the two countries to agree on alternative procedures for dispute resolution at any time. In this case, empowering the Entities successfully moved the dispute to a point where operations could proceed at a technical level although the two countries continue to disagree about interpretations of the Treaty text. In this sense, the LCA represents a creative solution that ‘found’ operating flexibility within the status quo, illustrating an element of the Treaty’s existing adaptiveness. The fact that a way was found to accommodate conservation flows for sturgeon can be interpreted as hopeful for the successful resolution of future conservation challenges.

An alternative interpretation is that the Treaty’s flexibility in the Libby case may be insufficient to meet evolving conservation needs. As Mattson and Clark (2012) state (based on Birkland 2006), “incidents are plausibly one phenomenon that can trigger transitions in stable states, but typically only within destabilizing contexts that substantially undermine the influence and power of dominant discourses and coalitions” (p.2). Importantly, the LCA strategy further consolidated the Entities’ decision-making authority regarding species conservation issues and shifted normative expectations about how such disagreements should be approached in the future. In the process, this outcome demoted what are arguably more values-neutral formal dispute-resolution options available under the Treaty. This shift may be more practical for dam operators but it overlooks potential benefits of third-party oversight regarding conservation-based decisions in the context of a dispute, a potentially maladaptive standard given that the Entities are not, at present, formally guided by conservation values under the Treaty. Without more symmetrical domestic commitments or formal Treaty amendments, the normative precedent of Entity-based dispute resolution does not send a strong signal that the same outcome would be likely for future conservation challenges.

5. What alternative strategies are revealed by the Libby Dam incident that may be of use in future similar situations involving Canada and the US and in other international settings?

While the LCA provided a path forward through the gridlock that had developed between Canada and the US on the issue of Treaty interpretation, it is only a temporary solution. The Libby incident revealed several persistent problems for species-at-risk in the Columbia River Basin that remain unaddressed by the sub-agreement, issues that will likely resurface if conservation needs continue to increase. These problems include, a) insufficient flexibility in the operating regime, b) impractical dispute resolution mechanisms, c) a limited definition of shared 'benefits', and d) asymmetrical conservation laws on either side of the border.

Accommodating future fish conservation needs under the Treaty will require greater flexibility in the current operating standards. Two of the problem discourses (Unrepresented Interests, Sturgeon at Risk) favour relaxing flood management rules or making them more responsive to real-time conditions in order to meet a wider range of interests. One solution was developed during and after the Libby dispute and is still currently in use. The US has applied variable flow ('VarQ') flood management to accommodate sturgeon flows at Libby as a standard operation since 2003, but some feel the technique could be expanded system-wide:

> …if we better coordinate how all of these projects operate, we do basically a system-wide VarQ, where the wet sub-basins get drafted much further...not only for local flood management but they're part of what becomes system flood management [and] the dry sub-basins draft less…we benefit the fish in the reservoirs, we smooth out the rivers for the fish downstream…(US state conservation agency representative, interview, Aprill 24, 2013).

The VarQ method mobilizes modern aerial survey, monitoring, and modelling capabilities to refine the coarser 'system' (i.e. basin-scale) flood management rules, thereby permitting a more flexible optimization of flows across more values than just hydropower and flood management. In its original form, the approach incorporates finer temporal and spatial resolution to better accommodate variability in the volume and timing of flows in individual sub-basins rather than averaging across the whole basin or basing rules during dry-year operations on a single monitoring location such as The Dalles on the Columbia River. VarQ is part of a broader set of actions called 'The Montana Operation' designed to permit a more responsive adjustment of operations at Libby as conditions change within a given year, and in a way that benefits downstream values while minimizing tradeoffs with upstream values.

The advantages of VarQ for species conservation are acknowledged on both sides of the border. One Canadian interviewee considers VarQ a "…very positive outcome from the amended Libby operation", stating that the operations "are a tremendous benefit to fisheries interests on the Canadian side" (anonymous interview, June 11, 2013) including for Kokanee and bull trout. However, VarQ has been altered from its original form at Libby due to ESA-based regulations. These adjustments contribute to additional Canadian economic losses with no ability for the Canadian Entity to self-compensate under the current terms of the LCA:

> …the US changed its operations to this VarQ, which is a slight change, but it does increase some of the losses. Maybe the original compensation isn't working quite as well as they [the Canadian Entity] thought, so I think one of the things that might have been built in to improve it [the LCA] would have been some ability to change the amount or the timing of the provisional draft [the self-compensating mechanism] with the changes in losses (Canadian Entity representative, interview, April 16, 2013).

These losses prompted Canada to object to VarQ on power and flood management grounds in what is referred to by one interview participant as a potential "Libby Dispute Part Two" (Canadian Entity representative, interview, March 4, 2013). Nevertheless, at the time of writing, it is expected that VarQ can be accommodated under the LCA with minor amendments. A return to earlier versions of VarQ and the original intent of the Montana Operations may be beneficial and are currently being modelled under the Columbia River System Operations Environmental Impact Statement process (Brian Marotz, Montana Department of Fish, Wildlife, and Parks, pers. comm., November 27, 2018):

> [VarQ flood management] can be fixed if we would go back to the essence of what this operation was supposed to be and remove some of the changes that were added to this operation over time by others [i.e.

> ESA-based regulations] (US state conservation agency representative, interview, April 24, 2013).

Regarding dispute resolution mechanisms, prior to the Libby Incident the normative expectation was that other options in Article XVI would first be considered (i.e. IJC, tribunal) in the event of a disagreement that could not be resolved by the Entities. As noted above, the new norm of bypassing these options and further consolidating dispute resolution authority with the Entities can be interpreted as both a successful alternative, and as a questionable precedent for future conservation challenges depending on one's point of view.

The incident also illustrates that multiple interest groups and Indigenous governments feel unrepresented in CRT-based decisions affecting species conservation and other issues. An alternative solution not revealed by our study but widely used in transboundary basins globally is establishment of a transboundary river basin organization (Schmeier et al. 2015). Article XVI (6) could be used to empower a third entity that is regionally based and composed of representatives from different interest groups and governments on both sides of the border. River basin organizations can play governance roles that extend well beyond dispute resolution and region-specific Canada-USA models already exist that may serve as guides alongside international examples such as the Mekong River Commission (e.g. Pacific Salmon Commission, Great Lakes Commission) (Schmeier et al. 2015). This option could address many of the problems raised by the Unrepresented Interests discourse coalition by providing a forum for those groups to provide input and technical expertise while still leaving management of day-to-day operations to the Treaty Entities. Further, failing to afford Indigenous governments a seat at the CRT negotiating table no longer aligns with Canadian domestic laws and policies. On April 26, 2019, the Canadian federal government announced that Indigenous Nations would participate as observers (without veto power) during current Treaty negotiations (Global Affairs Canada 2019), suggesting that contemporary shifts in domestic Indigenous laws are forcing the Treaty-based institutional arrangements to become more open. At time of writing, the US federal government has made no similar move to include Native American Tribes.

The CRT loosely contemplates ‘other benefits’ beyond shared hydropower and flood management, but these values are not currently considered in the calculation of shared benefits under the Treaty. Additional benefits such as fish conservation, irrigation, navigation, and recreation could be incorporated using modifications to the same payment scheme that is already implemented under the agreement (i.e., the Canadian Entitlement). Payments for ecosystem services are an established practice often used to incentivize upstream water users to protect or supply ecosystem services enjoyed downstream (Lopéz-Hoffman et al. 2010). As the Libby incident shows, the Entities in fact already use payments for ecosystem services of a sort. Formally, the Canadian Entitlement arrangement only applies to shared hydropower benefits. But after the countries have settled on the payment amount, the US can use Canadian water made available to it under the Treaty for any purpose. This arrangement means that regardless of the parties’ formal interpretations, the Canadian Entitlement is indirectly serving as an ecosystem service payment. The difference between the pre-determined Entitlement payment and actual power generation during a given year is what the US is indirectly paying annually for non-power services (likely only a small portion of the actual value). A transboundary payment approach could be expanded more formally within the Treaty to encompass a broader definition of ‘benefits’, or ecosystem services. As one Canadian interviewee asserts, “…the deal that would save the Treaty is that we would get some financial benefit whether it's downstream power benefits or not and the US will get a flood management operation” [italics added by author] (Canadian Entity representative, interview, April 16, 2013).

The issue of asymmetrical conservation laws across borders is not a new problem for transboundary species (Ehringhaus 2012; Lopéz-Hoffman et al. 2009; Boyd 2003). The Libby incident highlights the mismatch between Canadian and US conservation laws, demonstrating the contrast in legal powers between the US Endangered Species Act, the Canadian Species at Risk Act, and the BC Wildlife Act. Canada also viewed the Kootenay white sturgeon population as endangered, but Canadian species conservation laws at both federal and provincial levels were much more discretionary than the ESA (Boyd 2003). While the dispute did not reveal solutions to this issue, Canada, the US, and other countries have experimented with harmonizing conservation practices. The European Union (EU) has a unifying water policy framework with river-basin scale objectives for aquatic species conservation (the Water Framework

Directive) (Voulvoulis et al. 2016; Sommerwerk et al. 2010), the Waterton-Glacier International Peace Park is an example of the joint creation of a transboundary protected area (Quinn et al. 2012), and the Canada-US Pacific Salmon Treaty, Yukon River Treaty, and Migratory Bird Treaty are transboundary conservation agreements for individual species or groups of species (Williams 2007). To our knowledge, with the exception of the two salmon treaties (Pacific Salmon Treaty and the Yukon River Treaty), conservation measures for individual species-at-risk do not exist in major transboundary freshwater agreements globally (OSU 2012). However, in our review of 274 agreements in Oregon State University's Freshwater Treaties Database, we did find five international agreements that contain commitments to protect species more broadly. In the Columbia Basin, a similar integration of species conservation into a revised Treaty is a more likely scenario than full-scale harmonization of policies and laws across the Canada-US border.

4.8. Conclusion

Meeting conservation goals has proven challenging for international water management programs worldwide (Gilman, Abell, and Williams 2004; Medema, McIntosh, and Jeffrey 2008). Speculation about 'water wars' has incited a sense of urgency to assess the role of shared watercourses in international relations (e.g. Homer-Dixon 1999), but the close ties between transboundary water management and species conservation remain largely ignored. The disciplinary 'home' of transboundary water research in international relations and international law has encouraged a research emphasis on legal aspects of transboundary water governance and state-level politics (e.g. Wolf 1998, Paisley 2002, Zeitoun and Warner 2006). While these research efforts reveal valuable insights, such as the highly successful history of water treaties as platforms for cooperation (Wolf 1998), and more nuanced understandings that emphasize asymmetrical power relations and underlying tensions between cooperating states (Zeitoun and Warner 2006), they rarely give sufficient consideration to the ecosystems being governed. The state-level orientation that is typical of international relations research also mutes the importance of interactions between domestic environmental regulation and transboundary water institutions – a gap that is particularly relevant for species conservation. International freshwater agreements often have major implications for aquatic, avian, and terrestrial species that move across political borders.

Meanwhile, domestic conservation laws can be misaligned with these agreements and the interests they represent for water-sharing neighbors. The Libby Dam Dispute confirms what has been emphasized by other scholars (e.g. Pahl-Wostl, Gupta, and Petry 2008) – it is important to examine water treaties at multiple levels of governance, not only to properly understand international hydro-relations, but also to gain insight into how these agreements impact and are impacted by protected species regulations at the domestic level.

In this study we focused on an illustrative dispute that arose due to opposing interpretations about the right of the US under the CRT to adjust flows from a dam for sturgeon conservation. Domestic legal obligations to protect the sturgeon under the US Endangered Species Act (ESA) challenged status quo treaty operations, leading to a disagreement with Canada when the US altered flows accordingly. We found that four different discourse coalitions formed around the issue, each with their own interpretations of the problem, normative expectations about how it should be addressed, and power to shape the agenda. Based on the reactions of these groups, the ESA did impinge upon established institutional norms of transboundary water management under the CRT. Rather than fully incorporate new norms for fish conservation into the CRT-based institutional arrangements, the response was to utilize some wiggle room within the terms of the treaty and the existing status quo to satisfy the interests of both parties. Looking to the future of the CRT, the existing institutional arrangements will be confronted with increasing species conservation needs on both sides of the border. Depending on one’s interpretation of the new dispute resolution norms that emerged from the Libby case, the outcomes demonstrate flexibility to adapt to these needs, or a consolidation of decision-making authority that could make it more difficult to respond to these needs without better harmonization of conservation laws across the Canada-US border or formal changes to the Treaty text. Other available solutions revealed by the Libby dispute include opening up the current operating regime to be more flexible to species conservation needs, improving dispute resolution mechanisms to be more regionally appropriate, perhaps through the creation of a CRT-based transboundary river basin organization that is more representative of multiple interests, and expanding the Treaty’s definition of ‘shared benefits’ to include species conservation values.

Appendix 4.A. Key articles and sections of the Columbia River Treaty

Columbia River Treaty, Article VII

Determination of Downstream Power Benefits

(1) The downstream power benefits shall be the difference in the hydroelectric power capable of being generated in the United States of America with and without the use of Canadian. storage, determined in advance and is referred to in the Treaty as the downstream power benefits.

(2) For the purpose of determining the downstream power benefits:

> (a} the principles and procedures set out in Annex B shall be used and followed;
>
> (b} the Canadian storage shall be considered as next added to 13.000.000 acre-feet of the usable storage listed in Column 4 of the table in Annex B;
>
> (c} the hydroelectric facilities included in the base system shall be considered as being operated to make the most effective use for hydroelectric power generation of the improvement in stream flow resulting from operation of the Canadian storage.

(3) The downstream power benefits to which Canada is entitled shall be delivered as follows:

> (a} dependable hydroelectric capacity as scheduled by the Canadian entity. and
>
> (b} average annual usable hydroelectric energy in equal amounts each month. or in accordance with a modification agreed upon under paragraph (4).

(4) Modification of the obligation in paragraph (3) (b) may be agreed upon by the entities.

Columbia River Treaty, Article XII

Kootenai River Development

(1) The United States of America for a period of five years from the ratification date, has the option to commence construction of a dam on the Kootenai River near Libby, Montana, to provide storage to meet flood control and other purposes in the United States of America. The storage reservoir of the dam shall not raise the level of the Kootenai River at the Canada-United States of America boundary above an elevation consistent with a normal full pool elevation at the dam of 2,459 feet, United States Coast and Geodetic Survey datum. 1929 General Adjustment. 1947 International Supplemental Adjustment.

(2) All benefits which occur in either country from the construction and operation of the storage accrue to the country in which the benefits occur.

(3) The United States of America shall exercise its option by written notice to Canada and shall submit with the notice a schedule of construction which shall include provision for commencement of construction, whether by way of railroad relocation work or otherwise, within five years of the ratification date.

(4) If the United States of America exercises its option, Canada in consideration of the benefits accruing to it under paragraph (2) shall prepare and make available for flooding the land in Canada necessary for the storage reservoir of the dam within a period consistent with the construction schedule.

(5) If a variation in the operation of the storage is considered by Canada to be of advantage to it the United States of America shall, upon request, consult with Canada. If the United States of America determines that the variation would not be to its disadvantage it shall vary the operation accordingly.

(6) The operation of the storage by the United States of America shall be consistent with any order of approval which may be in force from time to time relating to the levels of Kootenay Lake made by the International Joint Commission under the Boundary Waters Treaty, 1909.

(7) Any obligation of Canada under this Article ceases if the United States of America, having exercised the option, does not commence construction of the dam in accordance with the construction schedule.

(8) If the United States of America exercises the option it shall commence full operation of the storage within seven years of the date fixed in the construction schedule for commencement of construction.

(9) If Canada considers that any portion of the land referred to in paragraph (4) is no longer needed for the purpose of this Article Canada and the United States of America, at the request of Canada, shall consider modification of the obligation of Canada in paragraph (4).

(10) If the Treaty is terminated before the end of the useful life of the dam Canada shall for the remainder of the useful life of the dam continue to make available for the storage reservoir of the dam any portion of the land made available under paragraph (4) that is not required by Canada for purposes of diversion of the Kootenay River under Article XI II.

Columbia River Treaty, Article XIV

Arrangements for Implementation

(1) Canada and the United States of America shall each, as soon as possible after the ratification date, designate entities and when so designated the entities are empowered and charged with the duty to formulate and carry out the operating arrangements necessary to implement the Treaty. Either Canada or the United States of America may designate one or more entities. If more than one is designated the powers and duties conferred upon the entities by the Treaty shall be allocated among them in the designation.

(2) In addition to the powers and duties dealt with specifically elsewhere in the Treaty the powers and duties of the entities include:

> (a) coordination of plans and exchange of information relating to facilities to be used in producing and obtaining the benefits contemplated by the Treaty,

(b) calculation of and arrangements for delivery of hydroelectric power to which Canada is entitled for providing flood control,

(c) calculation of the amounts payable to the United States of America for standby transmission services,

(d) consultation on requests for variations made pursuant to Articles XII (5) and XIII (6),

(e) the establishment and operation of a hydrometeorological system as required by Annex A,

(f) assisting and cooperating with the Permanent Engineering Board in the discharge of its functions,

(g) periodic calculation of accounts,

(h) preparation of the hydroelectric operating plans and the flood control operating plans for the Canadian storage together with determination of the downstream power benefits to which Canada is entitled,

(i) preparation of proposals to implement Article VI I I and carrying ,I out any disposal authorized or exchange provided for therein,

(j) making appropriate arrangements for delivery to Canada of the downstream power benefits to which Canada is entitled including such matters as load factors for delivery, times and points of delivery, and calculation of transmission loss,

(k) preparation and implementation of detailed operating plans that may produce results more advantageous to both countries than those that would arise from operation under the plans referred to in Annexes A and B.

(3) The entities are authorized to make maintenance curtailments. Except in case of emergency, the entity responsible for a maintenance curtailment shall give notice to the corresponding Canadian or United States entity of the curtailment, including the reason therefor and the probable duration thereof and shall both schedule the curtailment with a view to minimizing its impact and exercise due diligence to resume full operation.

(4) Canada and the United States of America may by an exchange of notes empower or charge the entities with any other matter coming within the scope of the Treaty.

Columbia River Treaty, Article XVI

Settlement of Differences

(1) Differences arising under the Treaty which Canada and the United States of America cannot resolve may be referred by either to the International Joint Commission for decision.

(2) If the International Joint Commission does not render a decision within three months of the referral or within such other period as may be agreed upon by Canada and the United States of America, either may then submit the difference to arbitration by written notice to the other.

(3) Arbitration shall be by a tribunal composed of a member appointed by Canada. a member appointed by the United States of America and a member appointed jointly by Canada and the United States of America who shall be Chairman. If within six weeks of the delivery of a notice under paragraph (2) either Canada or the United States of America has failed to appoint its member. or they are unable to agree upon the member who is to be Chairman. either Canada or the United States of America may request the President of the International Court of Justice to appoint the member or members. The decision of a majority of the members of an arbitration tribunal shall be the decision of the tribunal.

(4) Canada and the United States of America shall accept as definitive and binding and shall carry out any decision of the International Joint Commission or an arbitration tribunal.

(5) Provision for the administrative support of a tribunal and for remuneration and expenses of its members shall be as agreed in an exchange of notes between Canada and the United States of America.

(6) Canada and the United States of America may agree by an exchange of notes on alternative procedures for settling differences arising under the Treaty, including reference of any difference to the International Court of Justice for decision.

Article V of the Protocol Agreement to the Columbia River Treaty

Inasmuch as control of historic strearnflows of the Kootenay River by the darn provided for in Article XII(I) of the Treaty would result in more than 200,000 kilowatt years per annum of energy benefit downstream in Canada, as well as important flood control protection to Canada, and the operation of that dam is therefore of concern to Canada, the entities shall, pursuant to Article XIV(2) (a) of the Treaty, cooperate on a continuing basis to coordinate the operation of that dam with the operation of hydro-electric plants on the Kootenay River and elsewhere in Canada in accordance with the provisions of Article XII(5) and Article XII(6) of the Treaty.

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Chapter 5. Conclusion

In this dissertation, I aim to advance understanding about how species conservation needs can be better addressed in bi- and multi-lateral international freshwater treaties. I do this using the Columbia River Treaty and the river basin it governs to examine key barriers to the inclusion of species conservation in treaty negotiating agendas, and treaty implementation. In the introductory chapter I outline the omission of formal species conservation commitments in freshwater treaties globally and suggest that this omission may be explained, in part, by negotiators' aversion to complexity in favour of flexibility and consensus, a tendency to undervalue species relative to other values, and the limited ability of negotiators to fully understand the species-related trade-offs at stake. In Chapter 2, I tackle the second of these barriers by showing how the economic welfare benefits generated by salmon in the Columbia River are not fully realized, and, based on four ecosystem services provided by salmon, are certainly greater than the default value of zero that is implicit in the Columbia River Treaty by omission. In Chapter 3, I turn to the third barrier, illustrating with a decision analytic approach how more informed trade-offs can be made across salmon conservation, hydropower, and irrigation values in the Columbia River's Hanford Reach. In Chapter 4, I shift from these simulation-based approaches, using a method called incident analysis to illustrate the importance of political actors' normative expectations in defining how the Columbia River Treaty is actually interpreted and applied in practice with respect to species conservation.

A number of key findings are highlighted by my research. First, I show that relative to current operating practices, a 10% greater prioritization of salmon conservation via shifts in the current Columbia River flow regime would generate an increase of $4.8 million/yr in net economic benefit from a small subset of ecosystem services derived from salmon. While the proposition that salmon are worth more than nothing is not outlandish, particularly given the fact that Bonneville Power Administration's 2018 expenditures on its Columbia River Basin Fish and Wildlife Program were over $480 million USD, with $2.9 million attributable to foregone hydropower revenues largely in support of salmon conservation (NPCC 2019), results from Chapter 2 provide a conservative welfare estimate that should reinforce for Columbia River Treaty negotiators that the value of salmon to society is quite different from that reflected in the agreement's original formulation. For scale comparison, the entire value of the Canadian Entitlement, Canada's 50% share of hydropower benefits resulting from CRT operations, averages around $120 million/yr (Province of British Columbia, 2019). If salmon conservation services were included in the benefits calculation, and operations were adjusted to reflect their value, this shared benefit would clearly increase.

Second, transboundary fish conservation cannot be considered in isolation from other riverine ecosystem services people care about and depend upon like hydropower production and agricultural irrigation. Making these trade-offs clearer to Treaty negotiators can support the integration of fish conservation into a modernized Columbia River Treaty by improving negotiators' understanding of what is at stake, and by using computer simulation to "discover" alternative flow management strategies that produce a better balance across these three valued components. I show how a temporary, annually renewed, sub-agreement under the Columbia River Treaty is not currently providing the most optimal allocation of benefits across salmon conservation, hydropower and irrigation values. Although optimal levels are not physically achievable during many years historically, there are achievable sub-optimal increases to the current 1 million acre-feet (MAF) of flow augmentation delivered from Canadian reservoirs that would increase benefits across all three values. An important lesson from this study is that balancing multiple values rather than prioritizing a single value can be achieved with minimal negative impact to any single value. Based on my results, the US and Canada may wish to consider additional deliveries of water from Canadian reservoirs to Hanford Reach between March-July and to replace the current practice of temporary sub-agreements with a more formalized approach. Rather than relying on specific volumetric allocations, a more adaptive strategy given uncertainty about future flow conditions would be to allow, under the Treaty, for a range of flow augmentation volumes or an agreed-upon proportion of available storage.

Third, given that most of the world's freshwater treaties do not contain species conservation commitments, and that these agreements tend to have long revision cycles, if any, getting species conservation into negotiating agendas is only a partial solution. It is also important to consider how treaties are interpreted in practice regardless of the formal content of treaty texts. While the Columbia River Treaty is silent regarding species conservation, various sub-agreements enabled by the Treaty have occurred between Canada and the US to address species conservation needs. The existence of these agreements reveals that Treaty-based institutional norms about how species conservation should be considered can significantly influence the fate of at-risk fishes in transboundary river basins. An incident of conflict over the use of CRT flows for sturgeon conservation (the Libby Dam dispute) illustrates that the nature of these agreements depends very much on the normative expectations of politically relevant actors – in this case, the Treaty Entities (BC Hydro, Bonneville Power Administration, and the

US Army Corps of Engineers), national and provincial/state governments, and onlooking groups with a stake in the outcome. Rather than fully incorporate new norms for fish conservation into the CRT-based institutional arrangements, the resolution of this dispute was to utilize some wiggle room within the terms of the Treaty and the existing status quo to satisfy Canada's hydropower and the US's fish conservation interests. I project that this status quo will be increasingly confronted with species conservation needs on both sides of the border and that the Treaty-based institution will struggle to adapt without new normative interpretations of the agreement or formal changes to the Treaty text. Solutions to this challenge include better harmonization of conservation laws across the Canada-US border, opening up the current hydro-operating regime to be more flexible to species conservation needs, improving dispute resolution mechanisms to be more regionally appropriate (e.g., via the establishment of a transboundary river basin organization), and expanding the Treaty's definition of 'shared benefits' to include species conservation values. Given that the Treaty is currently undergoing changes, another key recommendation of this dissertation is that negotiators embrace complexity in the agreement, revising its text to include a greater degree of specificity regarding fish conservation. Harnessing modern decision-support tools to afford fish conservation with the same level of specificity as commercial values like hydropower and irrigation will make the Treaty more responsive over the long term.

In conclusion, the integration of species conservation into bi- and multi-lateral freshwater treaties faces a number of obstacles. In this dissertation I have addressed some of these obstacles by showing how it is possible to avoid undervaluing transboundary species (Chapter 2) and to evaluate trade-offs from species conservation in a way that transparently communicates the costs and benefits of different management strategies across multiple values (Chapter 3). These contributions can support negotiations of new freshwater treaties or the renegotiation of established ones by surmounting two of the barriers to the inclusion of species conservation in negotiating agendas. For existing agreements with no revision cycle in sight, it may still be possible to meet species conservation needs in some cases if politically relevant actors shift their normative expectations about how formal treaty texts should be interpreted in practice.

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