Preparing for Water Change in the Columbia River Basin: An Integrated Analysis of Vulnerability & Climate Research Review

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Authorization to Submit Dissertation

This dissertation of Paris B. Edwards, submitted for the degree of Water Resource Law, Management, & Policy and titled "Preparing for Water Change in the Columbia River Basin: An Integrated Analysis of Vulnerability & Climate Research Review," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Water is fundamental to social and environmental systems, particularly throughout the Columbia River Basin (CRB). However, climate impacts and population growth pressure on water resources will affect everyone living in the Basin, but not equally and there is growing concern over whether the status quo is sustainable (Hamlet et al., 2007; Cosens et al., 2016). Significant changes to the quantity and quality of water resources are already apparent across CRB. Changing climate patterns and increased average winter temperatures have contributed to a shift from snow to rain dominant precipitation, particularly at mid-elevations (Nolin & Daly, 2006). The resultant declines in snowpack, coupled with limited water storage infrastructure, indicate risk of diminished water resources throughout the Basin (Mote et al., 2005; Payne et al., 2005). The attending changes to water volume and timing of availability have broad hydrologic, as well as social implications. The following three studies share in common exploration of regional water resource challenges and spatial analyses. From this work, we grain understanding of regional research funding patterns and conclude that there is a relative dearth of funded, peer-reviewed mountain climate research in the CRB that integrates the social and physical realms. In addition, we provide a novel approach to representing spatio-temporal distribution of social and physical vulnerability to climate change induced water resource loss at a water management scale (subbasin). Our results from two comparative methodological approaches, equal and variance weighting, uncover consistent patterns of vulnerability across the Basin, and suggest that "hotspots" of overlapping vulnerabilities also exist within the study area. We provide suggestions for further research and conclude that hotspot subbasins may be considered priority areas for next steps in targeting finite resources for integrated climate research and water loss adaptation efforts, in addition to community scale vulnerability analyses.

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Dedication

With love, appreciation, and admiration for all of the "curious cats" in my family, past, present, and future.

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Statement of Contribution

Coauthors for chapter one include: Courtney Cooper, Meghan Foard, Dr. Shana Hirsch, Dr. Adrienne Marshall, Micah Russell, & Dr.Timothy Link. The inspiration for this work came out of group discussions at the 2017 MtnClim conference in Leavenworth, WA. All authors contributed equally to the vision and research idea, the data analysis and methodologies chosen, and final review of research results. The original draft was lead by Meghan Foard and Adrienne Marshall, with writing contributions spread equally among the research team.

Overview

Introduction

Water resources are fundamental to the efficacy, function, and existence of social and environmental systems, particularly throughout the western United States and the Columbia River Basin (CRB). There is growing concern over whether the status quo is sustainable given increasing population growth and projected climate impacts (Cosens & Williams, 2012). Significant changes to the quantity and quality of water resources are already apparent across CRB. Changing climate patterns and increased average winter temperatures have contributed to a shift from snow to rain dominant precipitation, particularly at mid-elevations (Nolin & Daly, 2006). The resultant declines in snowpack, coupled with limited water storage infrastructure, indicate risk of diminished water resources throughout the Basin. The attending changes in water availability and timing have broad hydrologic, as well as social implications (Regonda et al., 2005).

Climate impacts and population growth pressure on water resources will affect everyone living in the Basin, but not equally. The effects of climate change, in particular, are specific to place and can be viewed as a temporally dependent function of social and environmental vulnerability (Cutter, 1996). Climate change and water loss consequences can be thought of as a long-term, pressing or “chronic” hazard with potential for increases in episodic “pulse” events or disasters (Collins et al., 2011). Proactive adaptation is critical and should be informed by social and physical sensitivities to water loss.

The current literature on snow loss and water resources in the western US tends to address hydrologic implications exclusively (Christensen et al., 2004; Mote et al., 2005; Barnett et al., 2008, and others). The social impacts of snow loss, when considered in the peer-reviewed literature, are commonly addressed independently (Adger, 1999; Young et al., 2006; Füssel & Klein, 2006; Cosens & Williams, 2012). As a result, interpretations of risk and vulnerability to water loss may be overly simplistic because they do not consider variability human-environment interaction dynamics. A notable exception is the water vulnerability study of the CRB conducted by Chang et al. (2013), which uses spatial analysis to assess physical and social indicators of water quality and quantity at the county scale within US portion of the Basin.

Presently, there are no known studies of this region that explore social and hydrologic vulnerability together at a sub-county scale; nor do they address the critical ethical implications of the equity of impacts across the CRB. Here, we present a systematic approach to operationalize vulnerability to social and environmental stressors at the hydrologic cataloguing unit or subbasin scale (also referred to throughout the document as HUC8) and apply it to all subbasins within Washington, Idaho, and Oregon to examine hotspots (or double exposure potential) of vulnerability to climate change-induced water loss. Subbasins envelop major tributaries to the Columbia River and are relevant to both management and hydrology in the Basin. We are compelled to address these pressing knowledge gaps by exploring questions that weave people and their environment together. In doing so, we acknowledge that aspects of vulnerability to water loss are rooted in social injustices from influences at multiple scales that threaten our most sensitive populations and may undermine adaptation efforts and therefore sustainability for the region (Kasperson et al., 2001). The socio-ecological systems literature frames the theoretical underpinnings of our integrated approach, highlighting the inextricable interconnection of water, humans, and the environment (Berkes & Folke, 2000; Berkes et al., 2003; Cumming et al., 2006; Folke, 2006; Armitage et al., 2009; Collins et al., 2011; Abson, 2012; Silva et al., 2012). Through this holistic lens, we take an interdisciplinary approach drawing primarily from social science, hydrology, and geography to contribute new knowledge and strategies for understanding and anticipating water loss vulnerability.

The following chapters explore social (chapter 1) and physical vulnerability separately before integrating and exploring these concepts together (chapter 2). The third and final chapter includes a systematic review of mountain climate research in the CRB. It aims to highlight areas of research focus as well as research gaps that represent opportunities for the next generation of actionable science to inform climate adaptation across the Basin.

Study Site Description & Hydrology

The CRB is situated in the Pacific Northwest (PNW) region of the United States and includes portions of 7 states (Oregon, Washington, Idaho, Montana, Wyoming, Nevada, and Utah), and the Canadian province of British Columbia where the Columbia River originates. More than 8 million people depend on the Columbia and its tributaries for drinking water, irrigation, power generation, flood control, navigation, recreation, and cultural-spiritual fulfillment (BOR, 2016). Our decision to include Oregon, Washington, and Idaho, acknowledges that these states make up over 70% of the CRB area and hold the majority of the Basin population (McGinnis & Christensen, 1996).

The impetus for this research is driven by current climate trends and predicted future conditions; changes to precipitation and the availability of freshwater resources are expected to be some of the most significant impacts of climate change (Raymond et al., 2014). The hydrology of the Basin is characterized by a temperature-sensitive cycle of snow accumulation and runoff and is highly dependent on winter snowpack for seasonal water supply (Payne et al., 2004). The CRB, like most of the western US, experiences seasonal precipitation from mid-late fall, through winter, and into early and mid spring with little to no accumulation during the summer and early fall months (Nolin & Daly, 2006). The seasonality of precipitation implies the need for water storage, particularly because water demand throughout the Basin is greatest during the driest summer and early fall months. The CRB is mountainous and has historically depended on high elevation mountain snowpack to naturally store seasonal water supply throughout much of the Basin. Several studies have concluded that average winter and summer temperatures in the Northwest are already increasing at higher rates than the rest of the region and are projected continue this trajectory (Mote, 2003; Mote et al., 2005; Hamlet & Lettenmaier, 2007; Mote et al., 2010). Regional studies of rain/snow shift indicate that changes in dominant precipitation regimes (from snow to rain) could lead to water resource scarcity, particularly during late summer and early fall months when demand (human and natural) is highest. Research by Regonda et al. (2005), Nolin & Daly (2006), Elsner et al. (2010) and others indicate that elevation areas with average winter temperatures near the 0 degree Celsius rain/snow threshold (1,000-2,000m [3,280-6,560ft]) are at greatest risk of precipitation phase change with only small increases in temperature. Hydrologic projections for the region indicate that peak snowmelt runoff could occur up to 3-4 weeks earlier than the current average by mid-century (Barnett et al., 2005; Brekke et al., 2009; Elsner et al., 2010). Variability in water resource timing and availability is one of the many impacts expected to intensify over time across the Basin with direct and indirect consequences to the region's dominant management challenges, including: protecting ecosystem health for federally protected salmon species, hydro-electric power generation (70% of power use in the PNW), recreation, navigation, and providing flood control (Payne et al., 2004; Barnett et al., 2005; Dalton et al., 2013).

Several climate studies use spatial analysis to represent water resource vulnerability in the region (Mote et al., 2005; Payne et al., 2005; Nolin & Daly, 2006; Hamlet & Lettenmaier, 2007; Mote & Salathe, 2010; Chang et al., 2013; Abatzoglou et al., 2014; Klos et al., 2014). While these studies provide powerful visuals and add valuable consensus over expected future warming and hydrologic impacts to the PNW, subbasin scale trends and social indicators of vulnerability are not included within these assessments.

Subbasin Scale Unit of Analysis

The Columbia River Basin is a first-field, regional hydrological unit, which is part of a hierarchical system delineated and classified by the U.S. Geological Survey (2007). The CRB is identified with a two-digit hydrologic unit code (17) with nested subunits ranging from the 4-digit (subregional) to 12-digit (subwatershed) scale (USGS, 2007). For the purpose of this vulnerability analysis, the major tributary units at the fourth-field, 8-digit HUC scale are used due to relevance to hydrology, management, and compatibility with community-scale vulnerability data (Parkes et al., 2008). We refer to HUC8 units interchangeably with “subbasins” throughout this paper. Specific aggregation approaches to assess vulnerability at the subbasin scale are addressed in chapters 1 & 2. Combining several vulnerability indicators poses the challenge of incompatible units e.g., poverty and runoff variability have different units of measurement and therefore can’t be directly compared (Alessa et al., 2008). Thus data normalization and aggregation is necessary, but come with drawbacks. While aggregation facilitates the identification of hotspots, creating a single, composite index loses significant meaning in the data. Specifically, the relationship between indicators is lost and the ability to see differences in indicator strength across space (e.g. an entire subbasin will have a single value for runoff variability and poverty, rather than visible patterns of difference within its boundaries). We include mapped representations of social, physical, and a combined index of vulnerability, and therefore at least partially address this pitfall with visual representation of the results.

Vulnerability Defined

Water resource vulnerability is determined by the place-specific conditions of the physical hydrologic systems, the social systems, and their interactions (Pampalon et al., 2009). Recent studies have been critical of the absence of precision in the term "vulnerability," pointing to the lack of a single, unifying definition (Barnett et al., 2008; Turner et al., 2003; Cutter et al., 2000). We combine common definitions of social and environmental vulnerability (O'Brien et al. 2004). *Social vulnerability* is "the differential capacity of individuals and social groups to cope, recover, or adapt to the effects of acute or chronic environmental changes that stress their livelihoods and well-being" (Kelly & Adger 2000, p.348; Collins & Bolin 2007, p.402). To address environmental dimensions, the IPCC defines climate vulnerability as "a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (McCarthy et al., 2001, p.1066). *Exposure* is the degree to which a system experiences internal or external system disruption, *sensitivity* is the degree to which a system is affected by disruptions (McCarthy et al., 2001), and *adaptive capacity* is the ability of a system to adjust form and function in order to cope with external pressures (Brooks, 2003; Abson, 2012). Each of these definitions acknowledges that vulnerability is specific to time and place and is dynamic in nature. A comprehensive definition that is relevant to both social and environmental concepts describes vulnerability as "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes (IPCC, 2001). This aggregated concept of vulnerability encompasses the multiple interconnected elements of exposure, sensitivity, and adaptive capacity related to socio-environmental conditions (Figure 0.1). Thus, like O'Brien (2004) we assume that current and future exposure to climate change influences sensitivity, and that subbasins with greater adaptive capacity will respond to changes in climate sensitivity. As a result, we select and combine indices of exposure, sensitivity, and adaptive capacity that are relevant to the CRB context.

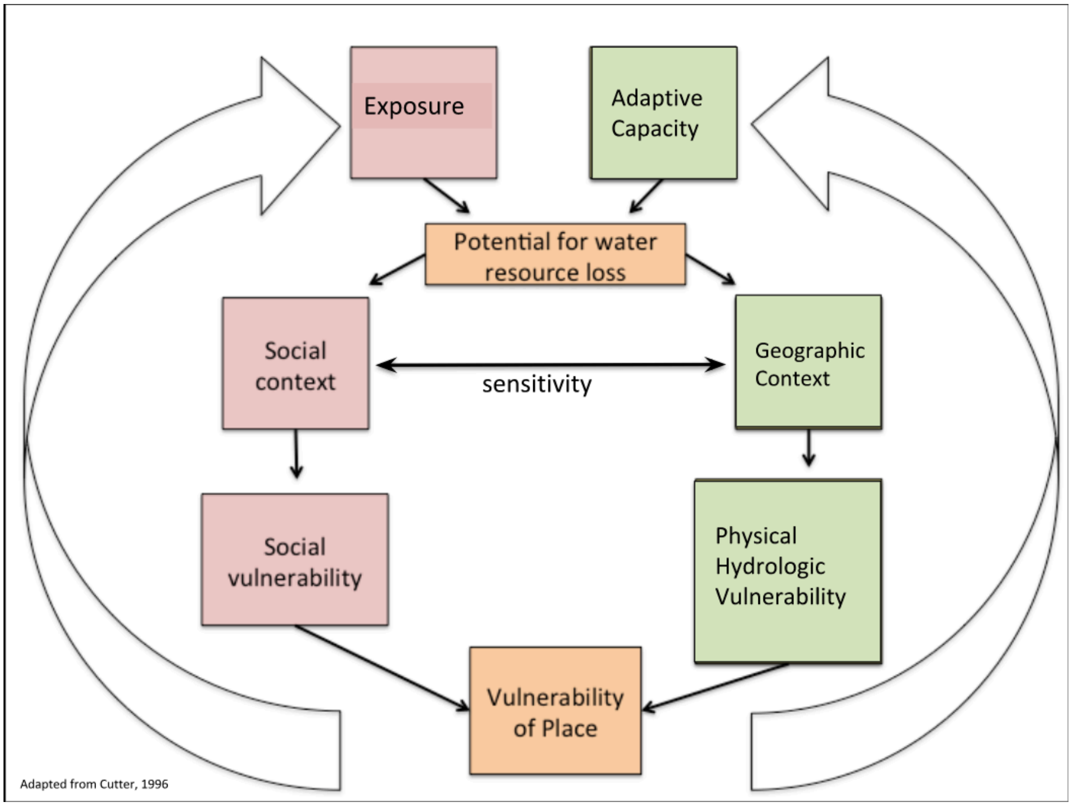


Figure 0.1 Dynamic interactions of the place-based, socio-hydrologic vulnerability model

Vulnerability & Spatial Analysis

We use a thematic mapping technique to represent vulnerability to climate-induced water shortage with a holistic interpretation of vulnerability that includes social as well as hydrologic vulnerability proxies. Over the last several decades multiple disciplinary fields have utilized vulnerability analyses to gain insight into place-specific challenges, patterns and relationships, and to provide a more universally accessible visual representation of results to a broad audience (Eakin & Luers, 2006). The integration of social and biophysical data has also gained popularity due to the potential for more robust elucidation of vulnerability (Johnson et al., 2012). Vulnerability studies are often accompanied by spatial analysis and mapped outputs. The combined index and mapping approach results in spatially explicit vulnerability assessments that produce functional visual tools that can be useful in dialog over policy development and in informing collaborative processes (Metzger & Schröter, 2006; Stelzenmüller et al., 2010). Comprehensive mapping processes have been applied across a multitude of socio-ecological systems and analysis scales to help identify groups and areas most susceptible to harm for a specific place at a particular point in time (Antwi-Agyei et al., 2012; Fraser & Stringer, 2009; Simelton et al., 2009). In the environmental hazards literature, Cutter et al. (2000, 2003) integrate biophysical data with socio-economic indicators to identify and map spatial patterns of hazards at the local scale. The mapping technique is similarly used for watershed scale analysis related to water scarcity. Collins and Bolin (2007) examine patterns of urban water scarcity in a rapidly growing region, integrating socio-economic factors and groundwater data for an integrated, spatially explicit representation of risk. These and other studies (Morrow, 1999; Luers et al., 2003; Turner et al., 2003; O'Brien et al., 2004; Zurovec et al., 2017), establish a comprehensive methodological foundation for integrating social and biophysical data to establish and test vulnerability indicators with meaningful, policy-relevant results.

Indicator Computation

There are a myriad of options for aggregating and ranking indices, including inductive and deductive methods (Adger et al., 2004). Yet there is no current method for determining relative importance of social vs. physical vulnerability or for establishing the importance of each variable and indicator. Therefore, we compare two separate computational methods: arithmetic equal weighting and a Principal Components Analysis using a variance weighting approach. We apply these methods to two separate indexes and maps. The social (chapter 1) and physical indexes (chapter 2) are combined to explore double exposure or "hotspots" of socio-physical vulnerability to climate induced water loss (chapter 2).

Equal Weights

We create context-specific composite indices of vulnerability using two comparative approaches. An equal weighting approach to computing composite indices provides a transparent, easily repeatable and modifiable approach to vulnerability analysis. We draw from previous efforts (Cutter, 2001; Wu et al., 2002; Alessa et al., 2008; Zurovec et al., 2017), and include the following steps to create an additive model of vulnerability: indicator selection, normalizing and "binning" data into quintiles, assigning weights (0-1) to each quintile, summing across indicators, summarizing scores as a scaled composite index, and finally mapping the results. The equal weights approach provides an additive model that does not require any a priori assumptions to be made about the factors used in the overall sum (Cutter, 2001).

Principal Components Analysis & Variance Weighting

Principal Components Analysis (PCA) offers another transparent approach to explicitly assigning weights to account for the range of variance in the social and physical datasets. We use PCA to explore the data and narrow the indicators to those with significant relationships and retain information about the strength of indicator/variable relationships (Adger et al., 2004; Abson, 2012). More broadly, PCA is an ordination-based, non-parametric statistical technique that helps to highlight patterns within multivariable data by converting a set of potentially correlated variables into a set of uncorrelated variables that capture the variability in the underlying data (Folke et al., 2004; Krishnan, 2010; Abson, 2012). Principal component rankings are based on eigenvalues for each variable in order of their significance and are based on how much of the variability in the data they capture (Folke et al., 2004; Krishnan, 2010; Abson, 2012). With this approach, each index (social & physical) is weighted on the PCA factor scores and represents the variables with the greatest influence on the Basin. A drawback of including only variables with high PCA scores in the index and eliminating low scores, is that high scores reflect variables contribute the most information, which does not necessarily reflect influence on vulnerability in a given location or situation (Jones & Andrey, 2007).

There is no “benchmark” or established standard for vulnerability to water loss in the CRB. Here, we use two methods, equal and variance weighting, to compare and contrast different approaches for calculating relative vulnerability and comparing across all subbasins. We intentionally select transparent methods to attract broader use of the index and to ease the process of updating and modification for all users. The following two chapters provide detailed methods for the social and physical indexing and mapping process, including detailed results and discussion.

Chapter One

*Spatial and Topical Distributions of Climate Change Research in the Mountainous Headwaters of the Columbia River Basin**

*This is a collaborative chapter co-authored by: Courtney Cooper, Meghan Foard, Shana Hirsch, Adrienne Marshall, Micah Russell, & Timothy Link

Introduction

Climate change in mountainous regions is projected to have serious consequences for social and ecological systems due to impacts on spatiotemporal snowpack dynamics, fire regimes, and biodiversity and ecosystem function, many of which are already occurring (La Sorte & Jetz, 2010; Nogués-Bravo, Araújo, Errea, & Martinez-Rica, 2007; Viviroli et al., 2011). These remote environments are critically important for many societies; for example, one-sixth of the global population resides in areas that depend on mountain meltwaters (Parry, 2007). Despite their importance, research in mountainous landscapes is relatively limited due to sparse monitoring networks and challenges associated with modeling complex terrain (Dobrowski, 2011; Strachan et al., 2016; Viviroli et al., 2011; Young et al., 1999). Systematic reviews are an important way to gain insight into the research status quo, identify areas of research dominance, and identify gaps or areas of opportunity. Our review synthesizes and provides insight into the current state of climate change research in the Columbia River Basin.

Impacts of Science on Management

One motivation for research syntheses is that scientific findings often have implications beyond their own disciplines. Research methods, spatial and temporal resolution and extent, amount of research conducted, and disciplinary diversity used to understand specific environmental issues influence how knowledge is applied. This includes not only how the natural environment is perceived, but also how it is valued and managed (Bocking, 2004; Yearley, 2008). In an ideal world, the relationship between environmental knowledge production and application may be one of supply and demand, where resource managers (science consumers) express knowledge needs that are then fulfilled by scientific research (science producers); however, many barriers exist that create a more complex relationship between science and management (Bisbal, 2018; deCrappeo et al., 2018). These barriers include difficulties identifying relevant actors and management priorities and challenges associated with aligning scientific and management priorities (Bisbal, 2018). With regard to complex environmental resource problems, characterizing research from multiple disciplines and understanding how these different fields of knowledge intersect is a critical step in synthesizing knowledge to ultimately make it useful for management needs. Doing so enables society to respond and adapt to the myriad challenges introduced by non-stationary climate regimes (Hulme 2010; Milly et al., 2008).

Calls for systematic assessments of climate change research are ubiquitous (Hulme 2010; Petticrew et al., 2011), yet conducting comprehensive reviews is challenging because the scope of climate change involves synthesis across multiple disciplines (Lenhard et al., 2006). Previous global reviews of climate change and water resources in mountainous areas have identified topical research priorities, highlighted the importance of environmental monitoring, and concluded that more detailed regional studies and linkages between disciplines are needed (Viviroli et al., 2011). Several other recent reviews synthesize knowledge in specific regions and river basins. In the Po River basin (Italy) and the Red River basin (Vietnam), Pham et al. (2019) apply a comparative freshwater ecosystem services framework to review basin-scale climate impacts on freshwater. Lima and Frederick (2019) review the evolution of primary environmental threats and stressors in the Athabasca River Basin in Alberta, Canada. They identify a gap in studies that explicitly link climate change to other stressors, such as mining, dams, or land use change. A synthesis in Bangladesh identified a bias towards economic, rather than environmental or social issues, and call for more transdisciplinary studies to support evidence-based public policy (Tuihedar Rahman et al., 2016). A review of adaptive capacity and climate change across Himalayan River basins concludes that adaptation projects take place mostly at local scales, emphasize disaster risk management, and are led by government agencies (Sud et al., 2015). Finally, systematic efforts to review climate change in the Canadian Arctic report that scholarship in this region would benefit from increased involvement of the social sciences and humanities and more research related to adaptation (Ford et al., 2012; Ford and Pearce, 2010). With these works as inspiration, this study aimed to quantify thematic and spatial gaps in climate change related research for the mountainous headwaters of a large and complex watershed, offering recommendations for future research and a transferable model for performing a research synthesis.

Background

Study Area

The Columbia River Basin (CRB) provides an ideal test case for understanding the state of knowledge about climate change in a mountain region that is profoundly affected by a non-stationary climatology. It is among many large, complex, and transboundary river basins with diverse ecosystems, complex socio-political histories, and a dependency on seasonal snowmelt to maintain water supplies and ecosystem function (Mankin et al., 2015). The region's water resources generate over half of the United States' hydroelectric power production, position the CRB as the leading producer of 22 key agricultural commodities, and sustain a population growing at more than twice the rate of the national average (EIA, 2018; USDA, 2018; US Census Bureau, 2017). The region depends on mountain water for environmental and economic well-being, has the scientific and policy-making infrastructure to support extensive research, and engages in climate change adaptation and mitigation efforts through, for example, government-led vulnerability assessments (Muccione et al., 2016; Olson et al., 2017).

Climate change and Water Resources in the CRB

Warming temperatures in the CRB cause a suite of hydrologic changes, including decreasing snowpack, warmer stream temperatures, increasing precipitation in the northern parts of the basin, and uncertain changes in total flow volume (Elsner et al., 2010; Ficklin et al., 2014; Hamlet & Lettenmaier, 1999; Isaak et al., 2017; Rupp, Abatzoglou, & Mote, 2016; Schnorbus, Werner, & Bennett, 2014). In many areas, climate change contributes to earlier snowmelt runoff and peak stream flows, along with lower summer flows (Stewart et al., 2005; Luce & Holden, 2009). Continued population growth and concomitant increasing water demands are expected across the CRB (Bilby et al., 2007; Huddleston et al., 2014). As is the case throughout much of the western United States, limited water availability invokes conflict among numerous actors who require this water for domestic, irrigation, navigation, hydropower, and municipal uses (Cotter and Sihota, 2015; Dettinger et al., 2015); limited water availability also creates challenges in supporting and upholding important cultural and spiritual values for tribal communities (Cosens et al., 2018). In addition to human water demand, watercourses and water bodies supply critical habitat to many aquatic species listed under the Endangered Species Act (ESA); the value of fisheries in the CRB is estimated at $150-$600 million (Cotter and Sihota, 2015).

Climate Change and Forest Resources in the CRB

Forests represent another source of critical ecosystem goods and services in the CRB that are strongly affected by climate change. In mountainous regions, federally-managed forests cover the greatest percentage of land, and they provide ecosystem services valued around $149 billion annually (Flores et al., 2017). Forests also supply habitat to many terrestrial species, such as the threatened Northern Spotted Owl (Thomas et al., 2006) and wolverine (Copeland et al., 2010), the latter of which was listed due to its sensitivity to climate change. Impacts of climate change on forests include more frequent high-severity wildfires, range expansion of invasive bark beetles, and fluctuations in water availability (Westerling, 2006; Kemp et al., 2015). Despite extensive study of climate change impacts on forests, adaptation remains difficult due to uncertainty in projecting specific local impacts and managers' limited time for integrating current climate change science in management plans (Kemp et al., 2015).

Multi-Disciplinarity in the CRB

Natural resource management in the CRB is complex and requires interdisciplinary approaches that address numerous interacting physical, social, economic, ecological, and technical factors (Cosens et al., 2016; Hand et al., 2018). For example, mountain forests influence the water cycle, water quality, streamflow, sediment transport, diverse habitats, and specific silvicultural practices. These variables in turn affect biophysical dynamics (Price et al., 2013), and all should be considered in the context of climate change. Governance in the CRB is also complex, involving the United States (US) and Canadian governments, distinct indigenous sovereign nations with differing objectives, as well as many state, provincial, local, and other management agencies (Hamlet, 2011). These complex interacting social and ecological systems underscore the necessity to address climate change from an interdisciplinary perspective using spatially explicit approaches (Alessa et al., 2015).

Synthesizing information related to climate change in the CRB serves to identify key disciplinary and geographic knowledge gaps while improving access to existing information for policymakers, scientists, and citizens (Pullin and Stewart, 2006). While the results of this approach are specific to the CRB, they may also generate hypotheses for other regions and provide a model for future research.

Research Questions

The general objective of this research is to expand the breadth and depth of existing knowledge by identifying the thematic content and spatial attributes of peer-reviewed research related to climate change in the mountainous regions of the CRB. The specific questions that we address are: (1) What are the common thematic foci and relative deficiencies in this body of research? (2) What are the spatial scales and distribution of climate change research in the headwater regions of the CRB? (3) Is the thematic content of research clustered spatially or conducted at specific scales in a way that suggests a need for further study of particular topics in specific places? The primary outcome of this work is the elucidation of knowledge gaps in areas of scientific inquiry that are strategically beneficial to improving our understanding of changing mountain landscapes. These outcomes are accomplished with a systematic review of peer-refereed literature to improve the potential for identifying research needs and untapped opportunities of greatest potential benefit. By extension, this improves the potential for the co-production of actionable science and management-relevant science, and facilitates a more tailored “call and response” relationship among science producers and science consumers or decision makers (DeCrappeo et al., 2018).

Methods

Document Collection

Our document collection methods identified studies that (1) are in the Columbia River Basin, (2) specifically address anthropogenic climate change impacts, adaptation, or mitigation, and (3) address mountainous environments (Figure 1.1). We used a multi-database search, incorporating literature from the Web of Science, Cabdirect, Proquest, and Crossref databases (see Appendix A for specific search terms). We assessed each of the articles for inclusion in the corpus of literature based on their titles and abstracts, and used full texts when necessary. Articles were included if they were peer-reviewed and included a substantial focus on climate change impacts, mitigation, or adaptation in mountain regions of the CRB. Articles were excluded if they did not address climate change, studied paleoclimate, or were conducted at a spatial extent greater than the western United States (Figure 1.1). It is important to note that the "gray" literature e.g., the legal scholarship and agency documents, is not included in our search. Therefore, our methods are limited to funded, peer-reviewed mountain climate papers specific to the CRB.

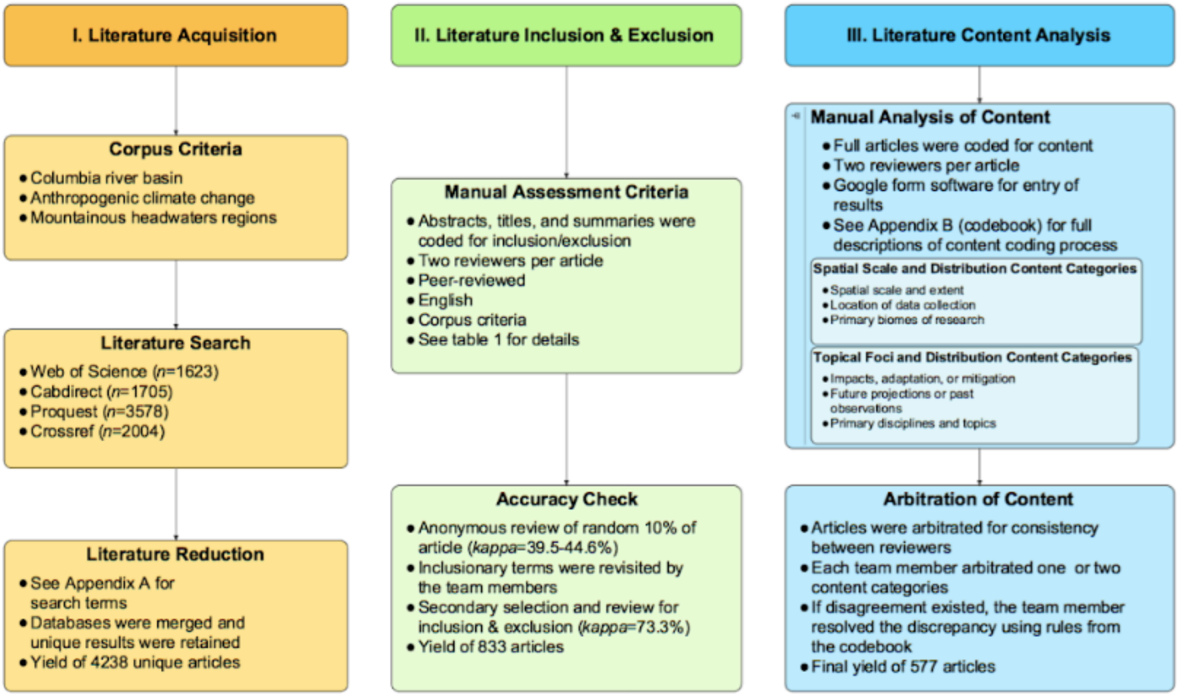


Figure 1.1 Methods overview

Content Analysis

Each article was analyzed to determine its spatial extent, location, and thematic content. We used a Google-form software questionnaire and a detailed codebook to ensure consistency among reviewers (see codebook, Appendix B). To record location, we selected the US Geological Survey six-digit hydrologic unit codes (HUC-6) to identify the watershed(s) where each study took place (Figure 1.2). If a study included data from fewer than six individual locations, the latitude(s) and longitude(s) were recorded. Spatial extent, which we defined as the largest area to which findings were extrapolated within the western United States and British Columbia, was selected from seven classifications. We also selected the biome(s) where each study took place from a list of global biomes from

Woodward et al. (2004). Freshwater biomes were added to distinguish studies between aquatic and terrestrial biomes.

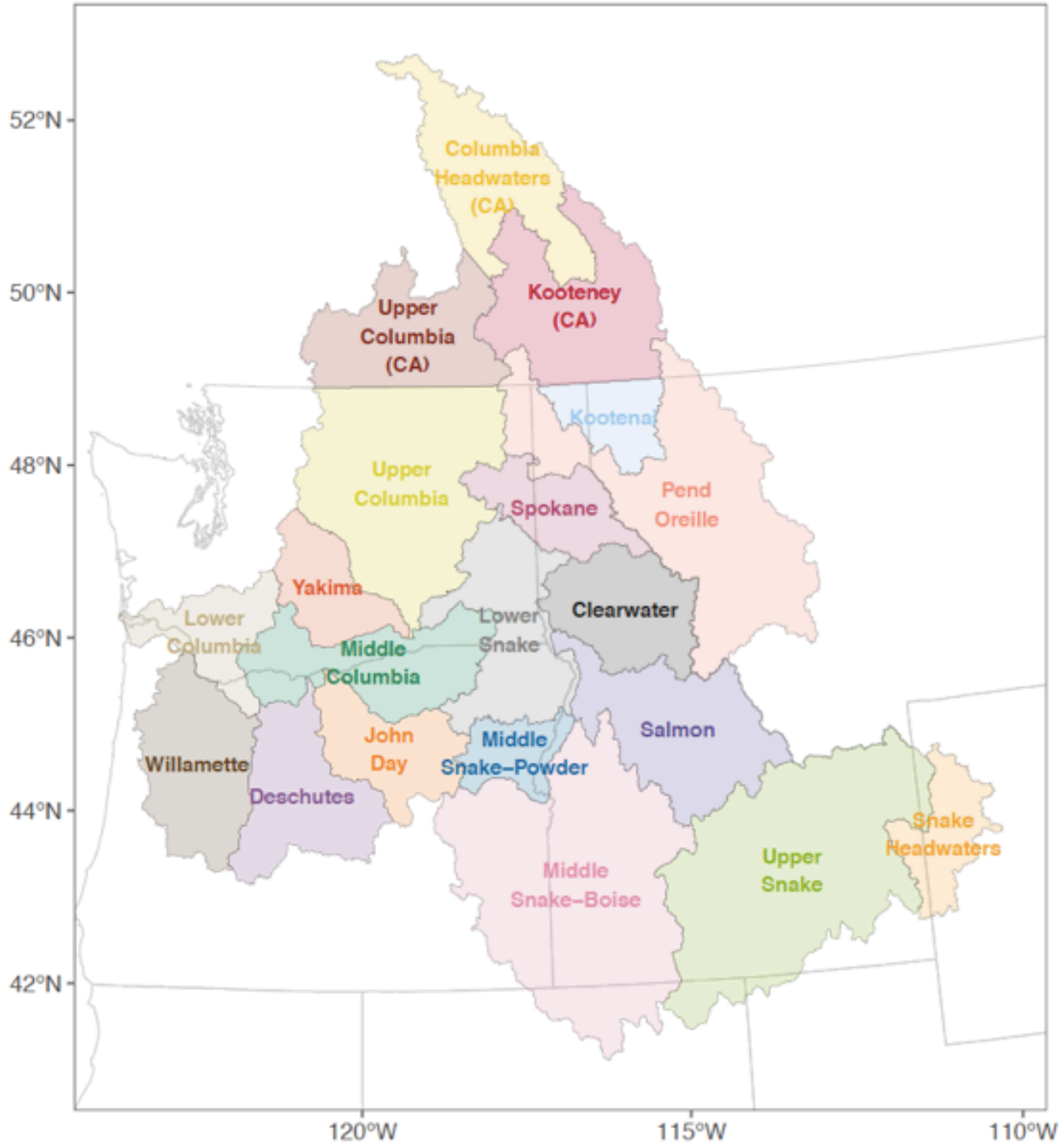
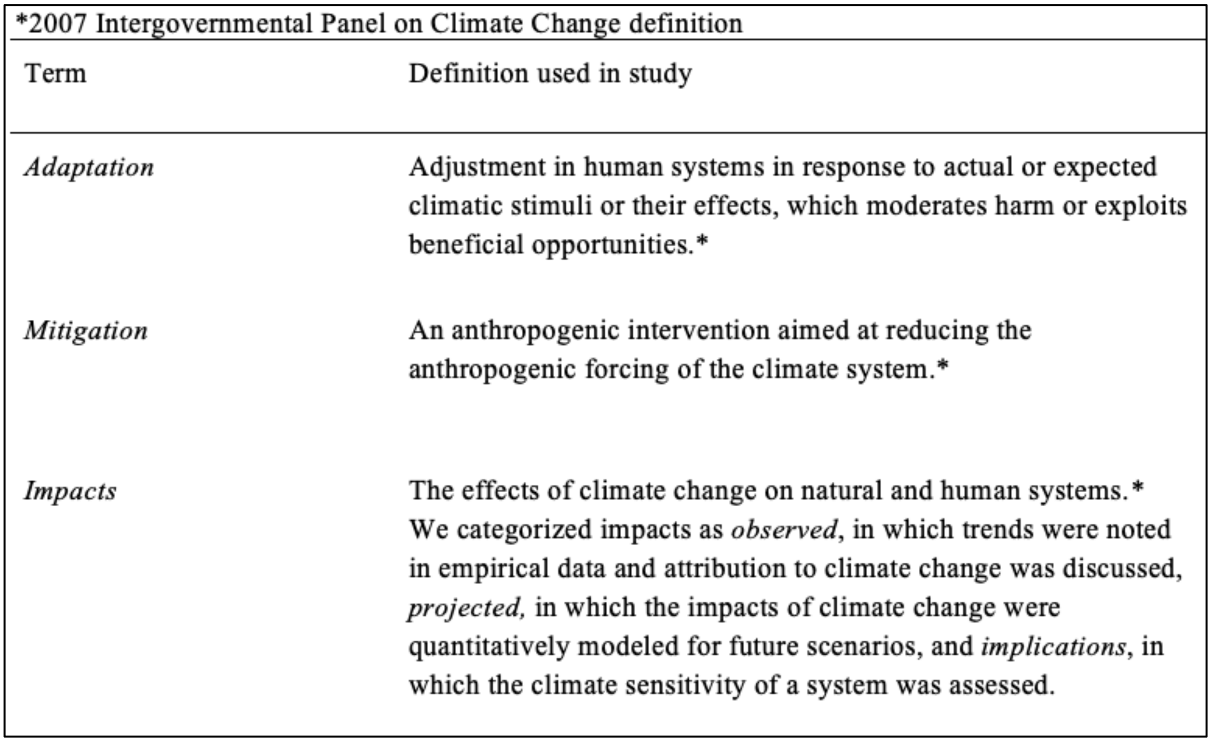


Figure 1.2 HUC-6 units with names

We developed several categories to analyze the topical and disciplinary content of the research. Using definitions from the Intergovernmental Panel on Climate Change, studies were categorized based on whether the primary knowledge contribution of each article was related to climate change impacts, adaptations, or mitigation (IPCC, 2007; Table 1.1). If the article addressed impacts, we determined whether evidence was presented regarding observed historic impacts and/or modeled projected future impacts. Finally, we specified the primary discipline(s) and topics addressed in each article (Table 1.2). Discipline was determined based on the article and journal titles, primary author's discipline, and the primary knowledge contribution of the article, while topics were selected more inclusively and included any important knowledge contribution. Topics that occurred extremely infrequently were binned into more inclusive categories.

Table 1.1 Definitions used to assess area of primary knowledge contribution



*2007 Intergovernmental Panel on Climate Change definition

Term	Definition used in study
Adaptation	Adjustment in human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.*
Mitigation	An anthropogenic intervention aimed at reducing the anthropogenic forcing of the climate system.*
Impacts	The effects of climate change on natural and human systems.* We categorized impacts as *observed*, in which trends were noted in empirical data and attribution to climate change was discussed, *projected,* in which the impacts of climate change were quantitatively modeled for future scenarios, and *implications*, in which the climate sensitivity of a system was assessed.

Table 1.2 Definitions of disciplines used in study, listed in alphabetical order

Discipline	Definition used in study
Biology	The study of life, including anatomy, physiology, animal behavior, genetics, morphology, growth, and more.
Climatology	Studies of weather and/or climate, including atmospheric and oceanic patterns and processes.
Ecology	The study of the interaction of biotic and abiotic factors in an ecosystem.
Economics	The study of the production, distribution, and consumption of monetary goods and services.
Engineering	The study of physical design and construction of functional structures.
Forestry	Studies that broadly include forest ecology and forest management.
Geology	The study of earth processes, plus rock & soil science.
Hydrology	The study of water processes, both above and below ground.
Sociology	Any study focused on human populations, human behavior, relationships, culture, and society.
Policy	Any studies related to rulemaking and decision making at an administrative level, including management.
Toxicology	Any branch of chemistry and toxicology that focuses on interactions among biological and chemical processes in the environment.

Data Analysis

Summary statistics were calculated to summarize frequencies for each of the content categories. To assess interdisciplinarity, we calculated the frequency of disciplinary co-occurrence to derive a network map. To explore the relationships among topics we conducted a hierarchical cluster analysis (HCA), using topics that occurred in at least five articles. We used Ward's least square error method of clustering because it is less susceptible to noise and outliers, and it yielded the highest agglomerative coefficient (Tan, 2007). This method groups topics into similar nested clusters and minimizes the similarity between clusters. Topics that co-occur more frequently are joined early in the clustering process. Inclusive clusters are joined together by branches in a dendrogram.

The relationships between different coding categories were also assessed using correspondence analysis. This technique calculates factor scores for two categorical variables and converts them to Euclidean distances, which can be mapped together to visualize relationships in two-dimensional space. The spatial proximity between variables indicates frequency of relationship (Abdi & Williams 2010).

In order to test the strength of our findings regarding the frequency of co-occurrence, we used a text mining analysis on the article abstracts. Abstracts were available for 515 out of our total corpus of 558 studies. Common stop words and words that occurred less than 20 times were removed, and Pearson correlation coefficients for each remaining pair of words were calculated based on the frequency of co-occurrence in each abstract. Correlations are only reported for cases where Pearson's $p < 0.05$. For cases where other analyses suggested that topics were particularly likely or not to co-occur, we used these correlation coefficients as an additional line of evidence to test our results.

To compare studies that occurred only in Canada, the U.S., or spanning the international boundary, we used a Fisher's exact test. This method identified whether there were significant differences in the topical distributions of national and transboundary studies. The Fisher's exact test was selected because we had small sample sizes. Results from a Chi-squared test were then used to determine which topics contributed to the differences.

Results & Discussion

In the remainder of this document we describe the thematic content of the research, and frequency of research theme co-occurrence (research question 1). We then describe the spatial distribution of research (research question 2) and present results on how specific thematic content is distributed spatially, including international comparisons (research question 3). We address assumptions and limitations and conclude with our most important results, including opportunities for further research.

Dominant Themes

Research in the CRB includes an abundance of studies on physical and ecological disciplines and topics. Articles in the corpus are generally focused on physical and ecological disciplines. The most commonly identified disciplines are ecology (204 articles), hydrology (160), climatology (120), and forestry (108), as shown in Figure 1.3. We found 156 (28%) articles with two or more disciplines and 402 single-discipline articles (72%). The most common combinations of disciplines are hydrology and climatology (39), and ecology and forestry (24) (Figure 1.3a); however, these disciplines are closely related and hence do not represent integration across truly disparate disciplines. We identified an average of 6.12 (±2.5 s.d.) topics per article. The six most common topics are temperature (86% of articles), precipitation (76%), forest ecology (47%), snow (40%), management (40%), and streamflow (37%). The frequency of these topics suggests a dominance of forest ecology and water issues, with fairly frequent discussion of management. The prevalence of management as a topic is important to note, due to the paucity of policy or management as a discipline (8%). This discrepancy arises because our methods were relatively exclusive when coding for discipline and inclusive when coding for topic, and suggests that many studies tend not to have management or policy as a primary focus, but still address management to some extent (e.g., Proctor et al., 2013).

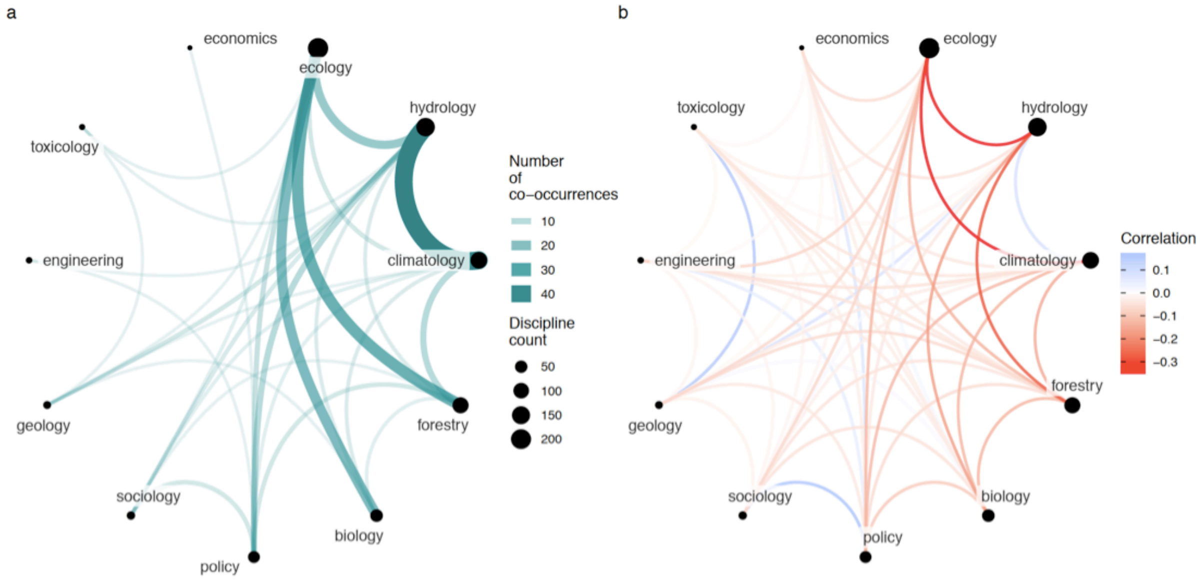


Figure 1.3 Network map of co-occurring disciplines, showing (a) number of co-occurrences, indicated by edge width and color, and (b) correlation coefficients between disciplines. Size of points indicates number of times each discipline occurred.

The hierarchical cluster analysis (HCA) illustrates the tendency for topics to be researched together. Physical science topics related to physical hydrology, precipitation, water quantity, streamflow, and snow are clustered together (cluster 1, Figure 1.4). The appearance of these topics in the first cluster demonstrates that hydrological topics are common in the corpus and confirms that they are consequential in relation to climate change in mountainous regions. The word correlation analysis of article abstracts provides supporting evidence for the HCA findings. Indeed, words associated with topics within cluster 1 (precipitation, streamflow, and snow) are positively correlated. The disciplines and topics that are uncommonly researched together represent opportunities for new research avenues and further disciplinary integration.

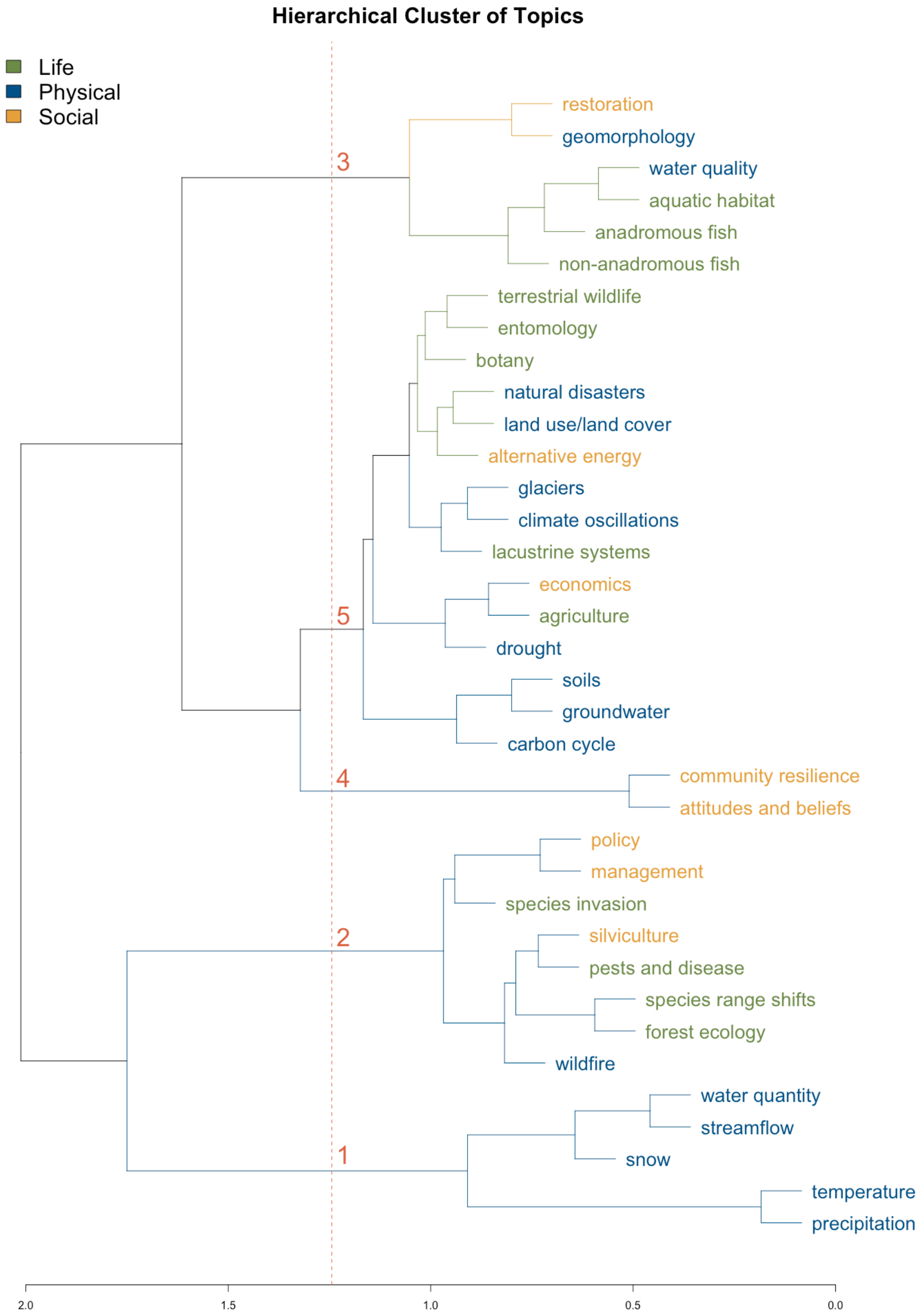


Figure 1.4 Dendrogram of hierarchical cluster analysis (HCA) of topical co-occurrences. The HCA measures the dissimilarity between variables and represents them in nested clusters. The x-axis shows the dissimilarity between topics. Topics that are grouped together near the right (distance = 0) are frequently coupled in the literature. Cluster numbers in red are referenced in the text. Colors of topics indicate whether each topic was classified as primarily related to the social (yellow), life (green), or physical (blue) sciences.

Opportunities for Integration

Several lines of evidence indicate that some disciplines and topics are relatively infrequently researched in conjunction with each other. These include the frequency of disciplinary co-occurrence (Figure 1.3), the hierarchical cluster analysis (Figure 1.4), and correlational analysis of abstract texts.

An opportunity for deeper disciplinary integration may be in further exploring the relationship between terrestrial and aquatic processes. For example, the disciplines of hydrology and forestry show a fairly strong negative correlation. In the HCA, topics related to forest ecology and water resources form two distinct clusters in branches two and three, also suggesting separation between these topics. The abstract text analysis also supports the idea that forest and aquatic issues are not well integrated; for example, word pairs with negative correlations include forest/fish and fire/fish. Of the minority of articles that do integrate topics related to forests, fires, and fish, five out of seven model the additive effects of climate change, altered forest vegetation, wildfire, and/or other disturbances on aquatic habitat (Davis et al., 2013), stream temperatures (Holsinger et al., 2013; Isaak et al., 2010) or sediment delivery (Neupane and Yager, 2013; Rugenski et al., 2014). All five articles conclude that that combined effects of climate change and forest disturbances are detrimental to aquatic habitat. The other two articles about fish, fire and forests do not directly investigate these topics, but instead consider their confounding influence on stream diversions (Walters et al., 2013) or as determining indicators of climate change (Klos et al., 2015). These studies reinforce the interconnection of forests, fires, and stream habitat and highlight both the necessity and further opportunities to integrate forest disturbances into climate change research on aquatic habitat.

Similarly, studies of fire and snow do not tend to be well integrated, as demonstrated by their distinct clusters in the HCA. The terms fire and snow are also negatively correlated in the abstract text analysis. The topic of snow appears in 42% (236) of the corpus studies, while the topic of fire appears in 20% (113) of articles. However, articles including both snow and fire make up only 5% (27) of the total. Given that snowpack and summer moisture deficit are thought to be leading causes of increases in large wildfire occurrence (Westerling, 2006; 2016), this may indicate an area where further thematic integration is needed. Several combined snow-fire studies address climate change impacts on fire severity or frequency, while integrating snow as an explanatory variable or discussing the importance of snowpack (e.g., Littell et al., 2010; Morgan et al., 2008; O'Leary et al., 2016). Several broader analyses appear in the corpus that address the impacts of changes in a broad suite of environmental variables, including both snow and fire (e.g., Brown et al., 2006; Holsinger et al., 2014), but only one study analyzes the impacts of fire on snowpack dynamics (Gleason et al., 2013). This suggests that there is an opportunity for more detailed analyses regarding potential fire-snow feedbacks in the context of rapidly changing climate.

Our findings also suggest that biophysical disciplines are generally not studied in conjunction with social science disciplines. Community resilience and attitudes and beliefs are separated from all other clusters in the HCA, indicating that they are more often discussed within the same publications than they are with other topics (Figure 1.4). This also appears to be true in the analysis of disciplinary co-occurrence. Of the five most commonly studied disciplines, none show positive correlations with social science disciplines, such as sociology, policy, or economics. However, the number of studies linking these pairs of disciplines suggests that there is at least some research linking these subjects. Many studies link biophysical subjects and policy issues; these include several studies of water resources engineering and supply management issues (e.g., Lee et al., 2009; Hatcher and Jones, 2013). Deeper integration across disciplines is very rare; only five studies represent sociology or policy in conjunction with biophysical disciplines. For example, these include agent-based modeling for planning around future watershed conditions (Nolin, 2012), a synthesis of biophysical climate change indicators and feedback from resource managers (Klos et al., 2015), and an analysis of forest managers' responses to climate change (Blades et al., 2016). These findings are generally in agreement with Bjurström and Polk (2011), who analyzed interdisciplinarity within climate change research through a co-citation analysis of the IPCC Third Assessment report and found that closely related disciplines commonly co-occurred, while more disparate disciplines were clearly separated.

Science Meets Policy

Some biophysical topical areas indicate strong connections with policy and management, while these connections are weaker among other topics. Forest ecology and policy and management are closely affiliated, as evidenced by the abstract correlation and cluster analyses (Figure 1.4). The second branch of the HCA includes many forest ecology topics, as well as policy and management. Topics within the cluster are positively correlated in abstract texts, as well. For example, management is positively correlated with: policy, fire, timber, forest, and ecological, confirming that management studies often focus on forest systems. Many of the aforementioned forestry terms also correlate highly with policy, suggesting that policy may be commonly tied to forest systems. There are 21 articles in our corpus from the United States that refer to forest ecology and/or silviculture as well as policy; of those, 81% (17) state that they are motivated by various policies related to forests, fires, and wildlife management, such as the Wilderness Act, National Fire Plan, National Environmental Protection Act, or the Northwest Forest Plan.

Fish species, habitat, and restoration commonly co-occur, and an analysis of the articles in our corpus suggests that the Endangered Species Act (ESA) may motivate the coupling of fish and critical habitat restoration. The ESA emphasizes restoration of "critical habitat" for endangered species throughout many river systems in the CRB. In our corpus, 56% (23) of the articles about fish and habitat suggest that the ESA motivates this research; for example, Leibowitz et al. (2014) write, "the threatened and endangered status of many of these stocks under the Endangered Species Act (ESA) often drive water and basin management in the region." Despite the fact that fish research in the region is often motivated by the ESA, policy is not the main focus of the research. Only 11% (12) of policy articles with the corpus pertain to aquatic habitat, while 25% (133) of the articles relate to aquatic habitat or fish. This may indicate that researchers are focused on habitat restoration rather than new policy changes to reestablish or protect the listed fish species.

The relationships between forestry and policy, and aquatic habitat and policy, illustrate "the co-production of science and law"—whereby science is needed to support legal action, and the resulting policies, in turn, mandate science to be conducted (Jasanoff, 2004). This can be done in straightforward ways, such as when the allocation of funding for scientific work determines the goals and priorities for science. For example, the ESA requires fish and wildlife agencies to develop Biological Opinions (BiOps) that determine the ecological impacts from operation of hydroelectric dams. This relationship between the ESA and scientific research is commonly observed in our corpus. Furthermore, much of the early riparian habitat monitoring in the Pacific Northwest has been carried out within the field of forestry, driven by concerns about the impacts of forest operations and the regulatory framework of the Northwest Forest Plan (Thomas et al., 2006). In these ways and many others, the regulations, institutions, and organizations in place in the CRB are determining factors in the kind of scientific work that is conducted in the basin.

Thick and Thin, Opportunities for Action

Articles analyzing climate change impacts are much more common than those addressing adaptation or mitigation: 88% (489) primarily focus on climate impacts, while 10% (56) focus on adaptation and 2% (13) are on climate change mitigation. Ford and Pearce (2010) observe an increasing “adaptation gap,” where the number of studies addressing climate change impacts is much larger than those addressing mitigation, and the gap between the two has grown over time, particularly as the number of studies on impacts has increased. The studies in our corpus similarly reflect an adaptation gap; comparing the 10-year periods from 1996-2005 and 2005-2015 shows that the gap between the number of adaptation and impacts papers has increased from 63 to 302, though adaptation papers represent a larger portion of the corpus in the later period than earlier, increasing from 3% to 11% of papers. A similar gap exists for mitigation studies.

Studies primarily assessing climate change impacts, adaptation, and mitigation have distinctly different patterns of disciplinary and topical distributions (Figure 1.5). Articles on climate change impacts tend to be associated with the disciplines of hydrology, climatology, and ecology, and are relatively evenly distributed among the top 20 most common topics. In contrast, studies of climate change adaptation are most commonly associated with the disciplinary categories of policy, forestry, biology, ecology, and sociology. The topics represented by adaptation articles are heavily skewed towards water quantity, silviculture, species range shifts, attitudes and beliefs, and pests and disease. A relatively small percentage of adaptation articles address groundwater (9%), climate oscillations (2%), or carbon cycling (4%); no adaptation articles studied glaciers. The relative lack of adaptation studies on these topics may suggest important funded research gaps and hence opportunities for adaptation research.

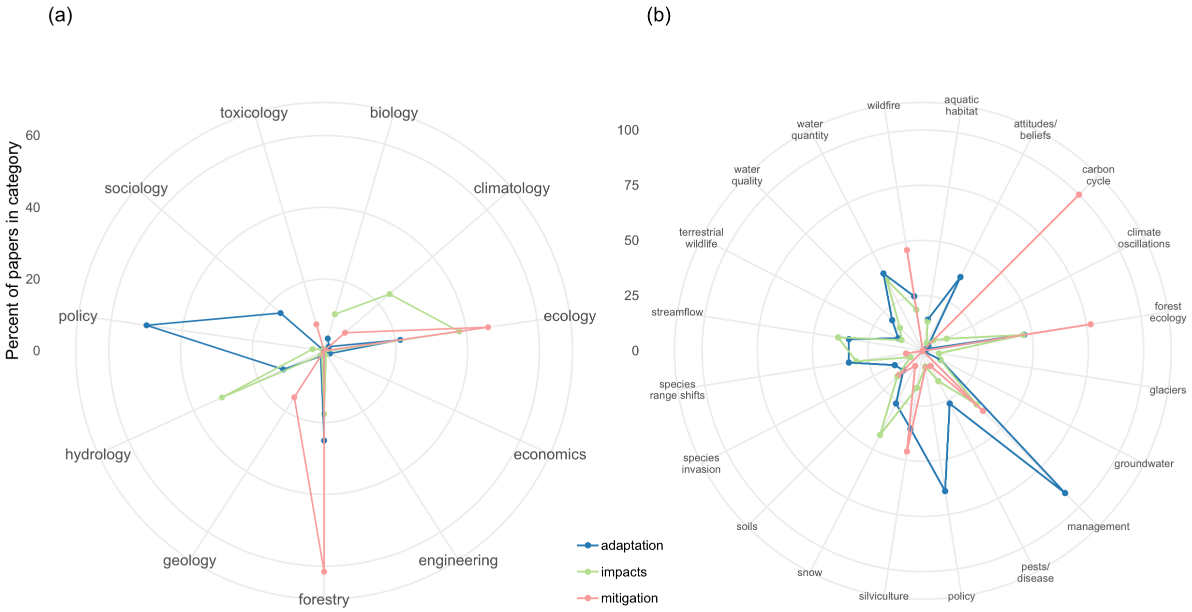


Figure 1.5 Radar plots showing the distribution of adaptation, impacts, and mitigation paper by (a) discipline and (b) topic. Axis displays the percent of papers in the adaptation, mitigation, and impacts categories that address a particular topic or discipline.

Mitigation studies are disciplinarily concentrated in biology, ecology and forestry, and topically focused on carbon cycling, forest ecology, wildfire, silviculture, and management. These findings reflect established understanding that forest management and wildfire are large components of carbon budgets in mountainous regions (Schimel et al., 2002). However, this also suggests potential research needs. For example, freshwater and soil respiration impacts on carbon budgets appear to be poorly represented in our corpus, despite their demonstrated importance (Cole et al., 2007; Falk et al., 2005). Only two studies in the corpus address climate change mitigation and soils (Wilson et al., 2013; Jauss et al., 2015); these are both focused on forested environments. Aside from forest management, human activities that affect carbon emissions appear to be under studied. Examples include recreational activities, carbon footprint analyses of mountain communities, and carbon emissions impacts of montane hydropower operations (Deemer et al., 2016). While policy research is needed to identify effective means for reducing carbon emissions (Klein et al., 2005), few of the mitigation articles in our corpus explicitly address policy. Instead, we identify several topic areas related to mitigation that could benefit from integrating policy analyses. Specific examples from the corpus include a study estimating the potential effects of prescribed burning on carbon emissions (Wiedenmeyer and Hurteau, 2010), and a quantification of carbon stored in wood products (Stockmann et al., 2012). Both prescribed burning and carbon stored in wood products are identified as complex policy issues related to reducing carbon emissions in mountainous regions of the CRB (Law et al., 2018).

Climate change impacts, adaptation, and mitigation are also studied at different spatial extents (Figure 1.6). Correspondence analysis indicates that the first dimension is driven by impacts and mitigation, and explains 64% of the variability, while the second dimension is mostly driven by adaptation, and explains 25% of the variability in the dataset. This analysis also demonstrates the relationship between the type of impact studied and spatial extent. Climate change implications are most closely clustered with the smallest scale in our study. Mitigation is associated with relatively small scales, while observed and projected impacts are associated with relatively large scales. Most mitigation studies provide analyses of forest carbon cycles; the small spatial extent suggests that this information is often process-oriented at specific sites and is typically not upscaled to the landscape level (e.g., Sanscrainte, McKay, & Peterson, 2003). In contrast, adaptation studies tend to fall within the medium to large extents.

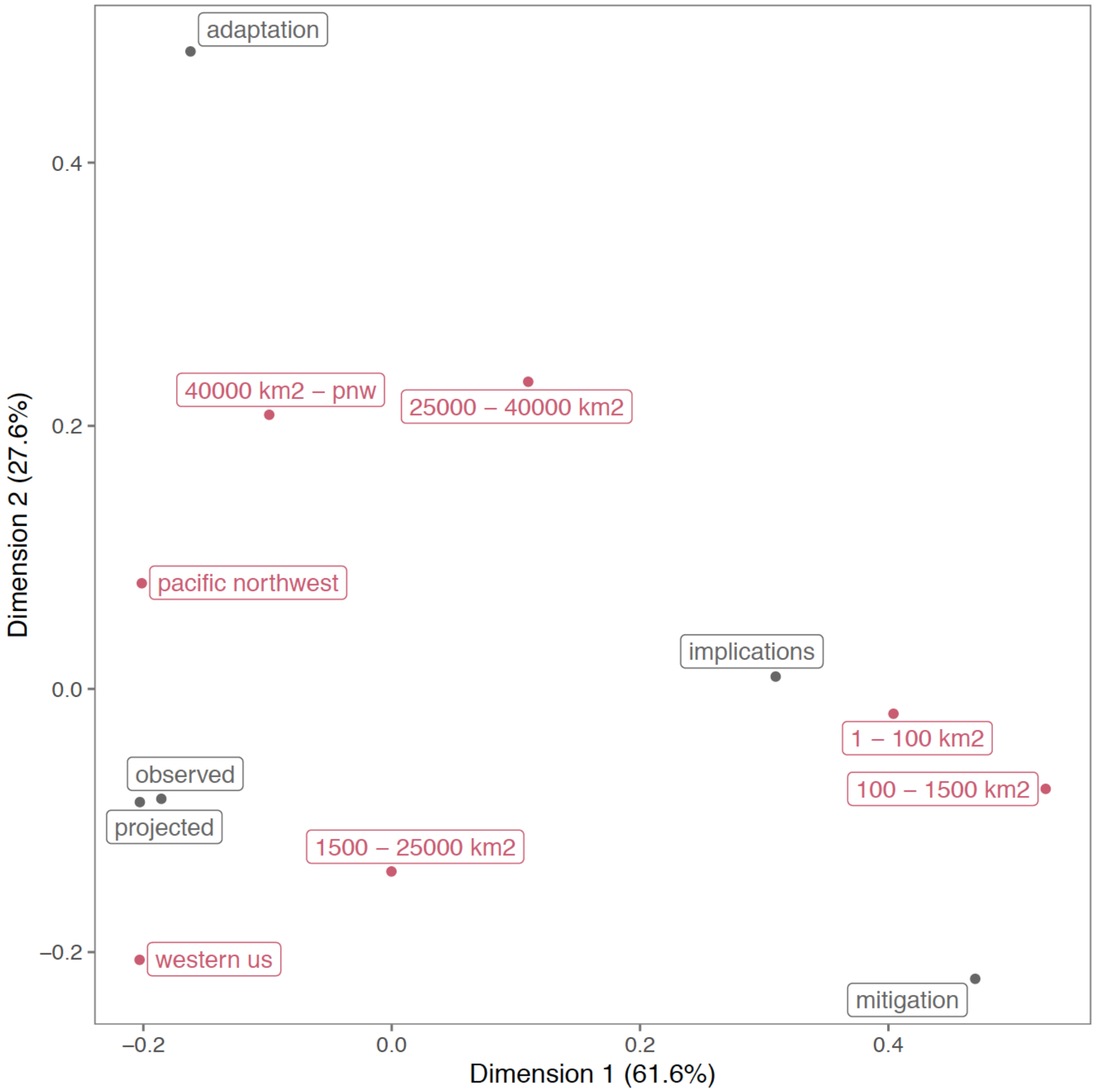


Figure 1.6 Biplot of correspondence analysis of impacts (observed, projected, or implications), adaptation, and mitigation (black labels) vs. spatial extents (red labels). variables that are close in Euclidean space are frequently coupled in the literature.

The Issue of Scale

Research has predominantly focused at relatively large scales, made projections of future rather than observed conditions, and used existing rather than new data. Articles included in the corpus ranged in spatial extent from point or plot scale to the western U.S. The Pacific Northwest (660,000km2) and the Western U.S. extents are the most common and include 37% of articles (205). Another 22% of articles (121) span between 40,000km2 and the Pacific Northwest (660,000km2). The remaining 42% of articles (232) report on studies at spatial extents less than 40,000km2. Different disciplines are generally associated with different spatial extents (Figure 1.7). For example, articles with climatology as a discipline tend to occur most often at larger extents. This is to be expected, given the nature of the discipline, though it may raise questions about whether microclimates and refugia are adequately studied from a climatological perspective (e.g. Curtis et al., 2014). Furthermore, the lack of small scale climate studies suggests that there may be a lack of knowledge about regional climate processes (Salathé et al., 2008), changes in microclimates (Daly et al., 2010), and rapid changes (Wiens, 1989). For example, rapid changes in vegetation, especially in ecotones, result from regional climatic changes which are often undetectable at larger scales (Allen & Breshears, 1998; Kelly & Goulden, 2008).

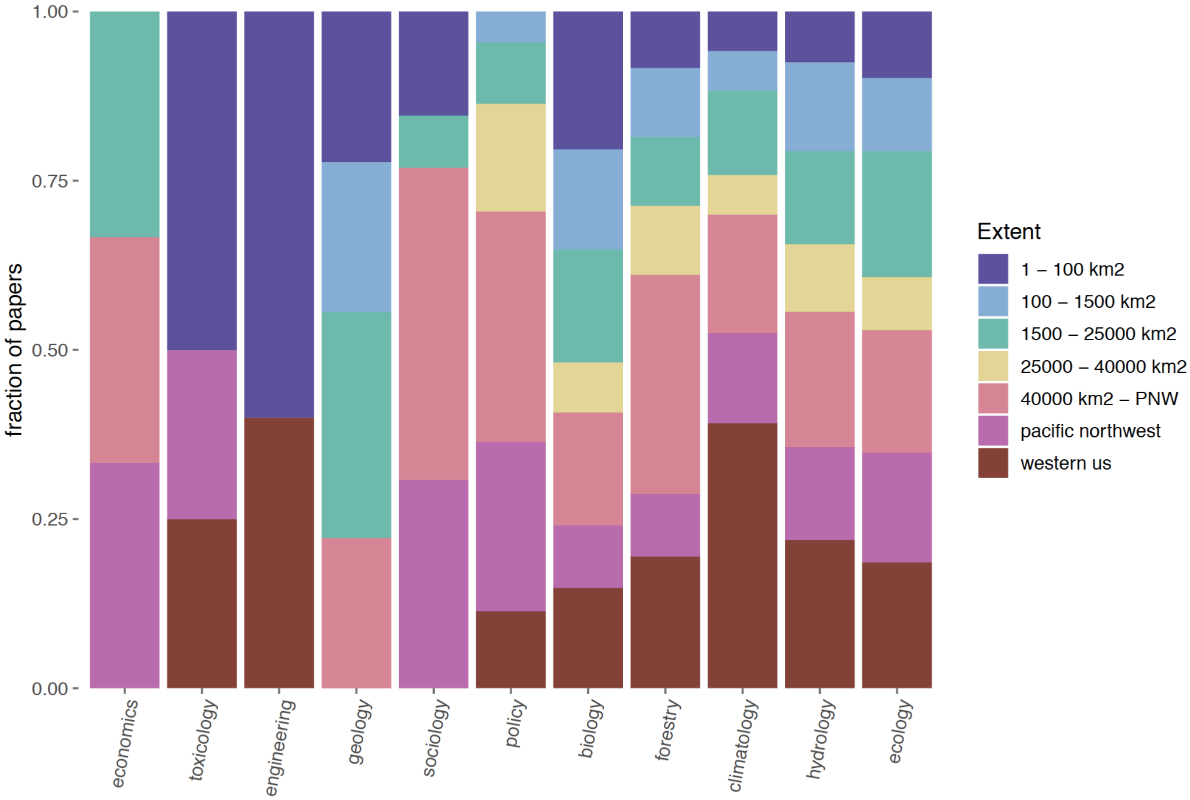


Figure 1.7 Spatial extent of disciplines. Disciplines are arranged in ascending order of frequency within the dataset.

Studies focused on projections of climate change impacts are more common than those that incorporate climate observations. Of the 507 articles that study climate change impacts, 35% (171) make formal projections of climate change impacts; 28% (139) observe an environmental trend and discuss its attribution to climate change, while 42% (205) assess a climate change impact but do not explicitly observe or project a trend. Reporting on new field data is also relatively uncommon; only 34% (188) of studies include new data. Studies that include observed or projected impacts vary by discipline (Figure 1.8). Articles with disciplines categorized as ecology, forestry, biology, policy, or geology tend to reference climate change implications, rather than explicitly making observations or projections of climate change. In contrast, hydrology and climatology have more studies of projected and observed climate change impacts. For most disciplines, excluding forestry and sociology, studies of projected impacts are more common than studies of observed impacts.

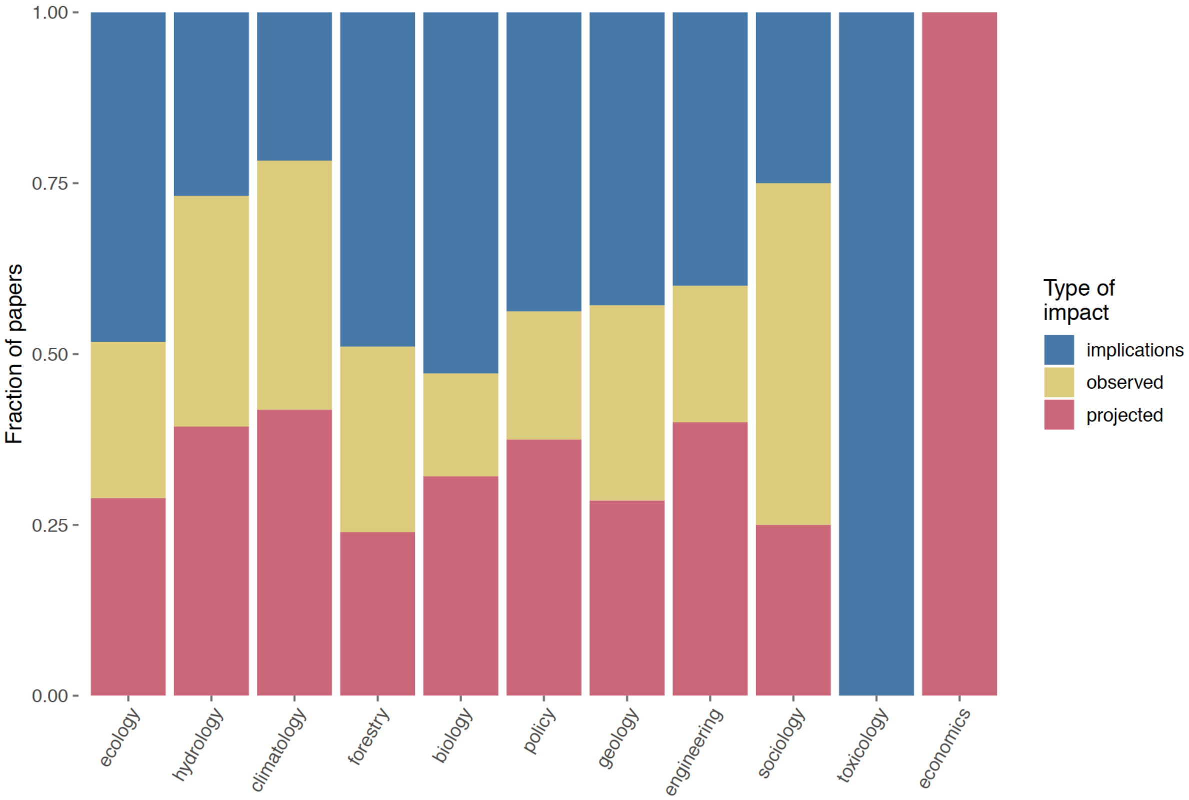


Figure 1.8 Studies of climate change impacts that identify climate change implications or observed or projected impacts, by discipline.

To a certain extent, the predominance of studies about projected impacts relative to observational impacts is expected: observed impacts require decades of data to establish, and these long-term in *situ* observations are often unavailable in many locations (Strachan et al., 2016). In some cases, climate change impacts remain difficult to detect, given the range of internal variability (Hegerl et al., 2006). While climate change implications studies may sufficiently provide the information needed to make projections, they may exclude important or unexpected changes that are only identifiable with long term observations (Hegerl et al., 2006). For example, long-term monitoring in other mountainous regions has identified paradoxical relationships between warming and frost damage of flowering plants (e.g., Inouye, 2008); these findings would not have been possible without long-term observations and may inform predictive modeling. This finding indicates the importance of long-term monitoring of environmental changes to assess the observable impacts of climate change across a range of disciplines and scales. Ultimately, this degree of investment is necessary to develop adaptation strategies to enhance the resilience of natural systems within the context of a non-stationary climate.

The dominance of projected rather than observed studies, large spatial extents, and relative dearth of new observational data may be reflective of an increased use of computer modeling. Numerical modeling has become critical in scientific work aimed at understanding large-scale, climatic changes (Edwards, 2010). The relative preponderance of studies based on simulated and/or remotely-sensed data at fairly coarse resolutions and large scales raises questions about whether these large-scale findings are supported by observed data, which is usually collected at much smaller scales or which may have important variations within grid cells (e.g. McKelvey et al., 2011). The predominance of studies without observational data reflects larger trends in scientific work, as understanding global environmental change increasingly relies on distributed and simulated data (Edwards, 2010). Further, modeling is increasingly employed over field-based studies in order to meet the challenge of predicting global change and managing uncertainty (Mauz & Ganjou, 2013). These trends also indicate a movement towards the use of “big data,” which can create challenges as it disrupts old knowledge structures and methods, but also creates opportunities for novel forms of interdisciplinarity and collaboration (Plantin et al., 2017).

Spatial Patterns in Basin Climate Research

The quantity of research conducted varies spatially, and is influenced by institutions, geographical features, and disturbance history. Research is unevenly spatially distributed across the CRB (Figure 1.9). The quantity of research we identified is much smaller in Canada (84) than in the U.S. (405). For studies conducted at smaller extents, research activities are concentrated at several locations that appear to be fairly well explained by geographical features, such as the location of long-term research sites. For example, notable concentrations of research appear to occur at the H.J. Andrews Experimental Forest, Mount

Rainier National Park, and in the Reynolds Creek Experimental Watershed. Another relatively high concentration of studies occurs in the Okanagan Basin, Canada, though these are not clustered at a particular research site.

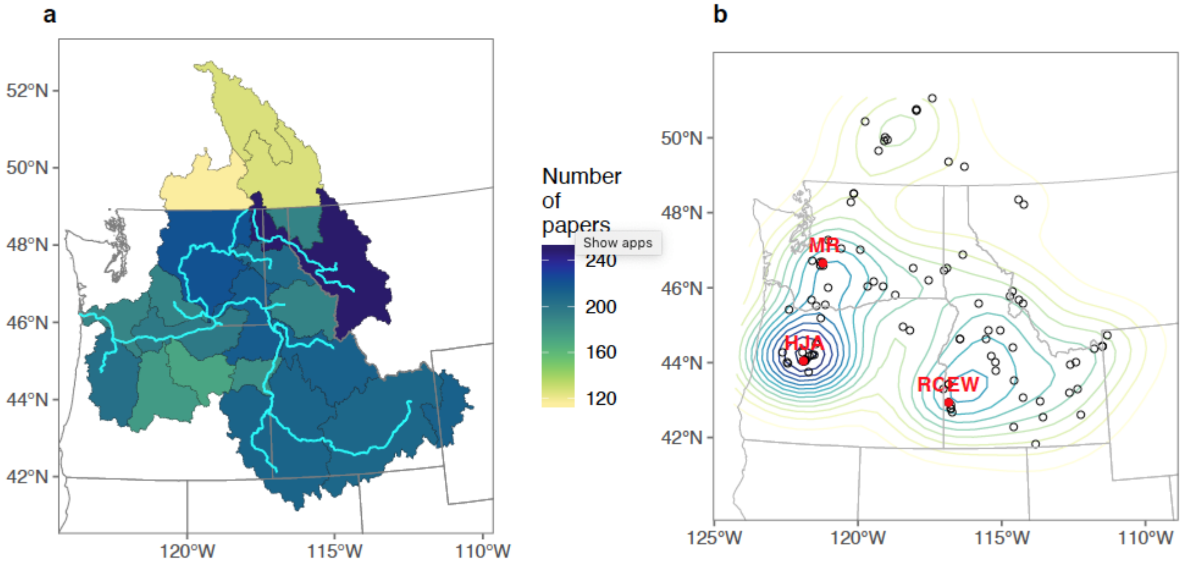


Figure 1.9 Spatial distribution of literature, displayed as (a) total number of papers per HUC-6 watershed and (b) point locations for studies with spatial extents less than 1500 km^2, with contours showing estimated density of studies. Rivers are displayed in cyan; points of interest with high concentrations of research are in red. MR = Mount Rainier; HJA = H.J. Andrews Experimental Forest; RCEW = Reynolds Creek Experimental Watershed.

This spatial distribution of research points to the "distributional consequences" stemming from the funded research conducted in the CRB, as well as the importance of considering both physical and sociotechnical aspects of research (Edwards et al., 2013). Large-scale investments in data-intensive knowledge infrastructures can have lasting effects on the type of science conducted, as data is made re-usable by other scientists (Bowker, 2000), and long-term research sites become a focus for intensive study. Research infrastructure includes more than the material aspects of technology that enable science to be conducted. The organizational and relational aspects of scientific work such as protocols, standards, and systems of field-gathered and remotely-sensed data are also important (Star & Ruhleder, 1994). Moreover, the particular histories of land use and management policy can affect the distribution of research; for example, one content analysis focused on treeline found that land use designations, such as National Parks, affected the type of treeline research conducted (Whitesides and Butler, 2011). Multiple aspects of research and legal infrastructure have legacy effects on the production of science in a particular location such as the CRB.

Spatial Themes

The thematic content of research is unevenly distributed across HUC-6 watersheds. Correspondence analysis reveals groupings of watersheds and disciplines (Figure 1.10). The first dimension accounts for 36.2% of the variability and the second dimension accounts for 18.5% of the variability. Research in the Upper Snake and Snake Headwaters tends to encompass the same disciplines and is closely associated with policy and ecology. Sociology is commonly coupled with the Okanagan (Canada), Columbia (Canada), and Spokane watersheds, with sociology studies in Canada commonly focused on social issues shaping forest management (Goemans & Ballamingie., 2013; Furness & Nelson, 2015; Carolan & Stuart, 2016). Hydrology is also associated with Okanagan (Canada), Columbia (Canada), Spokane, Yakima, and John Day watersheds. Forestry is closely coupled with the Willamette, Kootenai, and Upper Columbia River watersheds, though the topic's central location within the correspondence analysis graph indicates that it is common to most watersheds. Maps of the spatial distribution of selected topics support the correspondence analysis and demonstrate that the topical distribution of research varies in space (Figure 1.10). For many topics, the variability between the U.S. and Canada is much larger than within-country differences; however, we focus our discussion here on within-country differences followed by discussion of transboundary differences in section 5.8.

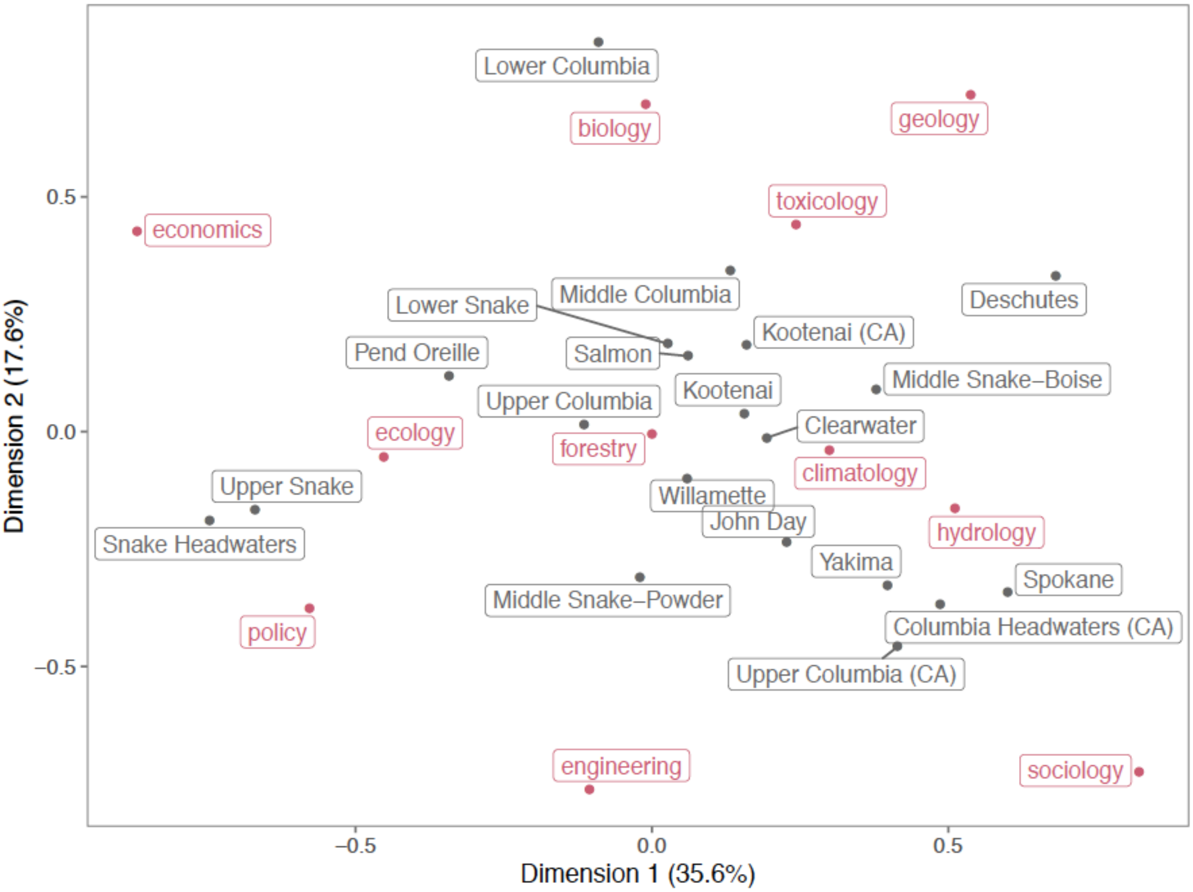
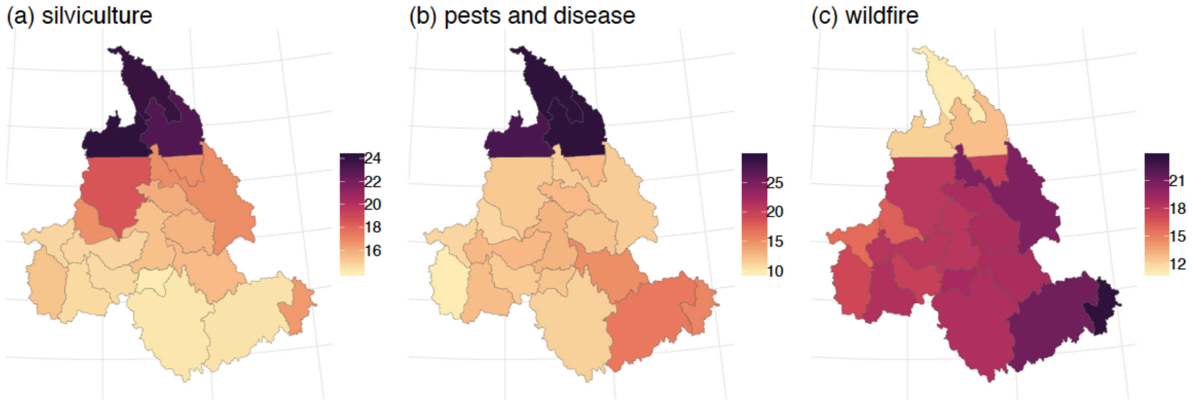


Figure 1.10 Biplot of correspondence analysis of watersheds (black labels) and disciplines (red labels). When variables appear close in Euclidean space, they are frequently coupled in the literature.

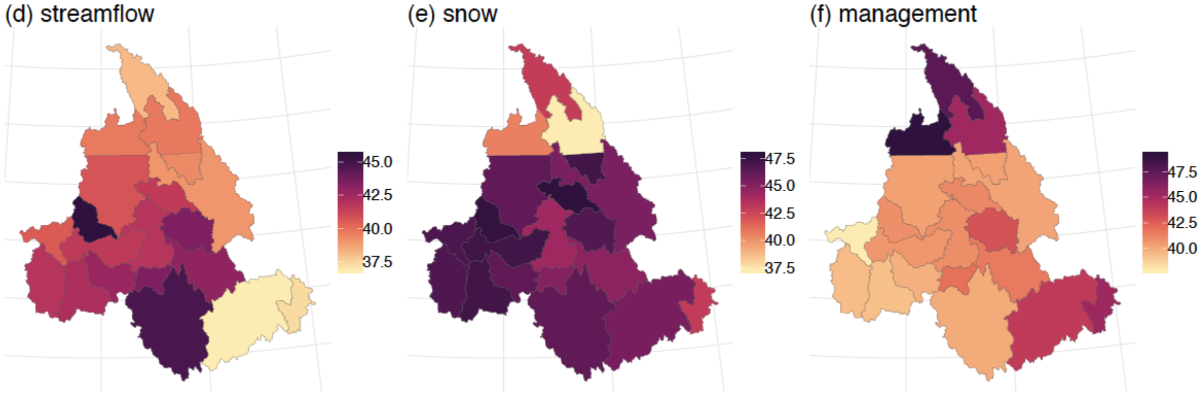
Disturbance history influences the topical distribution of research. For example, the preponderance of forest ecology and wildfire studies in the Greater Yellowstone Ecosystem may be due to the 1988 Yellowstone Fires, as evident in the many studies that reference these fires (e.g., Romme et al., 2011; Donato et al., 2016; Seidl et al., 2016; Zhao et al., 2016). Studies of pests and disease are also relatively common in the Greater Yellowstone Ecosystem, as well as the Salmon River watershed (Figure 1.11). Many of these studies are focused on pine bark beetle outbreaks (e.g. Buotte et al., 2016; Logan, MacFarlane, & Willcox, 2010; Seidl, Donato, Raffa, & Turner, 2016; Simard, Powell, Raffa, & Turner, 2012). A remote sensing analysis of bark-beetle induced tree mortality suggests that there are relative hotspots of bark beetle outbreaks within this region, particularly in the Salmon River watershed (Hicke et al., 2016). However, Hicke et al. (2016) also identify relatively high beetle mortality in parts of the North Cascades. In our data, the North Cascades do not appear as a hotspot for beetle studies, suggesting that the distribution of research is only partially explained by disturbance history.



(a) silviculture

(b) pests and disease

(c) wildfire



(d) streamflow

(e) snow

(f) management

Figure 1.11 Spatial distribution of selected topics by HUC. Each legend shows the percent of papers in a given HUC that addresses the topic.

The Lower Snake and Yakima watersheds have the highest fractions of research pertaining to streamflow. Two long-term research sites are located in the Lower Snake (Reynolds Creek Experimental Watershed and Dry Creek Experimental Watershed), while the Yakima watershed is an important region for irrigated agriculture (e.g., Vano et al., 2010), which may contribute to the prevalence of streamflow research. While streamflow in much of the region is snowmelt-driven, the spatial distribution of research related to snow is slightly different from that on streamflow. Similar to streamflow, snow-related research is also common in the Yakima watershed; however, snow studies in the Snake River headwaters are relatively lacking.

There is a relatively high recurrence of research that addresses management implications within the Upper Snake and Snake Headwaters. Articles addressing management in this area predominantly focus on interactions between water resources management and biophysical conditions under climate change (Loinaz et al., 2014; Qualls et al., 2013; Ryu et al., 2017; Sridhar and Anderson, 2017); forest and terrestrial ecosystem management, often specific to unique species such as whitebark pine (Logan et al., 2010; Macfarlane et al., 2013); or sagebrush steppe communities (West and Yorks, 2016). Interestingly, despite the relative prevalence of management topics in these two watersheds, the number of adaptation studies is comparable to the entire corpus. This finding suggests that many impacts-focused studies in this region also address management implications, which is perhaps a result of the long history of conservation planning efforts in the Greater Yellowstone Ecosystem (Clark et al., 1991).

Within Canada, management is frequently researched in the Upper Columbia watershed where Lake Okanagan is located (85% of Canadian policy articles, n=18). Of these management articles, 67% (12) focused on forests (e.g., Nitschki & Inns, 2008; Goemans et al., 2013; Seely et al 2015), 17% (3) on wildlife (Bunnell, Kremsater, & Wells, 2011; Festa-Bianchet, Ray, Boutin, Côté & Gunn, 2011; McNay, Sutherland & Morgan, 2011), 11% (2) on human dimensions (Turner & Clifton, 2009; Furness & Nelson, 2016), and less than 1% (1) on avalanches (Sinickas & Jamieson, 2016). Water management topics are not addressed in this subset of articles even though the topic is critically important due to the high demand for irrigation water in the Okanagan watershed (Neilsen et al., 2006). This could be reflective of funding mechanisms or priorities specific to Canada.

Canada Marches to a Different Beat

We compared thematic content of articles exclusively in the U.S., in Canada, and those that are transboundary and found significant differences in the thematic content of research among studies in Canada, the United States, and transboundary studies. The comparison suggests that the topical distributions of articles in these three categories are significantly different from each other (Fisher's exact test $p < 0.001$). The prevalence of articles addressing pests and disease and glaciers in Canada are the largest contributors to this difference, though topics related to human dimensions (policy, management, attitudes and beliefs, community resilience) are also more common in Canada than in the U.S. The extensive forested areas and recent pest outbreaks in the Canadian headwaters of the CRB may explain the greater research focus on forest pests and disease impacts. Climate change contributes to the rapid expansion of new bark beetle species at these latitudes, raising concerns for forest health in Canada (Anderegg et al., 2015; Bentz et al., 2010). The topical focus on glaciers in Canada within the corpus is likely due to the relatively high prevalence and hydrologic importance of glaciers (Moore et al., 2009).

Publications focused on Canadian regions also include more articles with topics relevant to human dimensions of climate change such as policy and management (Figures 3.10 and 3.11, e.g., McDaniels et al., 2012; Murdock et al., 2013; Parkins and MacKendrick, 2007). For example, Murdock et al. (2012) report on a bio-economic model intended to inform forest management decisions in a changing climate. Concerns about forest health issues due to the close proximity of communities and forests in Canada may influence the abundant occurrence of topics related to the human dimensions of climate change (e.g., Furness and Nelson, 2016; Parkins, 2008; Parkins and MacKendrick, 2007). The relative dominance of studies addressing social issues in Canada may provide research models that would be beneficial to apply in the U.S. portion of the CRB; studies analyzing transboundary social issues under climate change may also be needed in the region.

Many of the thematic differences between research in the U.S. and Canada relate to biophysical topics and likely emerge from differences in landscape characteristics such as latitude and land cover. However, differences in laws and policy between the two countries may also play a role. The greater U.S focus on topics related to hydrology, aquatic habitat, and wildfire is likely linked to differences in policy and management within the two countries. As discussed above, in the U.S., the ESA often motivates research on issues related to restoring federally listed fish habitat (Beechie et al., 2013). Snow-related research is more prevalent in the U.S. than Canada, which may be due to the fact that an important long-term snowpack dataset, SNOTEL, operates within the U.S. only, or could be due to expectations that snowpack in the colder Canadian portions of the CRB is more resilient to warming than in the warmer ranges found in the United States, and that precipitation is likely to increase in this part of the CRB (Hamlet et al., 2013).

Transboundary studies are distinguished by a high number of studies addressing climate oscillations, streamflow, anadromous fish, and restoration, and a relatively low occurrence of studies on policy, forest disturbances, silviculture, and carbon cycling. These include studies about climate change models across the entire CRB (e.g., Rupp et al., 2016);

downscaled impacts of climate change on hydrology such as hydro-climatological models (e.g., Hamlet et al., 2013); comparative streamflow and water temperature modeling (e.g., Ficklin et al., 2014); and models of declining snowpack (e.g., Abatzoglou, 2011). Reconstruction of historical flows or trends are also common across transboundary studies (e.g., Wapples et al., 2008). Only five transboundary studies explicitly address policy and management issues (Sopinka and Pitt, 2014; Beechie et al., 2013; Schwandt et al., 2010; Lee et al., 2009; Bisson et al., 2009), and only one of these represents a collaboration between U.S. and Canadian authors (Schwandt et al, 2010). These studies focus on flood control, streamflow, and anadromous fish issues. A potential issue in interpreting the thematic content of these transboundary studies is that many transboundary studies tend to occur at relatively large scales (70% were larger than the Pacific Northwest, in contrast to only 37% in the full corpus). There may be a confounding effect between topics that tend to be researched at large scales and those that are of particular interest across international borders. By excluding the gray literature, we have limited our view of the integrated literature as well. Still, these area represents a funded research gap and highlights the need to bring existing non peer-reviewed research to light to better represent the status quo regarding trans-boundary knowledge sets and existing opportunities for further progress in this critically important and policy-relevant realm.

Assumptions & Limitations

There are several assumptions and limitations that should be considered in the interpretation of our findings. Our methods required that each article was categorized as either adaptation, mitigation, or impacts. Therefore, while there may be studies that address both mitigation and adaptation, these would have been coded in only one category. We have also identified several areas of thematic content for which we argue that two important topics or disciplines are not well integrated. To support these conclusions, we use multiple lines of evidence where possible, but it is important to note that these analytical methods identify research integration that is *relatively* infrequent. We support these with discussion of the few studies that do address these potential gaps, but determining which areas are true and important knowledge gaps, and which are not studied because they are not particularly relevant, is ultimately subjective. Moreover, while we used multiple databases to identify research, there are likely some relevant articles that were omitted by our focus on peer-reviewed literature exclusively and thus “knowledge gaps” ultimately represent funded research gaps and point to an obstacle in information access among researchers. Discourse over mitigation and adaptation in the CRB can be found the gray literature, thus by selecting peer reviewed studies only we may have more accurately uncovered a funding bias in the peer reviewed literature toward large-scale impact studies over mitigation and adaptation work. More research of the gray literature is required to gather a true sense of research balance, however we can conclude that more funded research should be aimed at sorely needed adaptation and mitigation-focused work if near-future action is to be taken in the interest of reducing the negative consequences across the mountain dominated Basin. A major obstacle to including the gray literature is that it is spread across countless agencies and non-public niche databases, creating a real challenge to access not only by our research team, but by anyone interested in reviewing the total body of literature.

Nevertheless, we used multiple rounds of coding and multiple lines of evidence to support our conclusions, and as in any such investigation errors in coding may have occurred. It is also important to note that our literature search was conducted in December 2016; while there are undoubtedly many new studies available, we expect that the general patterns and trends characterizing the science conducted in this region are not likely to have changed substantially in the intervening time.

Conclusions

Science produced in mountainous headwaters of the CRB affects our understanding of climate change impacts on social and ecological systems, as well as our understanding of potential adaptation and mitigation strategies. While a number of trends in the thematic and spatial distribution of climate related research in the CRB can be discerned, it is the relative gaps in funding in particular knowledge areas that are of the most concern. Specifically, we recommend that funding agencies improve funding for the following:

(1) More funding for research on climate adaptation is needed. While 88% (489) of the studies included in this review focused on climate impacts, only 10% (56) focus on the adaptation of human systems to actual or expected climate change. This may be emblematic of a disconnect between the practice of science and the applications of science – especially applications that build adaptive capacity into social-ecological systems.

(2) More funding for research on climate mitigation is needed. Despite large tracts of forested lands, a significant biomaterials industry, and increasing concerns about climate change stressors (i.e. drought, fire, pests), only 2% (13) of the studies included in this review focused on improving knowledge of, or intervening in, carbon cycles to potentially reduce the effects of anthropogenic forcing on the climate system.

(3) More funding for climate-related social science research, and more integration of social science with biophysical disciplines, is needed. Only five of 558 studies included in this review represented sociology or policy in conjunction with biophysical disciplines, a glaring disparity given the feedbacks between a growing population, climate change, ecosystem services, and land management.

(4) More funding for transboundary climate change research with an integrated, basin-wide focus is needed. For example, only five of 558 studies explicitly addressed policy and management issues on both sides of the US-Canada border, and only one of these represents a collaboration between U.S. and Canadian authors. This is surprising, given the interconnectedness of ecological and social systems throughout the watershed and the pervasiveness of observed and predicted climate stressors.

This study quantified thematic and spatial gaps in climate change-related funded research for the mountainous headwaters of a large and complex watershed. Our results potentially allow science and management communities to leverage resources more effectively and, in turn, increase the potential for the co-production of actionable science and effective responses to research needs. However, our analysis also points to a fundamental problem and time-critical obstacle to improving our knowledge of mountain climate challenges in the Basin by uncovering disproportionate funding patterns that bias large-scale impact studies that are not necessarily regionally relevant, nor readily transformed to policy or management action on the ground. A body of gray literature exists that, at least in part, fills the “knowledge gaps” we identify, however these are unfunded research efforts that are not readily accessible via a comprehensive and widely accessible database system. This represents yet another obstacle to reviewing or exchanging information regarding existing research and findings, which in turn reduces overall research efficiency and breadth of impact of these timely studies. Addressing vulnerability across the Basin would be greatly improved into the future if funders increased the breadth of studies to support. More funding for regional and sub-regional interdisciplinary research is necessary, and particularly useful to the realms of adapting to and mitigating negative climate change impacts in the CRB. Further, improving efficiency of access to the gray literature generally would prove to be highly beneficial to addressing true research gaps and reducing redundancy.

Chapter Two

A Social Vulnerability Index for the Columbia River Basin

Introduction

As the Columbia River Basin's climate changes, water resources change with it and some communities will be affected more than others. The importance of moving forward with localized adaptation planning to reduce the inequity of impacts cannot be over emphasized. Our water vulnerability index and map tool can help communities and their leaders be better informed and more nimble in their efforts to think ahead and take action with the most sensitive communities and neighbors in mind.

Background

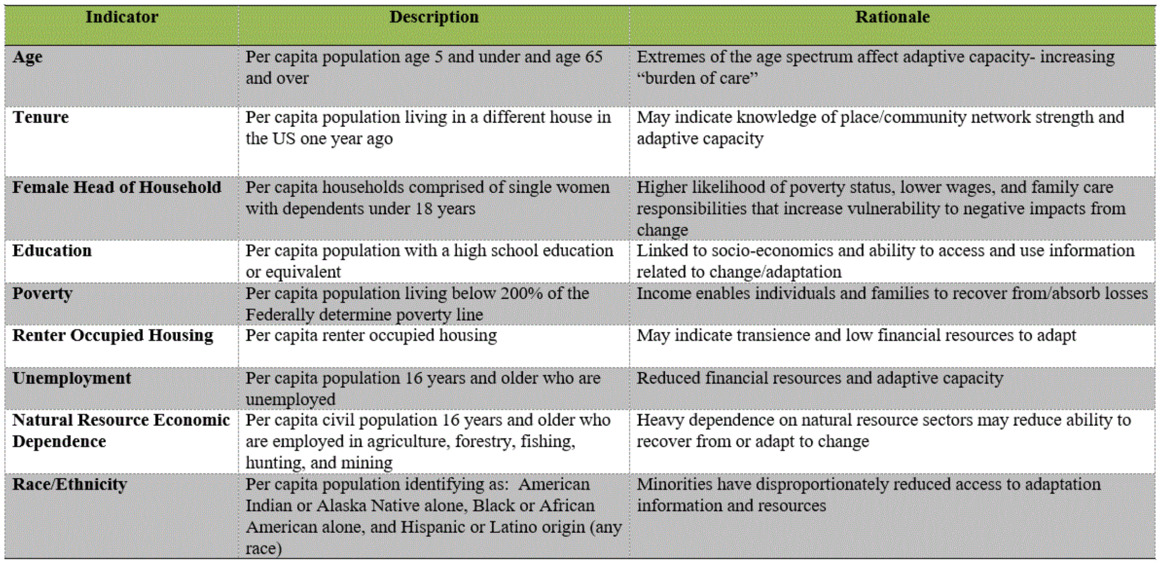
Vulnerability is fundamentally concerned with equity and, in this case, we focus on the potential for differential impacts of climate induced water loss to subbasins across the CRB due to social circumstance. The purpose of exploring social aspects of vulnerability is to ultimately view them in conjunction with hydrologic vulnerability for an integrated assessment and hotspot analysis. We define social vulnerability as the "the differential capacity of individuals and social groups to cope, recover, or adapt to the effects of acute or chronic environmental changes that stress their livelihoods and well-being" (Kelly & Adger 2000, p.348; Collins & Bolin 2007, P.402). Vulnerability research originates from social science fields and is commonly used in geography and the risk-hazards literature to explore the differential outcomes that stem from disparate contexts (Kasperson et al., 1995; Luers et al., 2003; Fussel & Klein, 2006). Social vulnerability is rooted in the concept of social justice and shares ethical foundations with climate justice, both of which deal with the inequitable distribution of wealth, opportunities, and privileges within society that have local consequences but are driven by many multi-scalar influences (Adger et al., 2009). Climate justice goes a step further to point out a double inequality: that vulnerable populations are the least responsible for climate change, but bear an unequal burden of its impacts (Barrett, 2013).

Social vulnerability is linked to poverty and associated factors like gender, minority status, and age, which are associated with limitations to adaptive capacity for a myriad of reasons, not limited to: poor health, lack of political power and voice, and limited access to educational and financial resources (Kasperson & Kasperson, 2001; Smit & Wandel, 2006; Tucker et al., 2015). Because social vulnerability is contextual, it is specific to place and reflective of the state of the social system's capacity to continue to function or adapt in the face of climate change. We referred to this as "adaptive capacity," or the ability of a system to adjust form and function in order to cope with external pressures, and is closely linked to resilience (ability to "bounce back" after disruption) of the socio-environmental system (Figure 0.1) (Holling, 1973; Brooks, 2003; Abson, 2012). Vulnerability of a particular place can increase or decrease from the aggregate effect of daily and long-term (including historical) actions of: individuals in a community (e.g. conflict or cooperation), investments, policies, social networks and institutions, the frequency and intensity of shocks or stresses, resource conservation or exploitation, etc. (Adger et al., 2009; Eakin et al., 2009).

To our knowledge, there are currently no other studies addressing social vulnerability or adaptive capacity to water loss within the CRB at the subbasin scale. This represents an opportunity to add to the current literature and to provide a platform for further exploration of how communities, families, and individuals cope with and respond to change differently due to socio-economic inequalities in the region. It is important to note that subbasins and the communities within them are not homogeneous or unified, but instead are interconnected, overlapping social "subsystems" (Pahl-Wostl et al., 2010). The ability to respond to climate impacts on water resources is shaped by their various histories and by a host of variables that influence access to social and economic resources (Elliot & Pais, 2006).

Here, we develop a set of proxy indicators (Table 2.1) of social vulnerability derived from well-studied aspects of social inequality (Aptekar & Boore, 1990; Enarson & Morrow, 1998; Peacock et al., 1997). We also draw from previously established social vulnerability indices, including: the Water Poverty Index (Sullivan, 2002); the Social Vulnerability to Hazards Index (Cutter et al., 2006); the Groundwater Vulnerability Index (Collins & Bolin, 2007); the Arctic Water Vulnerability Index (Alessa et al., 2008); and the Socio-Ecological Systems Vulnerability Index (Leslie et al., 2014). We held informal meetings and presentations with agencies and commissions from Idaho, Oregon, and Washington to introduce the research concept and to solicit feedback the selection of social vulnerability indicators appropriate for the CRB context.

Table 2.1 Social Vulnerability Indictors



Indicator	Description	Rationale
Age	Per capita population age 5 and under and age 65 and over	Extremes of the age spectrum affect adaptive capacity- increasing "burden of care"
Tenure	Per capita population living in a different house in the US one year ago	May indicate knowledge of place/community network strength and adaptive capacity
Female Head of Household	Per capita households comprised of single women with dependents under 18 years	Higher likelihood of poverty status, lower wages, and family care responsibilities that increase vulnerability to negative impacts from change
Education	Per capita population with a high school education or equivalent	Linked to socio-economics and ability to access and use information related to change/adaptation
Poverty	Per capita population living below 200% of the Federally determine poverty line	Income enables individuals and families to recover from/absorb losses
Renter Occupied Housing	Per capita renter occupied housing	May indicate transience and low financial resources to adapt
Unemployment	Per capita population 16 years and older who are unemployed	Reduced financial resources and adaptive capacity
Natural Resource Economic Dependence	Per capita civil population 16 years and older who are employed in agriculture, forestry, fishing, hunting, and mining	Heavy dependence on natural resource sectors may reduce ability to recover from or adapt to change
Race/Ethnicity	Per capita population identifying as: American Indian or Alaska Native alone, Black or African American alone, and Hispanic or Latino origin (any race)	Minorities have disproportionately reduced access to adaptation information and resources

Indicators Explained

Poverty

According to Cutter (1996) and others (Aptekar & Boore, 1990; Enarson & Morrow, 1998; Peacock et al., 1997), people from different socio-economic backgrounds perceive, prepare for, and experience water loss and other climate impacts differently. These differences in impacts on social class extend from response to recovery and adaptation (Fothergill & Peek, 2003). Bonnano et al. (2010) point out by that the psychological stress of hazards is greater among low-income populations, likely due to differences in the relative scale of risk to wellbeing and loss of employment or property damage. Additionally, recovery from short or long-term losses are much more significant for those with fewer economic resources. Lower income individuals are less likely to have access to social support networks, and tend to have intensified economic stress from less insurance, fewer savings and personal resources, and additional lagging stressors from previous economic burdens (Cooper & Laughy, 1994). Poverty is also often associated with other factors like gender, minority status, and age, and linked to poorer health outcomes, political disempowerment, and limited access to educational and financial resources (Kasperson & Kasperson, 2001; Smit & Wandel, 2006; Tucker et al., 2015).

Education

Education is related to adaptive capacity and is thought to foster preparedness, have influence on perceived personal control over potential outcomes, and influence interpretation of hazard warning signals and response (Turner et al., 1986; Turner & Killian, 1987; Vaughan, 1995). Education is also linked to higher earning potential and associated with human capital, such as leadership, marketable skills, knowledge, and information communication (Flora & Flora, 2004). We consider subbasins with a higher proportion of the population with a high school education only to be more vulnerable (Cutter et al., 2001; Reid et al., 2009).

Race

Race is a marker of inequality in our society, but race alone does not determine vulnerability; rather it is the overlapping influence of oppression and lack of opportunity on race that disproportionately impacts and marginalizes non-white populations. We examine race to specifically highlight patterns of inequity among African American, Hispanic, and Native American populations across the Basin. The CRB is predominantly a rural and natural resource dependent region that is the indigenous territory of at least 32 Tribes and First Nations (BOR, 2016; NPCC, 2019). Racial diversity is not pronounced outside of some reservation lands, urban areas, and agricultural communities, which may indicate particular vulnerability to marginalization for racial minorities within some subbasin communities. We examine racial diversity at the subbasin scale and posit that a higher proportion of minorities is indicative of higher vulnerability.

Gender

Gender, specifically women and especially single mothers, are found to have higher economic insecurity and a more difficult time recovering from material losses (Fordham, 2001). Further study has shown that women are less likely to have resources to take action to avoid climate impacts like water loss, and they recover (materially) much slower (Enarson & Morrow, 1998). This is due in part to employment opportunities, lower wages, and familial responsibilities (Blaike et al., 1994; Peacock et al., 1997). Here, we focus on the potential for overlapping and exacerbating inequalities that intersect with single female heads of household with young dependents who are more likely than their male counterparts to experience higher rates of poverty and more “severe experiences” of poverty (Demetriades & Esplen, 2008). Subbasins with higher proportions of single female heads of household with dependents are considered to be more vulnerable.

Natural Resource Economic Dependence

Natural resource economies dominate the Basin and are sensitive to climate change and altered timing and volume of water resources (Thomas & Twyman, 2005). Therefore, subbasins that are primarily economically dependent upon natural resources (higher proportion of the population employed) are most vulnerable to climate impacts. The natural resource economies included in our study are: forestry, agriculture, fishing, mining, and hunting.

Renter Occupied Housing & Tenure

Higher proportions of renter occupied housing may indicate lower socio-economic status as well as transience, which is relevant to local knowledge and important to adaptation processes (Cutter, 1996). Renters are also considered to be less likely to prepare for climate related shocks than homeowners (Burby et al., 2003). We examine the proportion of renter occupied housing units as well as the proportion of the population who moved to the subbasins in the last 12 months. We assume that newcomers and growing populations are also less likely to have local knowledge and awareness of hazards, and as a result may be less likely to engage in adaptation strategies. Additionally, trust and social networks, considered important to adaptive capacity, take time to develop and may be less likely in areas with higher population turnover (Putnam, 2001; Flora & Flora, 2004).

Age

Populations under the age of five and over 65 are considered to have higher sensitivity and lower adaptive capacity to climate change. Their collective ability to be self-sufficient and respond to shocks or disruptions in their environment that affect wellbeing is hampered (Wood et al., 2010). Families with dependents (young or old) are more likely to have limited finances and experience more barriers to preparing for or responding to environmental change or surprise (Cutter et al., 2003).

Methods

Indicator Aggregation

The average size of subbasins in the study area is about 3,700 km^2 and the average population count per HUC8 is approximately 65,000. Ten social vulnerability indicators were included from the US Census American Community Survey data 2012-2016 5-year estimates, the most up to date demographic data available at the time of the study (see Appendix C)(ACS, 2019). The decennial census provided more extensive data with higher accuracy estimates at the block and block group scales, but we chose to use more current data. We used the smallest unit of analysis available for each vulnerability indicator and aggregated to the subbasin (HUC 8) scale using areal weighting interpolation (Flowerdew & Green, 1993). Area weighted population totals were normalized as per capita values ([area weighted proportion/total HUC8 population]*1000). In the most rural regions, blocks and block groups did not significantly differ in size. To avoid problems of the modifiable areal unity problem (MAUP) (Openshaw, 1984) it was important to choose units smaller than the HUC8 boundary and this was achieved with block groups (Dark & Bram, 2007). We used ESRI ArcMap 10.4 to aggregate each social vulnerability indicator to the subbasin scale using areal interpolation (AI) techniques and to create maps to visually represent spatial variation in the data across the study area (Mayer et al., 2014). The AI approach resulted in population counts for each HUC8 that were normalized as per capita values (per 1,000 population) to facilitate computation and comparison across subbasins. We conducted an equal weighting process to assess vulnerability across the basin, as well as a variance-weighted method using Principal Components Analysis (PCA).

Equal Weights

To carry out the equal weighting approach, each of the social indicators was given a cumulative weight of one. A linear scaling technique was used where each indicator is normalized to a scale of 0-1 (Figure 2.1) (UNDP, 1990; Adger et al., 2004; Abson, 2012).

$\delta = (X - X_{min}) / (X_{max} - X_{min})$ where δ is the normalized value, X the original value and X_{min} and X_{max} the minimum and maximum values for each indicator in the dataset.

Figure 2.1 Linear scaling formula

Equal weights were determined by dividing the value range for each indicator into quintiles and assigning each quintile a score between 0-1 (Alessa et al., 2008). Because higher values were oriented to indicate higher vulnerability, the highest quintile values were assigned a value of 1 and the lowest quintile assigned a value of 0 (Q1= 1, Q2= .75, Q3=.5, Q4=.25, Q5=0; see Table 2.2). Indicator scores were summed across all 144 subbasins and 10 indicators included in the study, with a highest possible score of 10 and the lowest possible score of 0, then normalized again to produce a final, comparable index with values ranging between 0-1 (Figure 2.1) (Abson et al., 2012). A key benefit of equal weighting is that it simplifies the process of recalculation when modifying dynamic indicators to ensure index relevance and/or updating over time.

Table 2.2 Assigned quintile values for the hydrologic vulnerability index

Social Vulnerability Scale	**Assigned Value Before Summing**
Lowest	0.0
Low	0.25
Moderate	0.50
High	0.75
Highest	1.0

Variance Weighted PCA

We used a principal components analysis as a comparative approach to the equal weights composite vulnerability index construction. The PCA was conducted using SYSTAT v13 statistical software, and a Pearson test was conducted prior to the PCA and no variables were eliminated due to collinearity (max correlation = 0.842) (Krishnan, 2010; Abson et al., 2012). A Varimax rotation was performed on the data to simplify the output and reduce the number of individual indicators that have a high loading on a component (Abson et al., 2012). All of the original ten indicators were retained and three PCs were extracted, which explained 76% of the total variation in the data. The first PC (PC1) explaining a higher percentage (46%) of the variation than the second (13%), and the third (17%). The dissimilarity in the percentage of variation signals differences in their influence and thus their weight. The variance weighting method (Figure 1.2) included calculating the proportion of total variance for each of the principal factor scores with an eigenvalue greater than 1.0, following the Kaiser criterion (Kaiser, 1960). The values for each factor score for each subbasin were normalized (δ=X-X_{min}/X_{max}-X_{min}) between 0-1 and then summed to provide an overall vulnerability that facilitated direct comparison across all 144 subbasins. (Hightower, 1978; Antony & Rao, 2007; Krishnan, 2010). Higher scores indicate higher vulnerability

X= (variance of factor 1/total variance)(factor 1 score)+(var. factor 2)/tot. var)(factor 2 score)+(var. factor 3/tot.var)(factor 3 score)

Figure 2.2 Formula for the proportion of the percent variation as weights on factor score coefficients.

Mapping

The equal weighting and variance weighted PCA methods are mapped for comparison using quantile classification and warm to cool color spectrum weighting. Warm red and orange hues highlight higher vulnerability and cooler blue and green hues indicate basins with lower vulnerability. The maps display methodological differences and communicate results that are helpful to the researcher for exploring patterns and clusters in the data. The maps play an arguably more important role in clearly communicating locations of high and low vulnerability to non-expert users. A primary goal of the hotspot mapping is to provide a conversation piece that facilitates dialog between participants and leaders of water loss adaptation planning processes.

Results

Equal Weights

The results of the equal weights analysis show that geographically, the most vulnerable subbasins were concentrated in western Oregon (Willamette Valley region), northern and southern Idaho (Snake River Plain), and throughout central Washington (scablands). See Appendix D for a master map and key of subbasin names and Appendix E for subbasin population totals. Low vulnerability is predominant in eastern Oregon and central Idaho (Figure 2.3). The largest concentration of highly vulnerable subbasins is in Idaho (10 subbasins) and the lowest concentration is in Washington (5.5). Idaho also has the greatest number of subbasins with the lowest vulnerability (23), followed by Oregon (8). Interestingly, none of the subbasins in Washington scored in the lowest vulnerability range (Table 2.3).

Table 2.3 Top three high and low equally weighted social vulnerability scores

Most Vulnerable Subbasins	**Least Vulnerable Subbasins**
Lower Yakima, WA (#18) Score= 1	Upper Selway, ID (#132) Score= 0
S. Fork Coeur d'Alene (#88) Score= 0.97	Palisades, ID (#91) Score=0
Yamhill, OR (#63) Score= 0.97	Upper Middle Fork Salmon, ID (#126) Score= 0.03

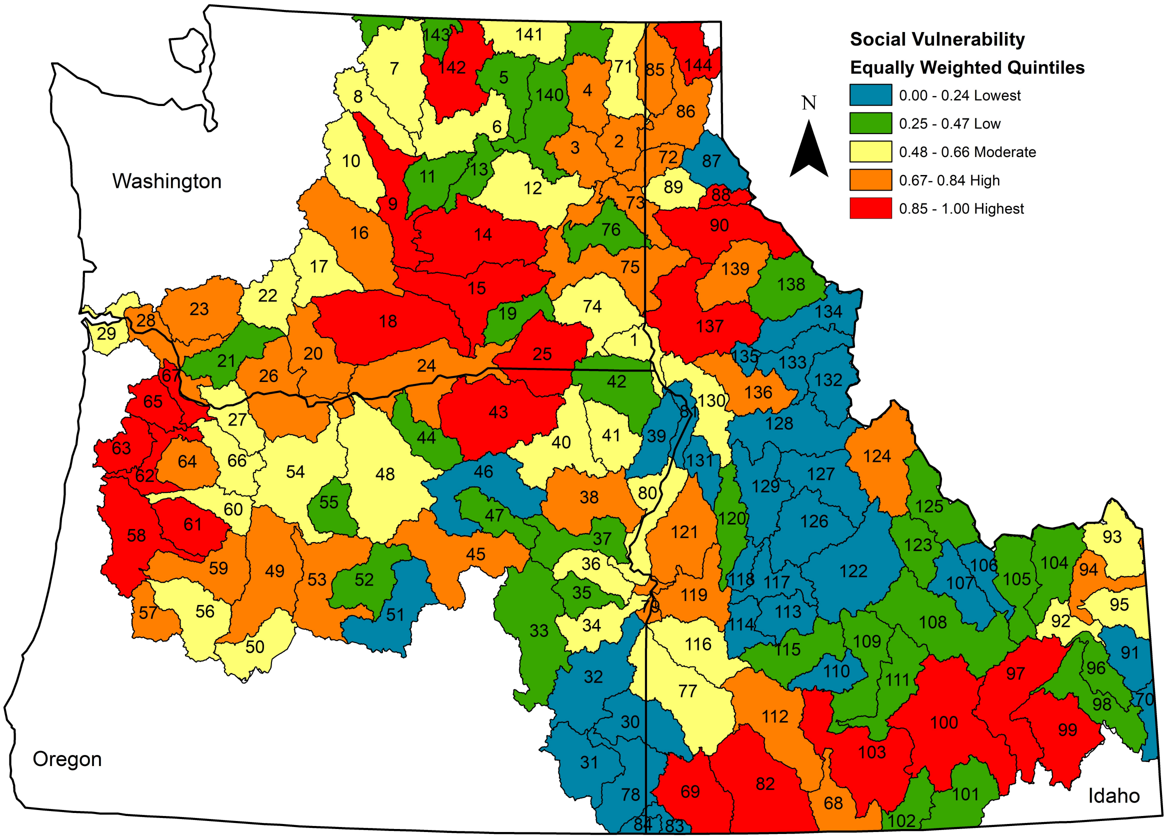


Figure 2.3 Social vulnerability map of the equally weighted indicators

Principal Components Analysis, Variance Weighting

The first three principal components (eigenvalues >1) explain 76% of the variance in the data, with the first, second, and third components accounting for 46, 13, and 17% respectively. Several indicators loaded on the first component with high significance, these included: female heads of household (0.91), age (0.90), mobility (0.88), education (0.88), poverty (0.82), and renter occupied housing (0.81). Each of these indicators are considered to be highly related to lower income, therefore we reclassified the first PC as "socio-economic status." Component two is heavily loaded by natural resource economic dependence (0.87) and Native American race (0.67), which we associate with rural areas in the Basin and thus reclassified as "rurality." African American and Hispanic race loaded highly on component three (0.89 and 0.71 respectively) and reclassified as "minority status." We weighted and summed each of the 3 principal component scores per subbasin and mapped the results, using the equation shown in Figure 2.2.

Table 2.4 Varimax rotated loading matrix of social vulnerability indicators

	PC1 31.0%	**PC2** 17.1%	**PC3** 17.3%
Female headed household	**0.908**	0.248	0.218
Age	**0.900**	0.208	0.169
Tenure	**0.883**	-0.010	0.207
Education	**0.878**	0.354	-0.112
Poverty	**0.823**	0.461	0.258
Renter occupied housing	**0.807**	0.237	0.451
Nat. Resource Dependence	0.154	**0.869**	0.054
Native American	0.256	**0.669**	-0.009
African American	0.206	-0.167	**0.896**
Hispanic	0.184	0.490	**0.712**
Reclassified name:	**Socio-economic status**	**Rurality**	**Minority status**

Compared to the equal weights approach, 76% of subbasins retained the same class of vulnerability, while 8% increased and 16% decreased vulnerability class. The results between the two methods were very consistent, with no significant increases or decreases (one class change, maximum) in vulnerability. Like the equal weighting method, the most vulnerable subbasins were concentrated in western Oregon, northern and southern Idaho, and throughout central Washington. Low vulnerability is consistently predominant in eastern Oregon and central Idaho (Figure 2.4). The concentrations of vulnerable subbasins by state did not change significantly.

We note that three of the top-10 subbasins with the highest variance weighted vulnerability index scores of "highest vulnerability" include cities with populations of 100,000 or more. In particular, the Lower Willamette subbasin, ranked 5th in overall variance weighted vulnerability score, is home to Portland, Oregon with a population of 637,683 in the metro area as of the 2010 Census- the highest population in our study area. Portland is also the fastest growing urban area in the state of Oregon and was ranked the 21st fastest growing city in the US in 2018 (Njus, 2018). Boise Idaho and Spokane Washington rank second and third respectively for the largest population centers in the study area. The Lower Boise subbasin is considered "vulnerable" and Spokane is located at the nexus of three "vulnerable" (Hangman, Lower Spokane, Little Spokane) and one "highly vulnerable" (Upper Spokane) subbasin. At the other end of the spectrum, there are several "highly vulnerable" subbasins in Idaho with no population centers over 100 people, these include the Bruneau and Upper Owyhee (second and third ranked for total VW score, respectively). The Middle Salmon Prather and Middle Fork of the Clear Water subbasins, also located in Idaho, similarly exhibit the highest vulnerability classification with 1-3 population centers ranging from 100-3,000 inhabitants. These differing results signify the various drivers of vulnerability in the Basin. The notable implication of highly vulnerable and highly populous areas overlapping is the potential for higher overall potential for exposure to climate change-induced water loss. Questions remain that are outside the scope of this study as to the benefits (increased tax base resources) and challenges (rapid increases in water demand) of large populations and rapid growth on overall adaptive capacity.

Table 2.5 Top three high and low variance weighted social vulnerability scores

Most Vulnerable Subbasins	Least Vulnerable Subbasins
S. Fork Coeur d'Alene (#88) Score=1.00	East Little Owyhee, ID (#84) Score=0.00
Bruneau, ID (#82) Score=0.75	South Fork Owyhee, ID (#83) Score=0.01
Upper Owyhee, ID (#69) Score=0.70	Middle Owyhee, ID (#78) Score=0.03

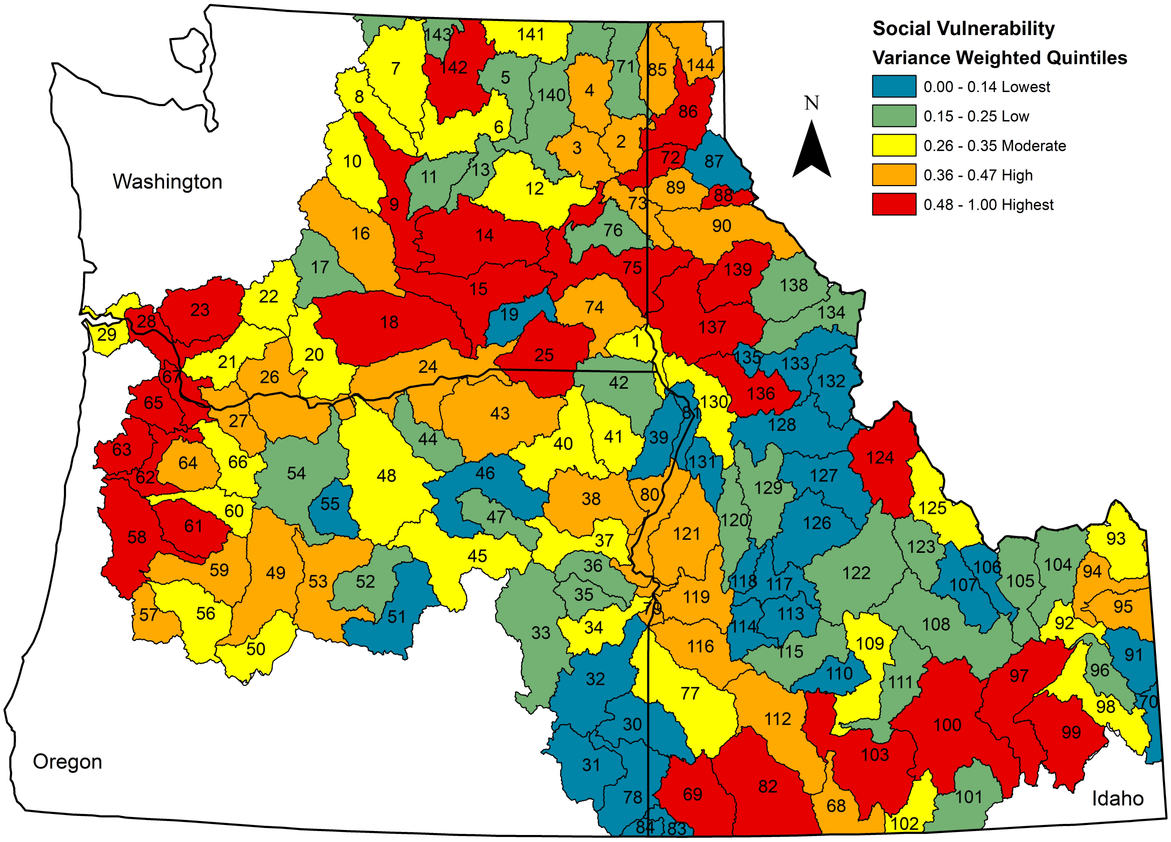


Figure 2.4 Social vulnerability map of variance weighted indicators

The equal weights process assigned equal influence to every indicator, while the variance weighted method distributed weights according to the influence of the three principal components (reclassified as “socio-economic status,” “rurality,” and “minority status”). The consistency in the results of the two methodological approaches improves reliability of our social vulnerability analysis.

Discussion

A primary objective of the social vulnerability assessment is to create an index of overall vulnerability from an array of indicators. Our study offers a “30,000 foot view” of the regional distribution of social vulnerability throughout the CRB. From this, we can get a clearer picture of where social vulnerability is located and concentrated and we get a sense of the diversity of water use and management settings. One silver lining of uncovering social vulnerabilities is the potential to make significant change over relatively short periods of time with a clear idea of how to improve a system and the ability to obtain and feedback. This is in contrast to landscape changes.

We intentionally chose publically available, frequently updated datasets, a manageable set of key indicators, and two fairly simple computational methods in order to enhance reproducibility, duplication, and enhancement. The HUC8 boundaries used in our analysis are ubiquitous to the US and are accompanied by a suite of nested hydrologic boundaries. Census block and block group data are national as well, therefore our approach to exploring social vulnerability at a water resource-relevant scale is accessible to any region in the country, though indicators should be altered to reflect context. Next steps could include engaging with communities within highly vulnerable subbasins about proactive adaptation to water loss. Further study of community-scale resilience and vulnerability could enhance adaptation over the short and long-term. One of the named benefits of this particular study is its current relevance to the ways that water management agencies within the Basin often request communities to demonstrate need and identify priorities to access funding. This type of programming comes with its own set of limitations, but our map and index could help inform the evolution of what we hope is the budding process of more place-specific management for all subbasins.

Limitations

Weighting and aggregating indicators are primary weaknesses in the value of vulnerability indexes. In our case, there are notable drawbacks to the areal interpolation approach, including what Goodchild et al. (1992, p. 383) refer to as the “arbitrary nature of such socioeconomic reporting zones” that can lead to the Modifiable Areal Unit Problem (Openshaw, 1984), or “the dependence of the results of spatial analysis on the arbitrary spatial basis of the data used.” We must assume in our analysis that population distributions are evenly distributed throughout the Basin. This unlikely to be the case near watershed boundaries that, in a mountainous basin such as the CRB, are likely to be demarcated by mountain ridges that are less likely to be populated areas. Consistent population distribution is more likely in urban areas, of which there are relatively few within the Basin. Though it is unlikely to have a direct impact on this study, changes in the boundaries of block groups (though well documented by the Census), may provide an obstacle to the study of vulnerability change over time. These changes correspond with population growth and are more likely in the short-term to occur in urban areas and less likely in the rural subbasins that currently dominate the region (Torrieri et al., 1994). Despite challenges, better alternatives are still lacking.

The computational approaches used in our analysis come with several limitations. Equal weighting, while standard in vulnerability analyses, treats all elements of vulnerability as if they have the same impact- for better and for worse. We acknowledge the challenges inherent to subjectively assigning values, including bias. The scope of our study does not and cannot capture the infinite ways in which race, poverty, education, etc. are experienced at every location, nor can it capture the strengths and weaknesses that come from the ever-transformative unfolding of each location's history. Dynamic social, political, and economic influences at great scales affect subbasin vulnerability but are not directly linked or aligned geographically.

In addition to weighting challenges, the study is limited by the actual indicators included in the study, which are influenced by data availability. We chose to use publically available datasets consistent across the whole study area. This improves accessibility and flexibility in updating the index, but it is not without limitation. The social indicators we ultimately chose to use, though common in the literature, are invariably limited in telling the whole story of social vulnerability. We intentionally sought out feedback from water leaders and managers across the Basin early in the research process with the goals of framing the work to reflect the needs of the region and informing indicator selection. Because the purpose of this study is to ultimately inform adaptation and processes and resource prioritization, our hope is that this work provides a platform for dialog and further exploration of meaningful elements of resilience and adaptive capacity at smaller scales of analysis.

Conclusions

Much of the hazards literature addresses social vulnerability in the same manner- through the use of widely available measures, such as the US Census. These measures are some of the best of what is available, but still leave much to be desired with regard to understanding the nuances of adaptive capacity. Many county-scale datasets offer alternative information that may provide a better view of adaptive capacity through the framework of

Community Capitals (Flora & Flora, 2004; Emery & Flora, 2006). The consideration of multi-faceted aspects of environmental, social, built capitals, for example, present the opportunity to gain an understanding of issues of trust, power, and legacy effects that imprint upon a region's ability to adapt to the changes afoot.

We conclude that social vulnerability can be explored from myriad angles and that it should be context based. As populations grow and shift throughout the CRB, it will be important to consider rural and urban water dynamics carefully. We recommend further research addressing a "core-periphery" perspective that considers changes of "frontier" areas near the boundaries of urban regions (Hughs & Holland, 1994). These areas represent important dynamics between water management social equity and may foreshadow regional changes to supply and demand that would benefit from proactive water adaptation planning.

We explore elements of social inequality at the subbasin scale to gain better understanding of the status quo challenges. We can reasonably anticipate that current climate trends and impacts to water resource availability in the Basin will be exacerbated by the expected increase in the frequency and intensity of climate events. History, current science, and our collective conscience tells us that those within our society who are more sensitive and less privileged bear a heavier burden of climate change impacts now and into the future. These burdens are exceptionally dynamic and influenced at multiple scales, so much so that any single approach to mitigate them is unlikely to be adequate. However, we have benefit of foresight to work with and to help begin to mould what our next policy and management steps must consider in order to "lift all boats" and in doing so set us on a more just and therefore sustainable path forward by way of increasing the chance of peace, prosperity, and well-being in the face of environmental tumult and uncertainty.

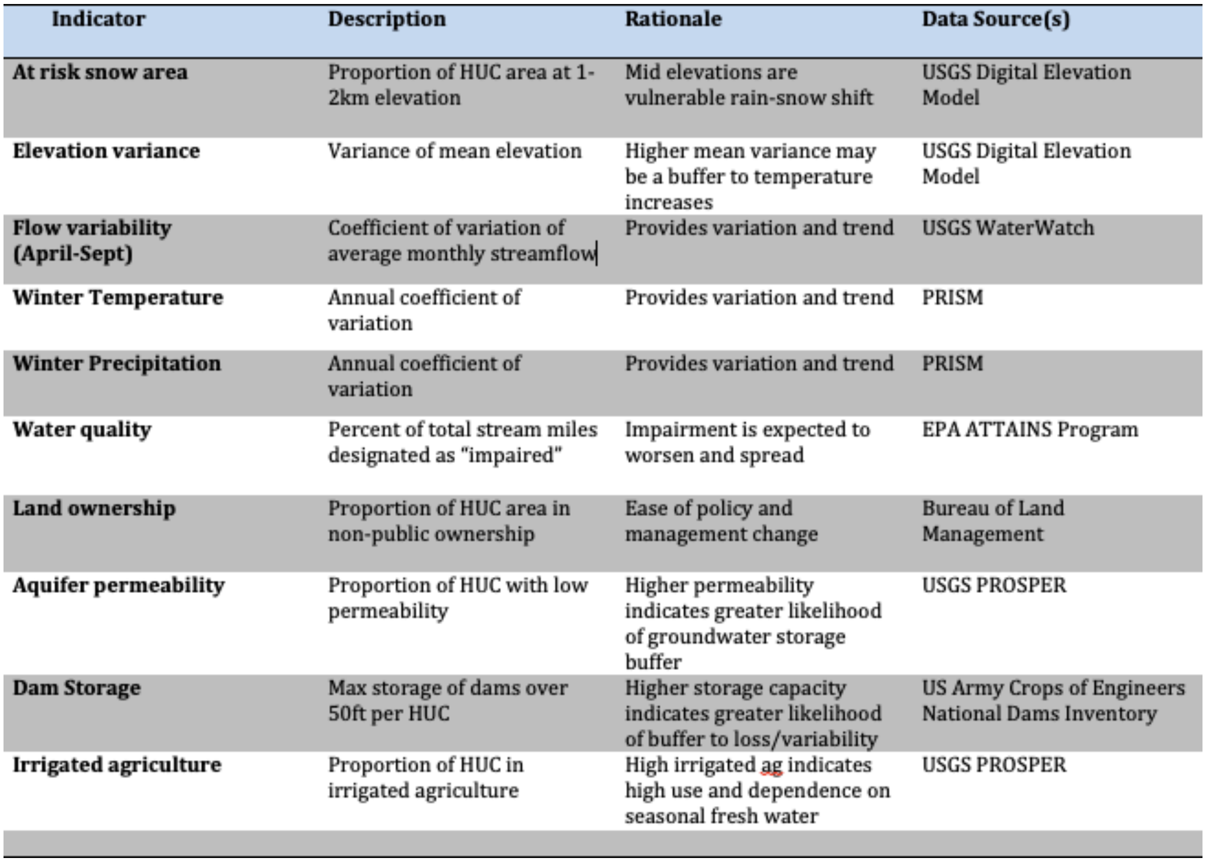
Chapter Three

A Hydrologic Vulnerability Index for the Columbia River Basin

Introduction

Current and expected future impacts of climate change and variability on water resources are well studied for the Columbia River Basin, yet significant uncertainty pertaining to the spatial distribution of internal vulnerability remains. We address this knowledge gap by examining ten indicators of hydrologic vulnerability relevant to the Columbia River Basin (CRB). Subbasins with higher combined values of the vulnerability proxies (Table 3.1) are considered to have higher hydrologic vulnerability to climate change-induced water loss. The selected indicators are encompassed by the Intergovernmental Panel on Climate Change (IPCC) definition of climate vulnerability, or "a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (McCarthy et al., 2001, p.1066). Together, the hydrologic vulnerability indicators indicate aspects of sensitivity (e.g. water quality), exposure (temperature variability) and adaptive capacity (land ownership). We provide a mapped index of hydrologic vulnerability with the express goal of improved understanding of hydrologic vulnerability at the subbasin scale. It is expected that the results of this study will stand alone and be combined with a study of social vulnerability to help identify potential priority areas for adaptation planning. Our intention is to provide a jumping off point for further study and to smooth the way for communication over proactive adaptation planning among communities and their water managers.

Table 3.1 Selected indicators of physical/hydrologic vulnerability



Indicator	Description	Rationale	Data Source(s)
At risk snow area	Proportion of HUC area at 1-2km elevation	Mid elevations are vulnerable rain-snow shift	USGS Digital Elevation Model
Elevation variance	Variance of mean elevation	Higher mean variance may be a buffer to temperature increases	USGS Digital Elevation Model
Flow variability (April-Sept)	Coefficient of variation of average monthly streamflow	Provides variation and trend	USGS WaterWatch
Winter Temperature	Annual coefficient of variation	Provides variation and trend	PRISM
Winter Precipitation	Annual coefficient of variation	Provides variation and trend	PRISM
Water quality	Percent of total stream miles designated as "impaired"	Impairment is expected to worsen and spread	EPA ATTAINS Program
Land ownership	Proportion of HUC area in non-public ownership	Ease of policy and management change	Bureau of Land Management
Aquifer permeability	Proportion of HUC with low permeability	Higher permeability indicates greater likelihood of groundwater storage buffer	USGS PROSPER
Dam Storage	Max storage of dams over 50ft per HUC	Higher storage capacity indicates greater likelihood of buffer to loss/variability	US Army Crops of Engineers National Dams Inventory
Irrigated agriculture	Proportion of HUC in irrigated agriculture	High irrigated ag indicates high use and dependence on seasonal fresh water	USGS PROSPER

Background

Indicators Explained

The set of physical vulnerability indicators is informed by previously established indices, including the Water Poverty Index (Sullivan, 2002); Social Vulnerability to Hazards Index (Cutter et al., 2006); Groundwater Vulnerability Index (Collins & Bolin, 2007); Arctic Water Vulnerability Index (Alessa et al., 2008); the Socio-Ecological Systems Vulnerability Index (Leslie et al., 2014), and the water resource vulnerability indicators for the CRB developed by Chang et al. (2013). These were modified in an iterative process with input from research experts and regional water managers.

Flow

Interannual variability in spring and late summer flow (April-September) may imply uncertain water availability and could lead to unpredictable water right fulfillment and conflict (Stewart et al., 2004; Cosens et al., 2014[a]; Clifton et al., 2018). The timing of available water is crucial to most users, from recreationists, to irrigators, and especially for salmonid migration and habitat (BOR, 2016). Basins with higher variability are considered to be more vulnerable due to uncertainty in water availability and because high variability in the present is expected to increase under future climate conditions (Hamlet & Lettenmaier, 2007).

Permeability

Surface geology plays a role in the subsurface storage and transport of snowmelt and runoff and is a major determinant of basin-scale hydrologic character (Vallet et al., 1997). It also influences surface erosion, infiltration rates (thus evapotranspiration) and subsurface pathway structures (Taylor et al., 2013). Surface geology also mediates groundwater-surface water exchange and runoff residence time within a basin. Subbasins that are highly permeable are considered to be more likely to recharge groundwater storage than those with low permeability. Low permeability is classified as more vulnerable than high permeability.

Irrigated Agriculture

Over 80% of freshwater resources in Oregon, Idaho, and Washington are used to irrigate agriculture (USGS, 2015; Mucken et al., 2017). Agricultural land dependent on irrigation may see changes to volume as well as the timing of water availability. These changes could lead to interruptions to water rights, increased exploitation of groundwater, and potential related conflicts.

Winter Temperature Variability

Variability in temperature, particularly during winter months when precipitation and potential for snowfall is highest in the Pacific Northwest, may reduce seasonal snowpack. Temperature variability may also affect the timing of runoff, storage, volume, and thus seasonal water availability (Mote et al., 2005; Payne et al., 2005; Regonda et al. 2005). We examine the magnitude of temperature variability over a 30-year record in order to establish a trend (World Meteorological Organization standard) (Arguez & Vose, 2011). Our assumption is that variability will increase under future climate conditions, so that subbasins currently experiencing high variability have higher sensitivity to expected increases.

Winter Precipitation Variability

Increasing precipitation variability is expected with a warming climate and is associated with increased extreme wet and dry events (Pendergrass et al., 2017). Increased variability during winter snowpack accumulation months could lead to reduced seasonal water storage and changes to overall volume and timing of water availability. We examine the magnitude of precipitation variability over a 30-year period. Our assumption is that variability will increase under future climate conditions, so that subbasins currently experiencing high variability may see greater increases over time.

Dam Storage

Dam storage is already a common approach to contending with variation in timing of water supply and demand and may expand (where possible) as an adaptation strategy to address climate-induced water loss (Wisser et al., 2013). Water storage capacity is expected to become increasingly important for all watersheds, particularly during summer and early fall water months. We consider subbasins with higher acre feet of dam storage to be less vulnerable than subbasins with lower storage because they represent a reserve of water that may buffer arid periods and ease uncertainty around drought (Gober & Kirkwood, 2010). Along with providing some water security, dams represent opportunities to modify existing operations in ways that could buffer future climate impacts on water supply (including expanded storage and flood security) at the subbasin scale (Ehsani et al., 2017). These possible benefits do not account for the significant potential for dams to cause or exacerbate biophysical and water quality degradation.

Water Quality

Water quality is expected to decrease under future climate conditions, specifically temperature and dissolved oxygen. Increased storm intensity may also lead to increased runoff and water pollution from sediment, nutrients, and other pollutants (UCS, 2019). Under the Clean Water Act (sections 305(b) and 303(d)), the US Environmental Protection Agency enforces water quality standards and designates impaired waters. The number of assessed rivers in the Basin varies greatly from state to state. Similarly, the number of impaired *and* assessed rivers varies, with Idaho (12%), Oregon (41%), and Washington (20%) all experiencing some nutrient-related impairment (EPA, 2019). Inconsistent data collection and knowledge of impaired waters presents a potential drawback of this metric, however we present best available knowledge regarding water quality in our study area.

At Risk Snow Area & Elevation Variation

Low elevation snow cover at mid-latitudes is receding due to warmer average winter temperatures (Nolin & Daly, 2006). Subbasins with a higher proportion of high elevation area (larger potential snow accumulation area) are less likely than those with higher proportions of middle and low elevations to experience impacts of temperature increases on snow accumulation and ablation. For our purposes, low or "at risk snow elevation" areas are those that fall within the 1,000-2,000 meter range (approximately 3,000-6,000ft) where snow cover typically accumulates at temperatures near 0^{o} C and is therefore sensitive to even minor increases in temperature. Additionally, subbasins with higher variance in mean elevation may experience buffering effects to temperature increases relative to those with low variance (Tennant et al., 2015). We calculate the proportion of each subbasin area in the 1,000-2,000 meter elevation range, and we calculate the variance in mean total elevation. Subbasins with higher proportions of "at risk snow area" are considered more vulnerable. Separately, we calculate the variance of subbasin mean elevation and consider low variance of mean to indicate higher vulnerability.

Land Ownership

Public lands dominate the CRB and many of its tributary headwaters (Clifton et al., 2018). We posit that lands under public ownership may be more responsive to policy decisions and adaptation efforts. This is in contrast to privately owned lands where management decisions are often implemented on a voluntary basis or may lag in enforcement and response time. We consider subbasins with higher proportions of private land to have higher vulnerability.

Methods

Indicator Aggregation

Each of the ten hydrologic vulnerability indicators are spatially aggregated to the subbasin scale using a variety of methods and tools in Arc GIS described in detail below.

Flow

Flow aggregation included acquiring monthly computed runoff for HUC8 units from the USGS WaterWatch dataset and calculating the coefficient of variation of monthly flow data from the computed average and standard deviation (CV = (standard deviation/mean) * 100) (WaterWatch, 2018). This was done for six months, from April-Sept, for a 30-year period from 1987 to 2017 (Stewart et al., 2004; Clifton et al., 2018). Vulnerability was determined by degree of variability, or ranking by the largest CV per HUC where higher variability indicates higher vulnerability.

Permeability

The percentage of permeable surface geology data was available from the USGS PROSPER dataset at 30x30 meter grid resolution (Sando et al., 2018). Permeability percentage values were aggregated from pixels to the HUC8 scale in ArcGIS using spatial analyst tools. Vulnerability was determined by total percent permeable within each HUC, where subbasins with lower total permeability values were considered to have higher vulnerability. Original permeability data was derived from regional USGS geologic map data.

Irrigated Agriculture

Percent land cover classified as irrigated agriculture per subbasin was derived from the USGS PROSPER dataset that includes 30x30 meter continuous parameterized grid (CPG) data for the 2002-2012 time period (Sando et al., 2018). Grid data were aggregated to the HUC8 scale using ArcGIS spatial analyst tools. Original data were derived from remotely sensed MODIS data products produced by the USGS. Subbasins with the highest percentages of irrigated lands were considered to have higher vulnerability.

Temperature Variability

Average monthly temperature data were downloaded from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset for November, December, January, and February for a 30-year period from 1987-2017 (PRISM, 2018). Temperature variability for the core winter months was captured by calculating the coefficient of variation across all months (CV = (standard deviation/mean) * 100). Subbasins with higher winter temperature variability were considered to have higher vulnerability (Alessa et al., 2008).

PRISM raster data was aggregated to the HUC8 scale using a raster to point conversion in ArcGIS analyst tools.

Precipitation Variability

Average monthly precipitation data were downloaded from the PRISM dataset for November- February from 1987-2017 (PRISM, 2018). Precipitation variability during the region's peak precipitations months (Nov-Feb) was captured by calculating the coefficient of variation of precipitation values across all four months (CV = (standard deviation/mean) * 100) over a 30-year period. Subbasins with higher winter precipitation variability were considered to have higher vulnerability (Alessa et al., 2008). PRISM raster data was aggregated to the HUC8 scale using a raster to point conversion in ArcGIS analyst tools.

Water Quality

The Environmental Protection Agency (EPA) ATTAINS geospatial dataset of water bodies listed as "impaired" by the Clean Water Act was used to assess water quality at the subbasin scale. The total area of listed lakes and streams were aggregated to the HUC8 scale, and the proportion of impaired streams per HUC was calculated. Subbasins with larger areal proportions of impaired waters were considered to have higher vulnerability.

Land Ownership

The areal proportion of public lands per HUC was determined using land ownership data from the Bureau of Land Management (BLM) for Oregon, Washington, and Idaho and isolating federal lands exclusively. Using ArcMap, Bureau data for each state was re-projected (North America Albers Equal Area Conic) and joined, and the proportion of land ownership per HUC8 was calculated and summarized by the sum of the proportion of HUC8 area. Subbasins with larger areal proportions of private lands were considered to have higher vulnerability.

At Risk Snow Area & Mean Elevation

The areal proportion of "at risk snow" (Nolin & Daly, 2006), or proportion of area in the 1-2 Km elevation band, was constructed using the 1/3 arc second elevation contours

(1:50K with 1000 ft. contours) of the conterminous US from the USGS ArcGIS online Map Service (USGS, 2018) clipped to the CRB boundary in ArcMap. The area in the 1-2km band was determined for each HUC by calculating the proportion of total area within the target elevation range. We used the zonal statistics tool in ArcMap to derive mean elevation for each subbasin and calculated the variance in mean using Excel formulas.

Dam Storage

Maximum acre feet of dam storage per subbasin was determined using the U.S. Army Corps of Engineers National Dams Inventory map layer (USACE, 2019). The data was re-projected, clipped to the CRB boundary, and spatially joined with the HUC8 boundaries. Raw volume (acre feet) data per subbasin were normalized (δ=X-X_{min}/X_{max}-X_{min}). Basins with lower dam storage capacity are considered to have higher vulnerability. Dams included in the dataset are 50ft or higher with a normal storage capacity of 5,000 acre-feet or more, or with a maximum storage capacity of 25,000 acre-feet or more, from the 79,777 dams in the inventory (USACE, 2019).

Construction of the Physical Vulnerability Index, Weighting and Computation

Currently, there is no efficient method to measure, compare, and contrast water resource vulnerability criteria relevant to the CRB at the subbasin scale. The physical vulnerability index is intended to be a comprehensive, objective method for aggregating spatially explicit, hydrologic vulnerability indices. To operationalize the concept of water resource vulnerability and illustrate key conclusions, we developed a composite measure and ordinal scaling of ten mostly hydrologic (referred to throughout as “physical”) vulnerability indices (Table 3.1). Indicators that include elements of variability (e.g., runoff data) require the use of a 30-year record (World Meteorological Organization standard) (Arguez & Vose, 2011). We approached computation of the index in two ways, an arithmetic equal weighting method and variance weighting of a Principal Components Analysis. A simple explanation of the indexing process is as follows (Figure 3.1) : 1) indicator selection, 2) data processing (including normalization and aggregation), 3) equal weighting based on quintile ranges/or principal components analysis and variance based weighting; 4) computing vulnerability scores across all subbasins; 5) mapping vulnerability scores. Indicators of physical vulnerability are proxies of hydrologic vulnerability to climate change-induced water loss and were represented on a rating scale from 0-1. We chose a categorical design for the index that allowed for a standardized approach to reduce elements of physical vulnerability into a more readily conceptualized and rankable whole.

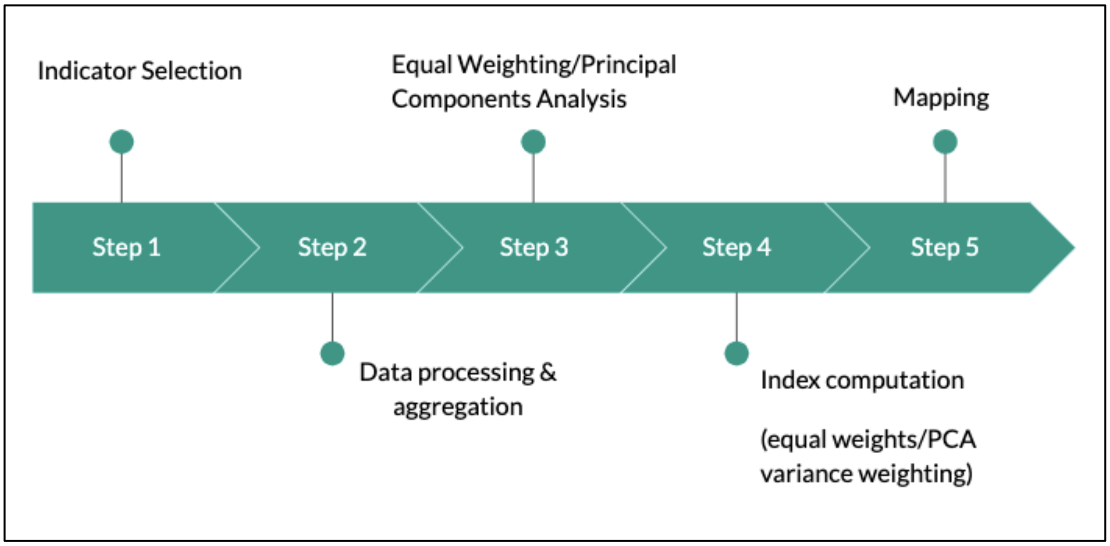


Figure 3.1 Indexing methods at a glance

Equal Weighting

To accomplish the equal weighting approach, each of the physical indictors was given a cumulative weight of one. A linear scaling technique was used where each indicator is normalized to a scale of 0-1 (Figure 3.2) (UNDP, 1990; Adger et al., 2004; Abson, 2012).

$\delta = (X - X_{min}) / (X_{max} - X_{min})$ where δ is the normalized value, X the original value and X_{min} and X_{max} the minimum and maximum values for each indicator in the dataset.

Figure 3.2 Linear scaling formula

This normalization approach addressed the issue of combining multiple indicators that are measured in different scales and units (Zurovec et al., 2017). Equal weights were determined by dividing the value range for each indicator into quintiles and assigning each quintile a score between 0-1 (Alessa et al., 2008). Because higher values were oriented to indicate higher vulnerability, the highest quintile values were assigned a value of 1 and the lowest quintile assigned a value of 0 (Q1.0= 1, Q2= 0.75, Q3=0.5, Q4=0.25, Q5=0.0) (Table 3.2). Indicator scores were summed and averaged across all 144 subbasins and ten indicators included in the study, with a highest possible score of 10 and the lowest possible score of 0. The scores are normalized again to produce a final, comparable index with values ranging between 0-1 (Abson et al., 2012). Higher scores indicate higher levels of vulnerability to water loss and low values indicate low vulnerability. A key benefit of the equal weighting approach is that it simplifies the process of recalculation when modifying dynamic indicators over time.

Table 3.2 Assigned quintile values for the hydrologic vulnerability index

Hydrologic Vulnerability Scale	Assigned Value Before Summing
Lowest	0.00
Low	0.25
Moderate	0.50
High	0.75
Highest	1.00

Variance Weighted PCA

We use a principal components analysis (PCA) and develop weights for each factor based on the proportion of variance explained by each principal component. The results of this method are compared to the equal weights composite vulnerability index construction. We derived all indicators as proportions per HUC and normalized all values using a min-max technique ($\delta = X - X_{min} / X_{max} - X_{min}$) (UNDP, 1990) before conducting a PCA. Both R programming language and the statistical software program SYSTAT, Version 13 were used to carry out all statistical procedures. PCA helps to detect patterns and highlight underlying factors that describe variation in the data (Jolliffe & Cadima, 2016). Each component is associated with a set of correlated variables with the strength of these relationships indicated by coefficients and factor loadings for each variable. We weight the variables of the composite index based on the proportion of variance explained by each principal component for each factor (with Eigenvalues > 1), so those that explain more variance (PC1 vs PC2) are assigned larger weights (Figure 3.3). The weighted values are summed for each principal component across all 144 subbasins. All values are standardized and indexed on a scale between 0-1, with higher cumulative scores indicating higher vulnerability.

X= (variance of factor 1/total variance)(factor 1 score)+(var. factor 2)/tot. var)(factor 2 score)+(var. factor 3/tot.var)(factor 3 score)+(var. factor 4/tot. var.)(factor 4 score)

Figure 3.3 Formula for the proportion of the percent variation as weights on factor score coefficients.

Our step-by-step process for carrying out the PCA included checking the correlation between variables using a Pearson correlation test, which justified our choice to retain all ten variables and carry forward with the PCA. A Varimax rotation was performed on the data to simplify the output and reduce the number of individual variables that have a high loading on a component (Abson et al., 2012). Four components were retained for further analysis, which was supported by eigenvalues for each component/factor, following the Kaiser criterion (Kaiser,1960). The factors with the strongest relationship to each of the four principal components (factor loadings) dictate what each factor represents and is re-named appropriately (Table 3.4). The composite index was created by computing the weighted average of factor scores across the set of physical vulnerability indicators . Vulnerability is numerically based on relative ranking, where the watersheds with the highest cumulative weights are shown as most vulnerable. The weighted factor scores for each subbasin were normalized ($\delta = X - X_{min}/X_{max} - X_{min}$) between 0-1 and then summed to provide an overall vulnerability score that facilitated direct comparison across all 144 subbasins (Fig. 2.3). Higher scores indicate higher vulnerability. A composite indexing approach was chosen due to the ease of interpreting numbers representing the construct of vulnerability, and because it can be easily integrated into spatial analysis. Mapping vulnerability adds additional opportunity to view vulnerability across space and note patterns or clusters of vulnerability that may be useful to planning or policy approaches (Parkes et al., 2008).

Mapping

The equal weighting and variance weighted PCA methods are mapped for comparison using a quantile classification and warm to cool color spectrum weighting. Warm red and orange hues highlight higher vulnerability and cooler blue and green hues indicate basins with lower vulnerability. The maps display methodological differences and communicate results that are helpful to the researcher for exploring patterns and clusters in the data. The maps play an arguably more important role in clearly communicating locations of high and low vulnerability to non-expert users.

In addition to the mapping physical vulnerability, we also provide an overlay of social and physical vulnerability to identify "hotspots" of double exposure throughout the study area. Aggregate indices based on indicators of socio-hydrologic vulnerability are useful in identifying where multiple aspects of vulnerability occur.

The mechanics of the spatial analysis process includes obtaining social and physical datasets and re-projecting to a single coordinate system (Albers conic equal area [WGS 1984] global coordinate system) Esri ArcMap Geographic Information System software. ArcGIS tools are used to calculate areal proportions and aggregate data to the subbasin scale. HUC 8 subbasin boundaries are clipped to the CRB boundary limits and publically available through the USGS's National Hydrography Dataset (USGS, 2017). The result of spatial representation of vulnerability is that normalized indices visually identify relative levels of vulnerability between subbasins.

The resulting vulnerability scores and maps represent current vulnerability and susceptibility to climate change-induced water loss. The value ranges depicted for each of the weighting methods are classified and mapped as quantiles, which is well suited to linearly distributed data (Alessa et al., 2008). We divide the value ranges into five classes to align with our low-high indexing approach, with the same number of data values in each class for interpretation ease. The qualitative values assigned to each quantile, in order from least to greatest are: lowest vulnerability, low vulnerability, moderate vulnerability, high vulnerability, and highest vulnerability. To depict the results geographically in an easily interpretable manner, they are thematically mapped with a cool to warm color ramp corresponding to low to high values using ESRI ArcGIS (Zurovec et al., 2018).

Data Sources

All data source are public to facilitate reproducibility, replication, and improvements. Flow, permeability, and irrigated agriculture data come from the USGS PROSPER dataset available through Science Base. These data are available at the regional scale and metadata are available with specifications regarding raw data sources and modifications. Average monthly temperature and precipitation data come from the Oregon State University PRISM dataset FTP site. Water quality data is from the EPA's WATERS geospatial downloads ATTAINS Program. The national elevation dataset used is available through USGS and ArcGIS online. Finally, the dam storage data is available through USACE National Dams Inventory spatial database. These variables were selected to reflect regional relevance. Regional managers were consulted and helped select and scrutinize the variables used. The list is not exhaustive, but is reflective of unique, key physical variables and available data (see Table 3.1).

Results

Equal Weights Analysis

The results of the equal weights analysis show that geographically, the most vulnerable subbasins are concentrated in the high desert region of eastern Oregon, throughout the Snake River Plain and southern Bitter Root Range in Idaho, and the leeward side of north Cascades in north-central Washington. Low vulnerability is predominant in the southern Cascades, urban northwestern and rural north-central Oregon; across southern Washington, throughout the scablands in the east, and in the north; and finally throughout north-central Idaho. The highest concentration of vulnerability is in Idaho, with 15 complete and 2 partial subbasins indicating the highest vulnerability status. Low vulnerability is dominant in Washington, with 15 complete and 4 partial subbasins indicated the lowest vulnerability status.

Table 3.3 Summary of equal weighting results, most and least vulnerable subbasins

Most Vulnerable Subbasins	Least Vulnerable Subbasins
Beaver-Camas, ID (#104) Score = 1.00	Sanpoil, WA (#5) Score= 0.11
Portneuf, ID (#99) Score = 0.96	Chief Joseph, WA (#6) Score = 0.11
Medicine Lodge, ID (#105) Score = 0.85	Lower N. Fork Clear Water (#139) Score = 0.00

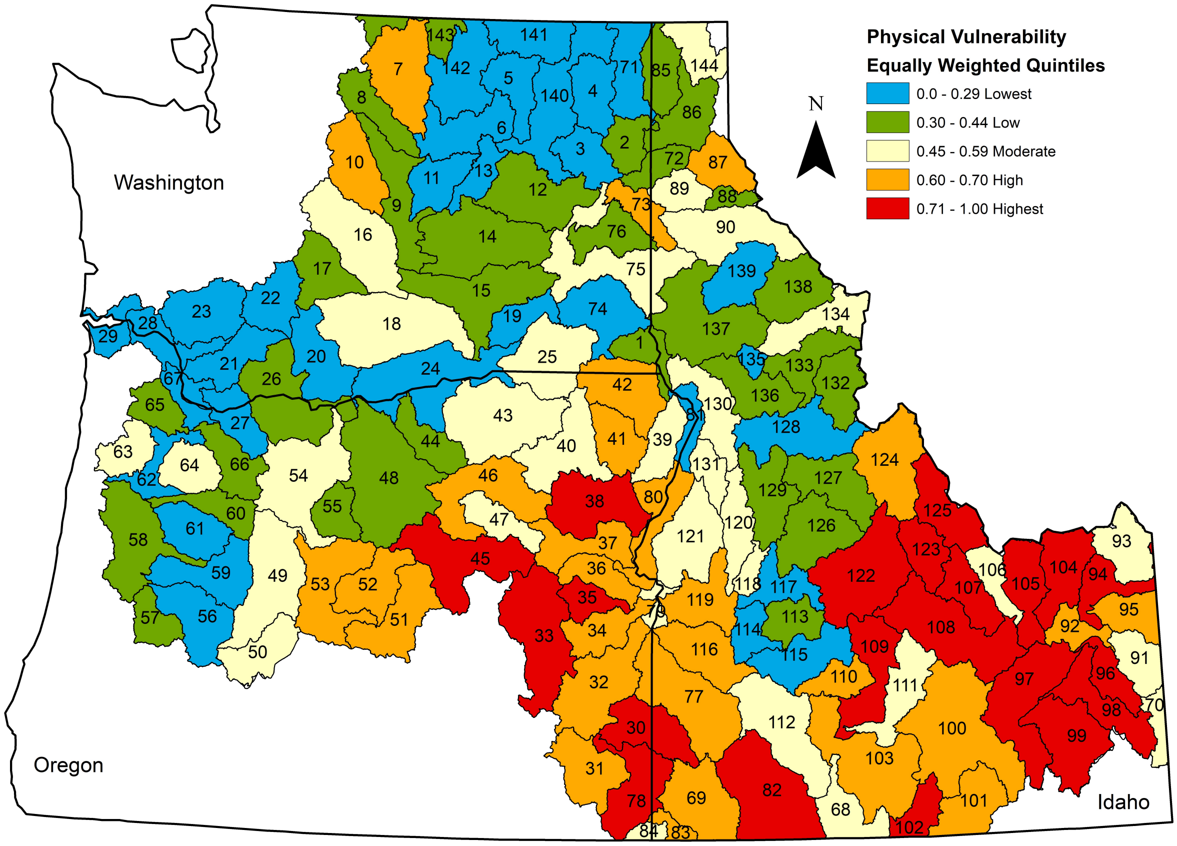


Figure 3.4 Vulnerability map of the equally weighted indicators

Principal Components Analysis, Variance Weighting

All of the original ten variables were retained and four PCs (eigenvalues >1) were extracted, which explained 63.9% of total variation in the data. The first rotated component explained 16.9% of the variation, the second 21.1%, and the third 13.1%, and the fourth 12.8%. Permeability (0.811) and irrigated agriculture (0.802) loaded highly on the first component (Table 3.4). We re-classified this as “irrigation dependence.” Component two is heavily loaded by “at risk snow” elevation (0.864), elevation variance (0.818), and land ownership (0.725). Component two is therefore reclassified as “elevation dependence.” Precipitation and temperature variance (0.783 and 0.782 respectively) are loaded highly on the third component and renamed “climate variability.” Lastly, dam storage and stream flow variability loaded highly on component four (0.775 and 0.751 respectively), reclassifying this variable as “water timing insecurity” to capture high flow variability and low dam storage.

We weighted and summed each of the four principal component scores per subbasin and mapped the results, shown in Figure 3.5.

Table 3.4 Varimax rotated loading matrix of physical vulnerability indicators

	PC1 16.86%	**PC2** 21.06%	**PC3** 13.13%	**PC4** 12.82%
Permeability	**0.811**	-0.197	-0.022	-0.049
Flow	0.143	0.028	-0.193	**0.751**
Water quality	0.157	0.195	-0.055	0.113
"At risk snow" area	-0.168	**0.864**	0.056	0.102
Land ownership	-0.470	**0.725**	-0.110	-0.076
Precipitation	-0.031	0.075	**0.783**	-0.247
Dam storage	-0.204	0.162	0.087	**0.775**
Irrigated agriculture	**0.802**	0.097	0.121	-0.023
Temperature	0.128	-0.216	**0.782**	0.117
Mean elevation	0.176	**0.818**	-0.102	0.106
Reclassified name:	**Irrigation dependence**	**Elevation dependence**	**Climate variability**	**Water timing insecurity**

Compared to the equal weights approach, 54% of subbasins retained the same class of vulnerability, while 35% increased and 11% decreased vulnerability class. In general, the variance weighted approach increases vulnerability across the study area. This difference is most pronounced in central and eastern Washington, which saw 8 (four partial and four complete) subbasins shift from low and moderate to high and highest vulnerability classes. Among these, vulnerability of the Lower Crab subbasin in central Washington differed the most between the two methods (VW= highest vulnerability, EW= low vulnerability), indicating that the more heavily weighted components (e.g. irrigation and elevation) likely had strong influence on vulnerability here. Outside of Washington the differences in vulnerability ranking was minimal with regional patterns retained throughout Oregon and Idaho largely retained.

The variance weighted results show the highest vulnerability located in Idaho, particularly south and south-central Idaho. Central and eastern Oregon and south-central Washington also appear to have groupings of very high and high vulnerability. The top six individual subbasins with the highest vulnerability scores for the entire study area resulting from the variance weighted method were all clustered in southeastern Idaho, these included, in order: American Falls, Beaver-Camas, Idaho Falls, Upper Snake Rock, Teton, and Portneuf. The least vulnerable subbasins, according to the variance weighting were located in western and northwestern Oregon, northeastern Washington, and throughout central and north-central Idaho. The individual subbasins with the lowest scores were predominantly located in Washington, these included, in order: Lower Columbia-Clatskanie, Lower Cowlitz, Lower Columbia, Lower Willamette (OR), and Franklin D. Roosevelt Lake (Table 3.5).

Table 3.5 Summary of the variance weighting results, most and least vulnerable subbasins

Most Vulnerable Subbasins	**Least Vulnerable Subbasins**
American Falls, ID (#97) Score = 1.00	Lower Columbia-Clatskanie, WA/OR (#28) Score = 0.00
Beaver-Camas, ID (#104) Score = 0.94	Lower Cowlitz, WA (#23) Score = 0.01
Idaho Falls, ID (#92) Score = 0.94	Lower Columbia, WA/OR (#29) Score = 0.01

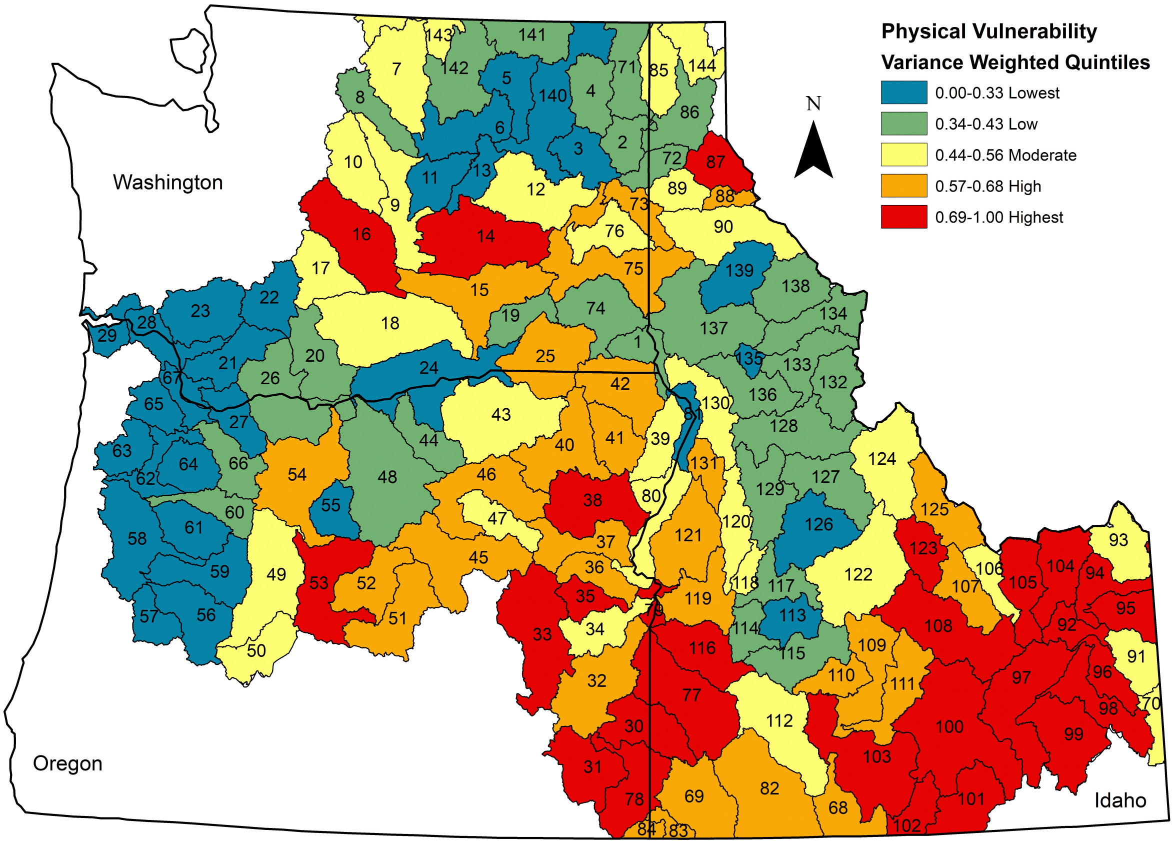


Figure 3.5 Physical vulnerability map of the variance weighted indicators

There are many factors at play that may influence vulnerability in one state over another, including the dominance of Idaho's land area in the Basin. Several subbasins cross state and international boundaries making clear counts subjective, but about 66 or 46% of all subbasins in our study area are within the state of Idaho. This compares to 43 (30%) and 35 (24%) in Oregon and Washington respectively. The low vulnerability indicated in eastern-central Washington does not consider significant water transfers and groundwater exploitation throughout this region via the Bureau of Reclamation 's Columbia Basin Project, which pumps water from the Columbia River, among other sources, to 10,000 farms and over half of a million agricultural acres (Simonds, 1998). This example serves to point out that the scale of our analysis is unable to capture important nuances that are significant to understanding hydrologic vulnerability on the ground. Reclamation projects across the Basin abound and should be given special consideration at a finer scale of analysis.

Political boundaries surely have indirect impact on current and historical management decisions that have lasting effects on some aspects of physical vulnerability (e.g. dam storage or water quality). Regardless, the majority of the highly vulnerable subbasins in Idaho are closely clustered in space and situated along the Snake River, a major tributary to the Columbia and an area dominated the majority of highly populated subbasins in Idaho (see Appendix E). The approximately fifteen subbasins showing high variance weighted vulnerability along the Snake River in southern Idaho show the highest vulnerability values for the entire study area, representing 14 of the top 25 highest vulnerability scores. These values are primarily driven by the elevation (14 subbasins or 56% represented in the top 25 irrigation vulnerability values) and irrigation variables (9 subbasins or 36% in the top 25), with water timing insecurity playing an important but lesser role in most instances (12% of the top 25 scores). It's highly possible that close proximity implies shared aspects of physical vulnerability, which lends to the advantage of more collaborative approaches to sharing resources and knowledge regarding adaptation strategies, aided by existing and well-established systems of water management for the Snake River system.

The equal weights approach assigned equal influence to every indicator, while the variance weighted method distributed weights according to the influence of four principal components (reclassified as "irrigation dependence," "elevation dependence," "climate variability," and "water timing insecurity"). The differences in the results can be expected given that these four principal components account for less than 65% of variance. Similar differences in the comparative computational approaches were found by Zurovec et al. (2018) and Wirehn et al. (2015).

Hotspot Analysis

Here we put into practice the integration of the social and physical vulnerability domains. Guided by a socio-ecological framework that recognizes the inseparability of humans and their environment, and the vital connection between society and water in particular, we seek to highlight where our most sensitive populations overlap with our most hydrologically challenged subbasins. This double exposure of higher potential for climate induced water resource loss and lower potential for social adaptive capacity may foreshadow future strife. The potential for conflict and negative impacts on safety, health, and well being generally could be mitigated or diminished with a clearer picture of where these double exposures are located. A better understanding of where water change impacts might be most severe may facilitate or ease dialog over proactive and place-specific adaptation planning processes. Our study of “hotspots” includes a geographic overlay of the social and physical vulnerability analyses in order to isolate subbasins. The following two paragraphs compare our separate methods to interpreting the overlay.

Equal Weights

A simple overlay of the independent social and physical indexes indicates that the equal weighting approach yields three subbasins with overlapping “highest vulnerability.” These are the Bruneau, Portneuf, and American Falls subbasins in southern Idaho (signified by red coloring and crosshatching overlay in Fig 2.6). These are accompanied by three additional adjoining Snake River Plain subbasins: the Upper Owyhee, Upper Snake Rock, and Lake Walcott, showing “high” physical vulnerability and “highest” social vulnerability that are worth noting (signified by orange coloring and crosshatching overlay in Fig 2.6). The overlay analysis also shows five “cool” spots, the Middle Fork Clearwater, Middle Salmon-Chamberlain, South Fork Payette, Boise-Mores (all in central Idaho), and Hells Canyon (OR/ID) where low social and physical vulnerability overlap.

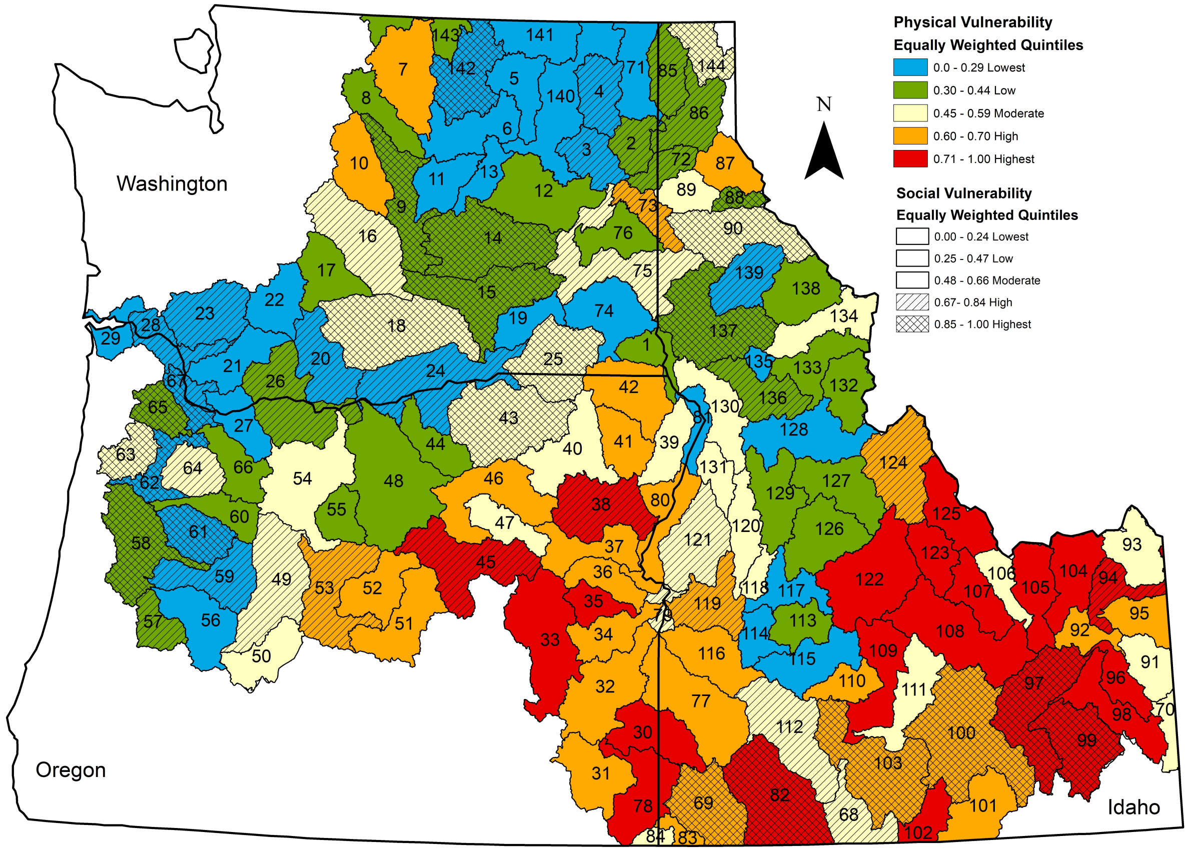


Figure 3.6 Map of equally weighted hotspots. Red coloring and crosshatching indicate overlapping vulnerabilities.

Variance Weighting

The variance weighted results suggest that double exposure to high vulnerability may be present for five hotspot subbasins, including the Lower Crab in Washington, and a series of neighboring subbasins in southern Idaho: Upper Snake Rock, Lake Wolcott, American Falls, and Portneuf (Figure 3.7). It should be noted that subbasins nearby the hotspots also show high physical and the highest social vulnerability values. The "cool spots" resulting from the variance-weighted analysis are the Middle Fork Clearwater (common to both methods), along with Upper Middle Fork Salmon, the North and Middle Forks Boise, Hells Canyon and Trout in Idaho and Oregon. All five of these subbasins rank in the lowest 20% of low vulnerability scores across the study area.

The results of the separate hotspot overlay analyses point to two common outcomes. The Portneuf and American Falls subbasins are consistently found to have both the highest social and hydrologic vulnerability in the region. These are two of the southeastern most subbasins in the study area near the Utah border and home to numerous rural communities, the Fort Hall Native American Reservation, and the two most populous cities outside of the Boise metro area, Idaho Falls (American Falls), and Pocatello (Portneuf) (US Census, 2012). Further study is necessary in order to accurately assess social and physical vulnerability for all communities within these subbasins. Our results could portend the need for proactive engagement over water resource challenges in a region where a reservation, two large cities, power production, and high-value agriculture compete for water. As we look to the future and anticipate further interruption to our current water systems, the hope is that this study can help to put sensitive populations at the forefront and justify targeting limited resources by prioritizing adaptation planning in hotspot subbasins.

Table 3.6 Summary results of hotspot analyses

Hotspot Subbasins, Equal Weights	**Hotspot Subbasins, Variance Weighted**
Bruneau, ID (#82)	Lake Wolcott, ID (#100)
Portneuf , ID (#99)	Upper Snake Rock, ID (#103)
American Falls, ID (#97)	American Falls, ID (#97)
	Portneuf , ID (#99)
	Lower Crab, WA (#14)

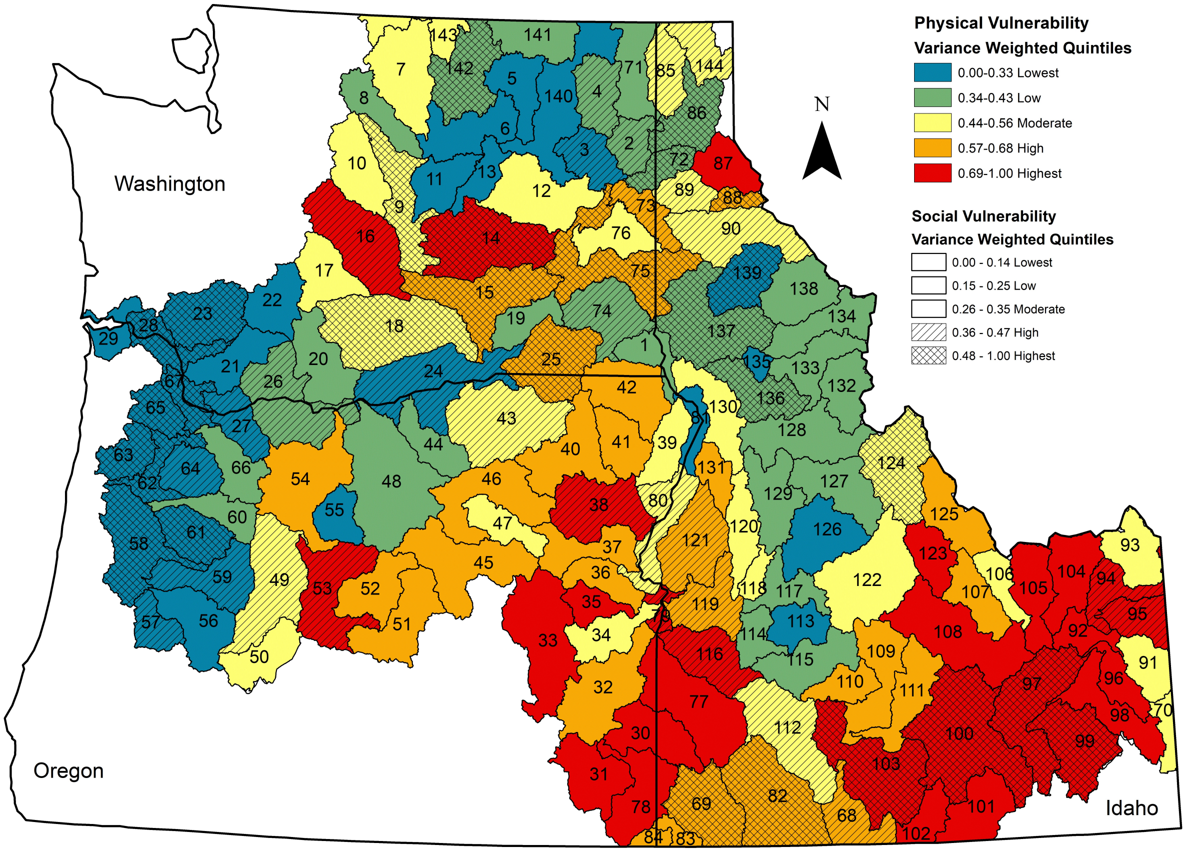


Figure 3.7 Map of variance weighted hotspots. Red coloring and crosshatching indicate overlapping vulnerabilities.

Discussion

It is expected that most of the indicators in our study have not previously been mapped at the subbasin scale, presenting an opportunity to bring meaningful, new information to climate change adaptation planning process across the CRB. It is important to note that variables and indicators must be specific to a region, thus our selections are specific to the CRB and not necessarily transferable. However, the methodological framework used, including the HUC8 hydrologic management units of analysis are highly transferable, relevant across the water vulnerable western US, and beyond. Additionally, all of the datasets used are publically available and frequently updated, easing reproducibility and modification.

One of the primary benefits of indexes is that they can be used to measure, simplify, and communicate complex realities (Farell & Hart, 1998). They are used in a variety of contexts: to easily convey information and results, to set targets and develop standards, to allocate resources, to provide baseline information and facilitate monitoring of change, and to facilitate comparison across space and time (Niemeijer 2002; Villa & McLeod 2002;

Briguglio 2003; Esty et al. 2005). Although they provide myriad benefits, the utility of indexes has been criticized due to challenges associated with standardization, weighting, aggregation, issues of scale, and difficulties related to testing reliability (Barnett et al., 2008). These flaws are common to indexing because they offer the ability to estimate relative vulnerability to climate change across large areas. In the case of this study, aggregating and normalizing the data limits the ability to understand within-subbasin vulnerability and generalizes across an entire basin. This leads to a decrease in the resolution and accuracy of the index and limits results to a rough estimation that may only be useful for pointing researchers in the correct general direction for more fine-scale study. Standardization of non-linear data decreases data resolution and may decrease accuracy and estimating the significance of relationship (Alessa et al. 2008). Concerning issues of scale, particularly with regard to the hotspot analysis, the physical (landscape scale) and social (individual) indicators of vulnerability function at various geographical and temporal scales and the relative gravity of these phenomena end up greatly simplified by indexing. Lastly, the subjective nature of constructing indexes adds additional challenge since the researcher makes ultimate determinations regarding relevant criteria (Vincent, 2004). Therefore careful development of vulnerability variables and indicators and transparency regarding limitations are fundamental to the legitimacy of the index (Adger et al. 2004). The value of producing a visual representation of vulnerability is many-fold and includes the potential to clarify and simplify dialog between water managers and the communities they serve.

An additional benefit is the ability for neighboring watersheds to identify shared challenges and to generate adaptation strategies collaboratively and more efficiently. Mapping vulnerability can help communities and regions formulate and implement measures to counter expected negative impacts, i.e. mitigate impacts via proactive, adaptive measures that are appropriate to place. Additionally, by revealing spatial gradients of vulnerability it is also possible to understand the various types of vulnerability present and prioritize how to target limited resources. For example, rather than providing a blanket amount of funds for adaptation to all communities in the region (resulting in lower overall available funds in a given time period), perhaps offering larger funds or easier access to a smaller number of communities exhibiting higher vulnerability could lead to reducing impacts in some areas.

Limitations

The study is limited to a coarse resolution that does not take into account several important hydrologic realities on the ground, including the significance of groundwater in the Basin, or the management of extensive human alterations in the form of dams, canals, dykes, and other water transfer systems that impact where and when water is available across the Basin. Our study is intended to provide a broad view of potential vulnerability, but requires finer scale study for accuracy. A prime example is the indication of low hydrologic vulnerability in east-central Washington, where large-scale water transfer programs and issues with groundwater exploitation threaten long-term water sustainability. This project and other water management details are not captured here, but would significantly improve the value of the study, particularly for state and sub-state level vulnerability analyses

The drawback of including only variables with high PCA scores and eliminating low scores is that high scores reflect variables that are statistically related, which does not necessarily reflect influence on vulnerability in a given location or situation (Jones & Andrey, 2007). The index provides a measure of inequality between subbasins, but it does not inform absolute levels of physical vulnerability within the CRB.

The physical and hotspot indexes offer baseline information about aspects of vulnerability that can be compared over time. Because HUC8 units are provided for the entire USA, the methods provided here are repeatable anywhere in the nation. The data used to create the vulnerability indicators is publicly available and frequently updated, however the indicators included in the study are regionally appropriate to a snow-dependent system and may not be entirely transferable. In the absence of other watershed-scale water vulnerability studies for the CRB, hotspot studies like ours may be very useful to efforts that monitor disparities of climate impacts to water resources, and for identifying communities that may benefit from targeted adaptation efforts and programs that aim to address health, welfare, and quality of life in the face of impending water stresses.

Hotspot analysis itself is imperfect and subject to inaccuracy, therefore making decisions about targeted funds should be given deep consideration. Hotspots provide a useful layer of analysis, but their explanatory power should not be overemphasized. Likewise, vulnerability analyses must also be considered with caution as there are significant limitations to data availability, differences in data scale, and course generalizations involved.

Rooting out the most vulnerable subbasins in the region is an ideal not likely to be reached with exactitude. However methods that endeavor to identify where the equity of impacts may be out of balance, or rather where needs may be great and resources could be targeted, could help the region home in on improved approaches to governance and more streamlined support for mitigation and adaptation planning processes.

Conclusions

We provide a unique study of ten indicators of hydrologic vulnerability for Idaho, Washington, and Oregon and an overview of socio-physical vulnerability hotspots at a scale that is relevant to hydrology, water management, and water-dependent communities. The HUC8 unit-scale analysis has national applicability and makes use of secondary data sources that are publically available and frequently updated. The chosen conceptual framework for this study views vulnerability as socially and physically driven, and specific to place. For the value of comparison, we used two computational approaches to assessing vulnerability and find that disagreement between the two is relatively minimal and suggests consistent geographic patterns of hydrologic vulnerability. We find that higher physical vulnerability is generally located in the southeastern and north-central portions of the Basin, and concentrated across southern Idaho. Lower vulnerability is patterned in western, northern, and mid-eastern borders of the CRB. Hotspots of overlapping social and physical vulnerability are located in southeastern Idaho and point to focal areas for further research and water resource planning.

Overall synthesis

Common across all three chapters is a focus on integrating social and physical components of climate change for a more complete picture of vulnerability to climate changes for a mountainous, snowpack-dependent Basin. Our analysis of mountain climate research for the CRB reveals funding gaps for actionable science, that is: interdisciplinary, smaller scale, adaptation and mitigation studies specific to the mountainous headwater areas that are vitally important to water resources throughout the Basin. Our analysis of vulnerability suggests that social and physical vulnerability varies in degree and location across the CRB, with distinct and sometimes overlapping patterns. This represents a potential feedback loop between the three studies by assessing research gaps and research needs on the ground for the benefit of our most sensitive groups. Understanding that there are limitations to available resources for such study, it would be prudent to consider “hotspot” subbasins where social and physical vulnerability overlap as target areas for future funded studies. The potential symmetry between research needs and benefits is worthy of further exploration, particularly with the inclusion of the gray literature.

The hope is that this integrated approach to examining and representing funded research gaps and vulnerability to water loss will lead to further study of these realms. At this stage, our hope is that this body of work can serve as a tool to facilitate conversations, particularly between academics and funding institutions, and between water leadership and the communities they serve about place-based approaches to proactive adaptation to water change.

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Appendix A

Chapter One: Search Terms Used for Databases

Database	**Search Terms**
Cabdirect *Proquest* *Web of Science*	1. “(("climate change" OR "global warming") AND (mountain* OR alpine OR subalpine OR headwater) AND (Snake OR Salmon OR Clearwater OR spokane OR kootenai OR kootenay OR Columbia OR Oregon OR Washington OR Idaho OR Wyoming OR Alberta OR Utah OR Nevada OR "Pacific Northwest" OR "Western United States" OR “Columbia River Basin” OR “British Columbia”))”.
Crossref *Multiple searches were independently developed by individual researchers, and search terms were determined by researchers’ discretion, to ensure a wide breadth of locations, disciplines, and topics.	1. "+'climate change' +'mountain' +'columbia river' +'alpine' +'subalpine' +'mountainous' +'headwater' +'washington' +'oregon' +'idaho' +'wyoming' +'montana' +'british columbia' +'kootenay' +'snake' +'salmon' +'clearwater' +'spokane' +'kootenai' +'Pacific Northwest' +'Western United States' +'Columbia River Basin'" 2. "+'climate change' +'mountain' +'columbia river' +'alpine' +'subalpine' +'mountainous' +'headwater'+'washington' +'oregon' +'idaho' +'wyoming' +'montana' +'british columbia' +'kootenay' +'snake' +'salmon' +'clearwater' +'spokane' +'kootenai' +'Pacific Northwest' + 'willamette river'+ 'clark fork river'+ 'john day river'+ 'sandy river'+ 'lewis river'+ 'methow'+ 'white salmon'+'Western United States' +'Columbia River Basin'" 3. "+'climate change' +'mountain' +'columbia river' +'alpine' +'subalpine'+'mountainous'+'snow dominant'+'headwater'+'washington' +'oregon' +'idaho' +'wyoming' +'montana' +'british columbia' +'kootenay' +'snake' +'salmon' +'clearwater' +'spokane' +'kootenai' +'Pacific Northwest' + 'willamette'+ 'clark fork'+ 'john day'+ 'sandy'+ 'lewis'+ 'methow'+ 'white salmon'+'Western United States' +'Columbia River Basin'" 4. "+'climate change' +'mountain' +'columbia river' +'alpine' +'subalpine' +'mountainous'+'snowdominant'+'headwater'+'washington'

	+'oregon' +'idaho' +'wyoming' +'montana' +'british columbia' +'kootenay' +'snake' +'salmon' +'clearwater' +'spokane' +'kootenai' +'Pacific Northwest' +'willamette' +'clark fork'+ 'john day'+ 'sandy'+ 'lewis'+ 'methow'+ 'white salmon'+'Western United States' +'Columbia River Basin'+ 'cascade'+'blue'+'selkirk'+'purcell'+'wallowa'+'teton'+'rocky'+'bitterroot'+ 'rockies'"
	5. "+'climate change' +'mountain' +'columbia river' +'alpine' +'subalpine' +'mountainous' +'headwater' +'indigenous' + 'knowledge' + 'local' + 'community' + 'Pacific Northwest' +'Western United States' +'Columbia River Basin'"

Appendix B

Chapter One Codebook

1. Confirmation

Confirm whether the article belongs in the corpus.

Exclude articles with the following characteristics:

1) Proposed, not conducted research
2) Paleo-climate
3) Articles for which full text was not available
4) Articles not in mountains/headwaters
5) Articles not explicitly about anthropogenic climate change
6) Articles with research not in the CRB
7) Articles with global scale

2. Spatial Scales and Distributions

A. Spatial Extent

Choose from these seven classifications for spatial extent:

1) 1 - 100 km^2
2) 100 - 1500 km^2
3) 1500 - 25000 km^2
4) 25000 - 40000 km^2
5) 40000 km2 - Pacific Northwest
6) Pacific Northwest
7) Western US

To categorize the spatial extent (i.e. scale), select the largest extent to which findings were extrapolated, in square kilometers. If a study includes several locations spread across the western US and British Columbia, the extent is categorized as “Western US.” If an article includes a collection of global studies with a case study in the CRB, consider the extent of the study as “40000 km^2 - Pacific Northwest.”

B. Location of data collection

Watershed determination

There are 16 Watersheds with Hydrologic Unit Code-6 (HUC6) in the CRB, plus three of approximately the same class in three Canada:

1) 0101 - Kootenai
2) 0102 - Pend Oreille
3) 0103 - Spokane
4) 0200 - Upper Columbia
5) 0300 - Yakima

6) 0401 - Snake headwaters
7) 0402 - Upper Snake
8) 0502 - Middle Snake - Power
9) 0601 - Lower Snake
10) 0602 - Salmon
11) 0603 - Clearwater
12) 0701 - Middle Columbia
13) 0702 - John Day
14) 0703 - Deschutes
15) 0800 - Lower Columbia
16) 0900 - Willamette
17) Kooteney (Canada)
18) Columbia (Canada)
19) Okanogan (Canada)
20) *Canadian watershed classifications do not utilize HUCs, thus, major Canadian sub-watersheds were selected.

Select the watershed(s) where the research took place. If given a river name, then search for the name at the USGS Boundary Descriptions website (United States Geological Survey 2016). If given the name of a location other than a river, search for it at USGS Geonames interface (United States Geological Survey 2018).

Point determination

Determine location(s) of the research for studies with data from spatially explicit sites. To find the location, identify the place name for the smallest unit of geography specified within the studies and obtain the GPS points (in decimal degrees) associated with the place names (a list of commonly used locations is available for efficiency). List separate geographic locations in cases where the study includes less than five separate study locations. If the study covers more than five study locations over a large spatial extent do not link the article to a specific geographic location, just select the appropriate watershed. Select "not place specific" for articles including reviews, landscape-scale modeling projects, etc.

C. Primary biomes of research1

The list of biomes in the CRB:

1) alpine/tundra
2) grassland: temperate
3) forest: temperate

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[1] A biome is defined as *a large naturally occurring community of flora and fauna occupying a major habitat with similar climate and physiognomy* (Smith and Smith, 2001). Biomes for this review are selected from a list of global biomes from Woodward et al. (2004). Biomes not found in the CRB include tropical rainforest, tropical deciduous forest, and boreal forest.

4) desert: semi-arid desert
5) freshwater: ponds and lakes
6) freshwater: wetlands
7) freshwater: streams and rivers

Freshwater biomes should only be selected when research specifically studies freshwater ecosystems. Thus, physical hydrology studies are not included in the freshwater biome, but studies about fish habitat or food webs within streams are included. The ecotone of alpine treeline should be recorded as “forest: temperate.” Select the “other” option when the study is non-applicable, not biome specific, or includes all biomes. Studies that are non-biome specific include foci such as gridded climate models, or regional models of physical processes.

3. Topical Foci and Distributions

A. Impacts, adaptation, or mitigation

Determine whether the article is about impacts, adaptation, or mitigation based on the *primary knowledge contribution* of the article. The primary knowledge contribution can generally be determined through the statements made in the abstract and sometimes conclusions. Definitions are as follows are from the IPCC (2014).

Impacts: “The effects of *climate change* on natural and *human systems.”*
Adaptation: “Adjustment in ... *human systems* in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.”

> *Note that we consider only human adaptation in this category, classifying the adaptation of natural systems as impacts. We do to better differentiate where research that considers societal response to climate change is occurring.

Mitigation: “An anthropogenic intervention aimed at reducing the anthropogenic forcing of the climate system.”

B. Future projections or past observations

Code only articles that address climate impacts to determine whether they primarily focus on observed historic impacts, and/or modeled projected future impacts.

Observed Impacts

Select articles as “observed impacts” an environmental trend was observed over time and its attribution to climate change was discussed, whether or not it is attributable to anthropogenic climate change. This requires multiple decades of data, but multiple decades of data don’t guarantee a “yes” for this column. Suggestion: read the abstract to determine whether the authors make a claim about whether observed changes are attributable to climate change.

Projected Impacts

Select articles as “projected impacts” if the study makes a quantitative estimate of climate change impacts on natural or human systems in the future. Code each article to determine if new data was collected, or if data was from existing data sources. Examples of new data include vegetation surveys, installed meteorological stations, or human interviews and surveys.

C. Primary disciplines and topics

Overall, be strict and exclusive with discipline, and be inclusive with topic.

Discipline

Choose from a list of 12 disciplines (Table 1, main text) and select the most appropriate discipline for the article. The protocol for coding article discipline(s) includes: 1) select primary discipline based on major themes and content in the articles, then 2) select discipline based on journal title (e.g. a journal with the title *Journal of Meteorology* would be categorized as “climatology & meteorology,” 3) next look to author discipline(s) indicated in the article credits or via an internet search. Select more than one discipline *only* where multiple disciplines (interdisciplinary articles) are thoroughly explored.

Topic

Choose from a list of 34 pre-selected topics (including an “other” category for inclusivity). Be very inclusive here. If a topic isn’t on the form, don’t stretch too much to fit it into the pre-determined categories; use “other” as needed, and type a new topic. Refer to keywords, article title, journal, abstract content, key terms, and figures for help with identifying major topical themes.

Final list of topics includes topics present in at least five articles

1) agriculture
2) alternative energy
3) anadromous fish
4) aquatic habitat
5) attitudes and beliefs
6) botany
7) carbon cycle
8) climate oscillations
9) community resilience
10) drought
11) economics
12) entomology
13) forest ecology
14) geomorphology
15) glaciers
16) groundwater
17) lacustrine systems
18) land use/land cover
19) management
20) natural disasters
21) non-anadromous fish
22) pests and disease
23) policy
24) precipitation
25) restoration
26) snow
27) soils
28) species invasion
29) species range shifts
30) streamflow
31) temperature
32) terrestrial wildlife
33) silviculture
34) water quality
35) water quantity
36) wildfire

Citations

Columbia Basin Trust. (2013). *Interactive Columbia River System Map.* Retrieved from: https://thebasin.ourtrust.org/resource/map/

United States Geological Survey. (2016). *Boundary Descriptions and Names of Regions, Subregions, Accounting Units and Cataloging Units*. Retrieved from https://water.usgs.gov/GIS/huc_name.html#Region17

United States Geological Survey. (2018). *Geographic Names Information Systems (GNIS)*. Retrieved from https://geonames.usgs.gov/apex/f?p=138:1:0::NO::P1_COUNTY%2CP1_COUNTY_ALONG:n%2C

Appendix C

Chapter Two Social Vulnerability Indicators Codebook

This codebook contains descriptions of each of the 11 social vulnerability indicators used to assess HUC8 subbasins of the Columbia River Basin. The indicator names, sources, and supplementary notes are provided below.

Indicators

The following were derived from the US Census 2016-2012 American Community Survey 5-year Estimates at the block group scale (600-3,000 people).

Age

Percent population age 5 and under and age 65 and over
B01001, age by sex. Male and female populations for children 5 and under and adults 65 and over were added to derive an age-vulnerable population total.

Residency

Percent population living in a different house in the US one year ago
B07202002 Geographical mobility in the past year for current residence

Female Head of Household

Percent of households comprised of single women with dependents under 18 years
S1101 Female householder, no husband present, family household with own children of the householder under 18 years

Education

*Percent population with a high school education only. *High school diploma and GED/alternative credentials were added to capture high school level education.*
B15003 educational attainment for the population 25 years and over

B15003017	Regular High School Diploma
B15003018	GED or Alternative Credential

Poverty

*Percent population living below 200% of the Federally determine poverty line. *All columns under 2.00 (.5-1.99) were added to derive population living below 200%.*
C17002 Income to poverty ratio for whom poverty status is determined.

Renter Occupied Housing

Percent renter occupied housing
B25008 Total population in occupied housing units by tenure- renter occupied

Single Sector Economic Dependence

Percent civil population 16 years and older who are employed in agriculture, forestry, fishing, hunting, and mining. C24030003 *Male and female populations were added to derive total for this sector

Unemployment
Employment status for the population 16 years and over
B23025 Percent civilian labor force 16 years and over who are unemployed

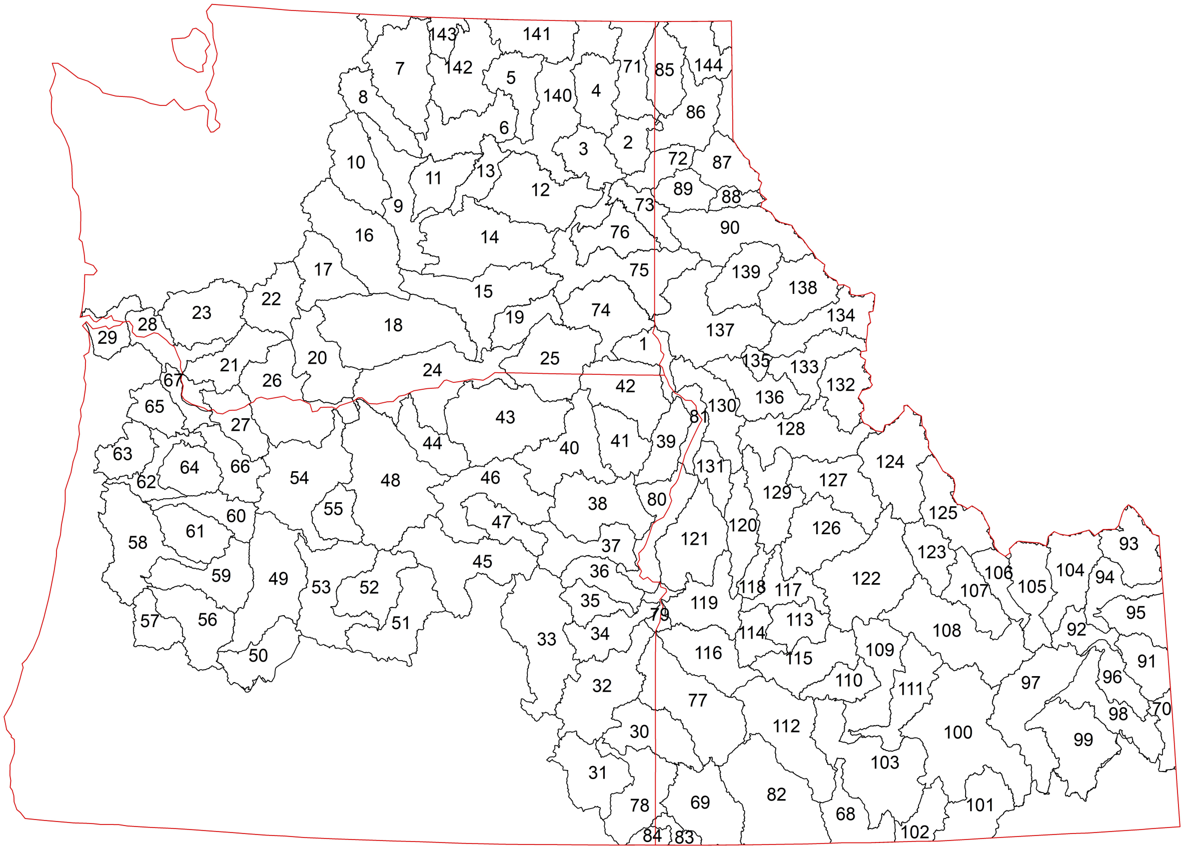
Native American
Percent population identifying as American Indian or Alaska Native alone
B02010

African American
Percent population identifying as Black or African American alone
B02001

Hispanic
Percent population identifying Hispanic or Latino origin (any race)
B03002

Appendix D

Master Subbasin Map and Key



Number (#)	Subbasin Name	#	Name	#	Name	#	Name	#	Name
1	Lower Snake-Asotin	31	Crooked-Rattlesnake	61	South Santiam	91	Palisades	121	Weiser
2	Little Spokane	32	Lower Owyhee	62	Middle Willamette	92	Idaho Falls	122	Upper Salmon
3	Lower Spokane	33	Upper Malheur	63	Yamhill	93	Upper Henrys	123	Pahsimeroi
4	Colville	34	Lower Malheur	64	Molalla-Pudding	94	Lower Henrys	124	Middle Salmon-Panther
5	Sanpoil	35	Bully	65	Tualatin	95	Teton	125	Lemhi
6	Chief Joseph	36	Willow	66	Clackamas	96	Willow	126	Upper Middle Fork Salmon
7	Methow	37	Burnt	67	Lower Willamette	97	American Falls	127	Lower Middle Fork Salmon
8	Lake Chelan	38	Powder	68	Salmon Falls	98	Blackfoot	128	Middle Salmon-Chamberlain
9	Upper Columbia-Entiat	39	Imnaha	69	Upper Owyhee	99	Portneuf	129	South Fork Salmon

10	Wenatchee	40	Upper Grande Ronde	70	Salt	100	Lake Walcott	130	Lower Salmon
11	Moses Coulee	41	Wallowa	71	Pend Oreille	101	Raft	131	Little Salmon
12	Upper Crab	42	Lower Grande Ronde	72	Upper Spokane	102	Goose	132	Upper Selway
13	Banks Lake	43	Umatilla	73	Hangman	103	Upper Snake-Rock	133	Lower Selway
14	Lower Crab	44	Willow	74	Lower Snake-Tucannon	104	Beaver-Camas	134	Lochsa
15	Upper Columbia-Priest Rapids	45	Upper John Day	75	Palouse	105	Medicine Lodge	135	Middle Fork Clearwater
16	Upper Yakima	46	North Fork John Day	76	Rock	106	Birch	136	South Fork Clearwater
17	Naches	47	Middle Fork John Day	77	Middle Snake-Succor	107	Little Lost	137	Clearwater
18	Lower Yakima	48	Lower John Day	78	Middle Owyhee	108	Big Lost	138	Upper North Fork Clearwater
19	Lower Snake	49	Upper Deschutes	79	Middle Snake-Payette	109	Big Wood	139	Lower North Fork Clearwater
20	Klickitat	50	Little Deschutes	80	Brownlee Reservoir	110	Camas	140	Franklin D. Roosevelt Lake
21	Lewis	51	Beaver-South Fork	81	Hells Canyon	111	Little Wood	141	Kettle
22	Upper Cowlitz	52	Upper Crooked	82	Bruneau	112	C.J. Strike Reservoir	142	Okanogan
23	Lower Cowlitz	53	Lower Crooked	83	South Fork Owyhee	113	North and Middle Forks Boise	143	Similkameen
24	Middle Columbia-Lake Wallula	54	Lower Deschutes	84	East Little Owyhee	114	Boise-Mores	144	Lower Kootenai
25	Walla Walla	55	Trout	85	Priest	115	South Fork Boise		
26	Middle Columbia-Hood	56	Middle Fork Willamette	86	Pend Oreille Lake	116	Lower Boise		
27	Lower Columbia-Sandy	57	Coast Fork Willamette	87	Upper Coeur d'Alene	117	South Fork Payette		
28	Lower Columbia-Clatskanie	58	Upper Willamette	88	South Fork Coeur d'Alene	118	Middle Fork Payette		
29	Lower Columbia	59	Mckenzie	89	Coeur d'Alene Lake	119	Payette		
30	Jordan	60	North Santiam	90	St. Joe	120	North Fork Payette		

Appendix E

Subbasin Population Distribution Map