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Assessing Adaptive Capacity to Climate and Population Change at the Urban-Rural Interface: Human-Water System Dynamics in the Hood River Valley, Oregon

By

Alexander Reid Ross

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

Doctor of Philosophy
in
Earth, Environment and Society

Dissertation Committee:
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Portland State University
2020

Abstract

An exurban nook on the Oregon side of the Columbia River Gorge named after the Hood River that runs northward from the glaciers of Mount Hood to the confluence seems ideally poised for the kind of relaxed, natural lifestyle that once brought suburban areas their appeal. However, like other exurban areas, Hood River also lies at an uncertain fault-line between economic and environmental transformation in the U.S.'s exurbs.

This study maps the socio-economic and climatological transformations of exurban areas as they contend with different approaches to sustainability and resilience. To determine the major climate and development hazards facing exurban areas and efforts to resolve them, it poses a theoretical framework based on coupled human-water systems, revealing a synthesis between hydrosocial studies and socio-hydrology.

This theoretical framework is applied to social relations using a qualitative analysis involving interviews with local stakeholders engaged in collaborative water resources management. A qualitative assessment of exurban places such as Hood River as "hydrosocial territories" garners better understanding of risk perception, ascertaining the impacts of climate change as the leading concern for those interviewed. A quantitative assessment is used vis-à-vis a system dynamics model, which supports the risk perception of stakeholders and offers effective methods generalizable across different hydrosocial exurbs.

This study shows the correspondence between coupled human-water systems sciences and a multiscalar framework for understanding exurban hydrosocial places. Approaches to resilience and transformation are described, along with paths toward possible collaboration across multifarious scales. Ultimately Hood River and exurbs like it have a difficult collaborative path to synthesizing different economic roles in pursuit of transformative adaptation to climate change and urbanization.

Dedicated to my father

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Introduction

The pre-Socratic philosopher, Thales, understood water as the first universal principle. At the heart of all existence, Thales believed, water brought life forth from seed. Among the things of the world, Thales thought place the greatest, because it contains all things (Hyland 1983). For Thales, then, every place is essentially a "hydrosocial territory."

Thales' philosophy presents fundamental truths of human society: it cannot exist without water. If water is the essence of place, perhaps the most essential study of human society in time and space derives also from its co-evolution with water. That is, the same fundamental truths that bring humanity together to form society also guide the development of civilization, which in turn shapes those resources on which society relies. Humans create places from materials wrought from the non-human world, which in turn becomes part of a metabolic process of making and remaking the world in a two-fold system as the world makes and remakes the human (Foster 1999). The earth and its materials engage in that system of co-constitution that Marx termed the "social relations of production" (Ingold 1986). Throughout the 20th Century, the study of social relations linked anthropology to cultural geography and ecology in the development of contemporary ways of studying the world through political ecology (Perreault et al. 2019).

As scientists developed new ways of understanding complex systems during the 1970s and '80s, obviating the flaws of authoritarian regimes of water management, a political movement to rescale water governance came into effect (Flitcroft et al. 2009; Brenner et al. 1999). In the Pacific Northwest of the United States, activists worked with stakeholders in places like the Klamath and tributaries of the Columbia, attempting to ameliorate the intense social conflict between farmers, Native fishers, and environmentalists caused by the enormous dams (Car 2004). Growing out of these efforts, new methods of social organizing from the watershed scale to the bioregional scale built momentum into the 1980s (McCool 2018).

This form of collaborative organizing of social relations grew in connection both to trends of the modern environmental movement gained pace and the growth of exurban areas that thrust populations further outside of the suburbs and into the urban-rural divide between producer and consumer, forging new post-productivist economies grounded in recreation and amenities (McKinnon 2016). The exurban interface of rural and urban socio-ecological metabolism proved fascinating incubators for dynamic political arrangements around inchoate watershed councils that employed consensus-based organizing to downscale water resources planning to local actors who understood their place, its development, and how to sustain it (Norman and Bakker 2009).

In this dissertation, I develop a novel framework to understand the dialectics of coupled human-water systems amid the rescaling of water resources management in a Pacific Northwest exurban watershed facing the dual challenges of urbanization and climate change. Thus, this study fosters important insights into and greater understanding of contemporary social conditions and their implications or impasses.

The growth of the exurbs forces us to contend with major tensions in modern life. Does rescaling water management really translate into resilient social practices through collaborative watershed groups? Do climate change and the growth of exurban populations present unsurpassable ecological and economic hazards to people living at the interface of rural and urban? What way forward for the development of human-water systems—“bouncing back” to a previous way of life or transformational adaptation to a sustainable future?

This dissertation begins with a chapter analyzing the study of human-water systems in socio-hydrology and hydro-social theory. While the former often assesses the co-evolution of ecological and social systems from an engineering perspective, seeking to present practical solutions to specific problems confronting humanity throughout the world, the latter takes a more critical approach to the fundamental questions of power and scale at play in water management (Pande and Sivapalan 2017). Through a careful review of the available literature, this effort finds an increasingly fruitful dialogue across subfields, developing innovative new syntheses worth considering for future study.

In the second chapter, the adaptation of resilience theory to hydrosocial research in terms of exurban political ecology provides the framework for a qualitative study of the Hood River Watershed Group as a model of collaborative water resources management. How do different stakeholder groups form in the basin, what interests do they involve, and how do they collaborate? What are their perceptions of hazards facing the basin, and does their collaboration entail a joint vision of a shared, transformative future? Through this study, the rescaling of water governance is shown to be part of ongoing transformations taking place across multiple scales with implications for common goals along different paths to further organizing.

The third and final chapter uses a System Dynamics model (SDM) to undertake a quantitative examination of the Hood River basin, from climatology to streamflow and irrigation districts. By analyzing the system’s multivariate complexity with climate scenarios projected by the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP5), the study can enhance our existing understanding of present hazards associated with a potential increase of temperature and decrease in precipitation-as-snow. Using an SDM helps reveal socio-hydrological system feedbacks to engender affirmative responses to potential hazards and determine the resilience and adaptive capacity of the basin's human-water system.

	Chapter 1	**Chapter 2**	**Chapter 3**
Field/Sub-field	Human-water systems studies	Hydrosocial	Socio-Hydrology
Methods	Literature review	Qualitative (Interviews and participant observation)	Quantitative (SDM)
Study Focus	Synthesis of theoretical approaches	Hazard Perceptions	Resilience Evaluation
Theories	Hydrosocial theory, Socio-hydrology	Hydrosocial territory, Urban Political Ecology, Transformative adaptation	Socio-hydrology, Systems science, Resilience

Table 1: Outline of dissertation chapters

Taken together, this study shows how hydrosocial and socio-hydrological methods and approaches can work together to form a broader, overall understanding of a human-water system [Table 1]. While it recognizes hydrosocial theory and socio-hydrology as discrete subfields, it deploys them in complimentary ways, drawing broader conclusions from the synthesis of findings. It resolves that adaptive measures set into place through collaborative water management can improve the resilience of socio-hydrological systems, especially by carefully calibrating balancing mechanisms that might sustain the relationship between riparian habitat and irrigation water. Longer-term visions of transformative adaptations to climate change and urbanization, however, continue to contrast in ways that pose challenges to collaboration on larger scales of space and time.

The exurbs lie at the interface (and intersection) of urban and rural, experiencing unique socio-ecological challenges, which hold broader economic and demographic implications internationally in terms of the feasibility of future agricultural production, trends of population expansion and development, and incumbent cultural shifts in rural areas. While the rescaling of water management studied here represents an effort to move from top-down approaches to community self-determination, this study reveals complexities that foreground the difficult tasks of collaboration.

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Chapter 1: Socio-Hydrology with Hydrosocial Theory: Two Sides of the Same Coin?

Alexander Reid Ross and Heejun Chang

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Abstract: This paper reviews socio-hydrology and hydrosocial research, finding a sophisticated relationship with emergent syntheses. We examined 419 papers by topic, region of study, theories implemented, journal, and year published to ascertain trends in both subfields. We found important overlap and considerable difference between subfields. Whereas hydrosocial research took years to develop, socio-hydrology commenced with an inaugural paper in 2012. While the former focuses on power and scale in studying water demand, the latter concentrates on practical responses to climate extremes. Hydrosocial research usually relies on qualitative methods, and socio-hydrology research the quantitative. In the geographic regions where the former does not focus, the latter does. The former often relies on post-structuralist theory, whereas the latter uses positivist approaches. Our review concludes that socio-hydrology and hydrosocial research exist in a complex epistemological relationship, offering fertile grounds for lively discussions from which both will continue to benefit.

Keywords: Socio-hydrology, hydrosocial, IWRM, resilience, drought, flood, water, theory, multi-scalar, actor-network

Introduction

Engaging with the literature on coupled human-water systems aids in analyses of water availability, quality, hazards, and related ecosystems services. As anthropogenic climate change places a strain on water resources around the world, the way scholars, policy makers, and resource managers understand such systems will prove instrumental to ensuring the sustainability of threatened communities and defusing potential social conflict (Cisneros et al. 2014). Without comprehending those interactive relationships, appropriate human responses to challenges and hazards involved in hydrologic systems becomes effectively impossible. Yet, the literature conceptualizing human and water interactions appears divided at times between those adopting a "hydrosocial" approach that centers power and scale, on the one hand, and those using "socio-hydrology" to effectively ascertain and adapt to specific needs from a positivist perspective on the other.

There has been one key literature review proposing collaboration between the two subfields by Wesselink et al. (2017) and another review proposing "interdisciplinary water resource geography" as a way of bringing socio-hydrology and critical geographies of water under the same umbrella (Rusca & Di Baldassarre 2019). The virtues of Wesselink et al. (2017)'s paper are myriad, including discussions about the crucial foundations of both subfields, distinguishing the two before calling for collaboration. In particular, their review extensively describes background information on Earth System Sciences as a kind of formative basis for socio-hydrology. Wesselink et al. (2017) also offer the valuable conceptual heuristic of "narrative" as a binding heuristic to promote collaboration across the divide, through which both disciplines can develop a (post)positivist grounding.

At the same time, Rusca and Di Baldassarre (2019) call for the integration of socio-hydrology with critical geographies of water (which encompasses hydrosocial theory) by accounting both for their own "moral obligation as scientists aspiring to change (rather than interpret) the world" and "the mutual shaping of society and hydrological flows" (p. 10). While the Wesselink review was published in 2017 when the number of socio-hydrological papers numbered 69 articles, today that number has more than tripled, giving rise to new innovations and epistemologies described by Rusca and Di Baldassarre (2019). Furthermore, by situating hydrosocial studies' discrete epistemological origins in critical geographies of water as long ago as the late-1990s, Rusca and Di Baldassarre (2019) identify different theoretical commonalities with socio-hydrology. Lastly, Rusca and Di Baldassarre (2019) importantly caution that "[p]erceptions of the irreconcilable differences and of asymmetrical collaborations between natural and social sciences deter opportunities of meaningful collaborations" (p. 2).

We offer a further analysis of integration in keeping with both these review papers, insofar as the careful formulation of narratives building on practical case studies and "preserving methodological and epistemological differences" can synthesize the subfields (Rusca & Di Baldassarre, 2019, p. 9). While both subfields study different aspects of the coevolution human-water systems, in doing so, they have developed strengths that compensate for what the other may lack. At the same time, our study finds encouraging collaboration occurring amid the dynamic relationship between the discrete subfields, indicating shared strengths and mutual aid. Without elucidation of such developments, alienation between interdisciplinary fields of research can lead to marginalization of important ideas, despite the increasing interest in the subject of coupled human-water research resulting from growing challenges of climate and urbanization.

The present review manifests an effort to comprehensively analyze both subfields of research, taking stock of their differences, and pointing to contributions from both sides that ultimately describe crucial intersections. We begin by examining the basis for socio-hydrology, interrogating its claim to the mantle of a “new science” coupling human-hydrologic systems. We situate its origin in the relatively recent site of coupled human-hydrologic studies in the late 1970s, discerning four discrete tendencies that have since emerged—hydrosociology, critical water studies, hydrosocial theory, and socio-hydrology. We then discuss critical water studies and its influence on fundamental premises of hydrosocial theory, followed by a review of the available hydrosocial literature. After investigating hydrosocial literature, we review the available literature on socio-hydrology, carefully examining its complex relationship with hydrosocial studies. Finally, we discuss, in depth, the contours of hydrosocial studies and socio-hydrology together, finding both important distinctions and significant intersections. By describing the complexity of the continued relationship between subfields with empirical evidence, we hope to widen the available tools and approaches possible within a general theoretical position involving the co-evolution of human-water systems. It is necessary to understand these subfields together if we are to use the strengths of both to achieve water sustainability.

Methods

We used a mixed methods approach to discern not only topics but also the methods used and study sites researched. To start, we downloaded the citations and abstracts for every article produced by a topic search in Web of Science for “hydrosocial” or “hydro-social” (n=207) on January 20, 2020, and analyzed them for thematic content, study site, and theoretical framework. We performed the same analysis on the 212 articles yielded from a Web of Science topic search of “socio-hydrology” during the same time.

Firstly, we tracked the increase in interest in these subfields over time by creating a timeline of the number of articles published with the topics “hydrosocial,” “hydro-social,” or “socio-hydrology.” We determined the main methods and theories utilized by each subfield and compared them to gain a sense of the overlap occurring over time. This process required qualitative study of the journal abstracts and, in many cases, the full articles, to facilitate a more robust exposition of the central themes and ideas of each subfield. We also developed graphs to describe the topical focus of each subfield over time, based on Water Demand, Quality, Climate Extremes, and Ecosystems Services. While there are some overlapping papers in these four topics, we chose the prevailing idea through content analysis. Viewing the changing topical courses of these subfields and their relative methods and theories over time helped to discern inflection points and overlap.

Lastly, we counted the numbers of studies per country and created a choropleth map showing the most-frequent study sites for each subfield. We then used data based on study topic, categorized according to the aforementioned four main themes, to create pie charts. Those pie charts were fitted as graduated symbols into the choropleth map to indicate both number and type of studies. We believe that this methodology breaks new ground in the field of coupled human-water systems by providing the most comprehensive quantitative and spatial analysis of the state of the research to date, as well as a useful qualitative review of their major theoretical positions.

Socio-Hydrology, Hydrosociology, or Hydrosocial Theory?

Locating the origins of hydrosocial theory and its precursor, critical geographies of water, may prove impossible, but the work of Wittfogel often serves as a useful starting point in the modern era (Wittfogel 1957**,** Banister 2014, Linton and Budds 2014**)**. Although not embraced by everyone, Wittfogel's assessment of the connection between political organization and hydrology provided the basis for adroit analyses of coupled human-water systems in the American West (Meisner 1963, Worster 1985). Perhaps even more pertinent to this paper, a term approximate to "hydrosocial" or "socio-hydrology" emerged in the work of Falkenmark, who opened her path-breaking 1979 article, "Main Problems of Water Use and Transfer of Technology," with the sentence, "Man and water are closely related to each other in a dualistic manner" (p. 435).

For Falkenmark, water serves as life-sustaining and producing while providing quality of life and symbolic value. The focus of Falkenmark's "hydrosociology" becomes the forecasting of potential issues with regards to human-water systems. As well, Falkenmark posits that a transfer of technologies will break through regional limitations and develop shared capacity for overcoming crisis. While others had written in the same vein as "hydrosociology" on the co-evolution of society, political organization, and hydrological systems (e.g. Wittfogel), Falkenmark's incisive commentary joined a sense of purpose to scientific methodology, laying the groundwork for today's efforts. Such efforts joined the development of socio-ecology in the 1980s and 1990s to promote studies of ecosystems that included social influences, adaptive capacity, and resilience. The more recent advent of a hydrosocial and a socio-hydrological field of research, however, remains both within but also outside of this course of study (Pande and Sivapalan 2017).

Hydrosocial research as practiced today comes largely from the junction of Political Ecology and Science and Technology Studies. Formed in the late-1990s through the work of a number of theorists scattered across the world, the concept of the hydrosocial cycle emerged slowly with vigorous discussions about hybridity and technology [Figure 1]. We locate the earliest threads in Bakker's work on flooding in England (2000) and Turton and Meissner (2002) on the "hydrosocial contract," along with Swyngedouw's exploration of "how the circulation of water is embedded in the political ecology of power, through which the urbanization process unfolds" (1997, p. 313). Swyngedouw writes of "nature's water" and a "historical geography of water control" through which water becomes domesticated. Although Swyngedouw did not name "hydrosocial" relations in 1997, as Bakker (2000), Warner (2000), and Turton and Meissner (2002) did, the former created the fundamental premises on which hydrosocial studies would develop by conceptualizing the complexity of power relations relative to water in terms of the economic, social, spatial, and political aspects of ecology.

On the other hand, socio-hydrology emerged first in 2012 with the near-simultaneous publication of two unrelated articles: "Irrigation and Development in the Upper Indus Basin" in *Mountain Research and Development* and "Socio-hydrology: A new science of people and water" in *Hydrological Processes*. The former paper, written by Nüsser et al. (2012), offered a "socio-hydrological framework [that] encompasses all dimensions and factors that are crucial for an integrated analysis of irrigated land use patterns and corresponding land cover changes" (p. 60). Sivapalan et al. (2012) published their paper just two months later, and aimed more generally at "understanding the dynamics and co-evolution of coupled human-water systems" (p. 1271). Both adopted a similar outlook, but Sivapalan et al. (2012) used a general approach that extended beyond just irrigation and land cover. However, like hydrosocial studies, which emerged through urban political ecology, socio-hydrology has traditionally focused on urban or rural areas rather than exurban or periurban areas (there are exceptions, e.g. Peloso and Harris 2017, Roth et al. 2019).

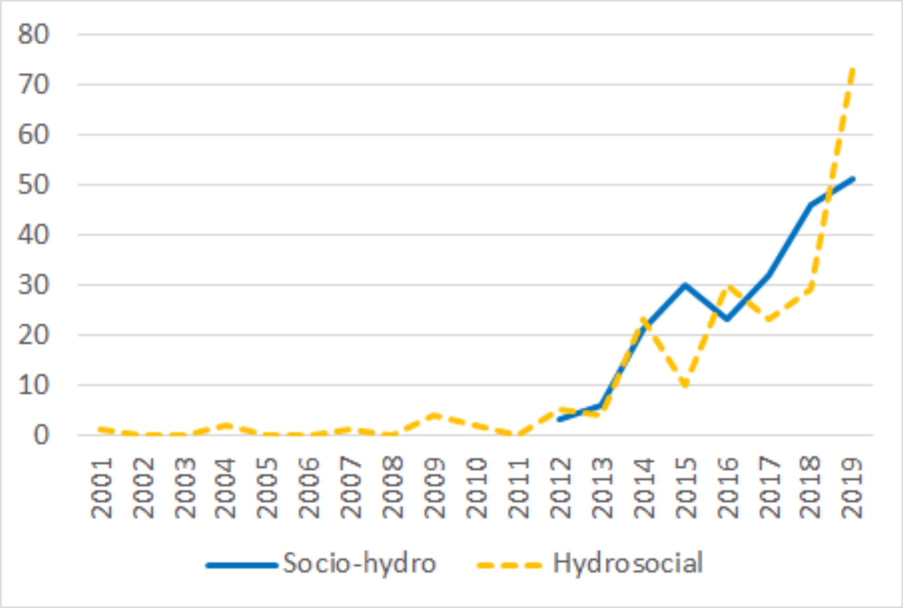


Figure 1: Trend in hydrosocial studies and socio-hydrology, 2001-2019

The two subfields have published different topics and publication outlets. Water resources dominates the research areas feeding into socio-hydrology, incorporated into 54% of articles gained through our topic searches. Meanwhile, "hydro-social" or "hydrosocial" studies show greater distribution between the topics "geography (34%)"

and “water resources (36%).” Most articles (11.1%) of the hydrosocial persuasion have been published in *Geoforum*, with 10.6% coming through *Water International*. This is likely due to a special issue of *Geoforum* dedicated to hydrosocial theory in 2014 and two in *Water International* in 2016 and 2019. Another special issue of *Water* was devoted to hydrosocial theory in 2019. On the other hand, 18.8% of socio-hydrological research comes by way of *Water Resources Research*, while *Hydrology and Earth System Science* published 13.6%, followed by *Hydrological Sciences Journal* (8.5%) and *Journal of Hydrology* (7%). Research areas were again dominated by Water Resources (70.4%), but Environmental Sciences took second place (41.3%) with Multidisciplinary Geosciences (25%) and Limnology (18.8%) coming next.

Through this analysis, it would appear that both subfields deal with Water Resources, but each in their own way and from nominally different research communities represented by different scholarly publications. Hydrosociology and socio-ecology might be seen as important taproots, but the epistemologies of hydrosocial research and socio-hydrology are distinct, as illustrated by the different composition of publication networks. We can safely conclude, then, that the two subfields are unique but intersecting and must first be examined on their own terms.

Origins of Hydrosocial Studies

Early hydrosocial research developed through critical geographies of water, conceiving of new ways to understand the coevolution of human and water systems. The “hydrosocial cycle” (Bakker 2000, Bakker 2003) ideated an inextricable relationship between the hydrological cycle and human societies, while the “hydrosocial contract” connoted the means through which technonatures deterritorialize water and integrate it within socio-political regimes of sanitation and water access underwritten by the government's responsibility to provide water to its citizens and protect them from water hazards like flooding (Warner 2000, Turton and Meissner 2002, Cantor 2017). These formative studies of the hydrosocial cycle carved out a new niche within critical geographies of water, which further developed through empirical work mobilizing the term into a subfield of research.

Hydrosocial theory emerged from a heterodox assemblage of marxian understandings of capitalist accumulation and development in correspondence with multifarious theories of power and scale often described as "post-structuralist" (e.g., Haraway 1991). According to this approach, the accumulation not only of capital but of power manifests spatial conditions for "uneven development" (Smith 1984) as a result of a "spatio-temporal fix" (Harvey 2006), whereby the overaccumulation of capital in the "interior" requires the transformation of the ecological "exterior" into productive sites of primary extraction (e.g., mines, timber, oil wells) to maintain an unsustainable "metabolic rate" of urban-industrial development (Foster 2000). Here, landscape and cultural geography enters into critical relation with geographies of development and resource management through "waterscapes," hybrid constructs that are "part natural and part social," embodying "a multiplicity of historical-geographical relations and processes" of internalization and externalization (Swyngedouw 1999, p. 445, see also Molle, Foran, Floch 2009, p. 2).

In relation to capital, these co-evolutionary relations and processes reify systems of inequality while manufacturing out of "nature" a "second nature" through natural resource management (Cronon 1991). As a result, the urban centers of capital determine the phenomenological value of the "world," vis-a-vis what Marx calls the "social process of production" (Marx 1999). This world-making process extends through networks, understood in the post-modern sense as natural systems semiotically mediated by way of representational networks that produce denatured social assemblages often determined toward a reconstructed socio-ecological hybridity (Latour 2004). Hence, in Maria Kaika's words, "the 'world' is a historical-geographical process of perpetual metabolism in which 'social' and 'natural' processes combine in a historical-geographical 'production process of socio-nature' whose outcome (historical nature) embodies chemical, physical, social, economic, political and cultural processes in highly contradictory but inseparable manners" (2005, p. 23).

Hydrosocial theory often views unequal water access and sanitation as products of two distinct regimes of power that determine the governance of health and wellbeing for the rich and poor through Foucault's ideation of biopolitical divisions between "haves and have nots" (Cantor 2017). According to Foucault, by mobilizing political economy to determine the fundamental socio-political arrangements of the population, the state can "conduct the conduct" of the population through dispersed manifestations of power without relying on a central authority that can be easily located and resisted (2008). Thus, hydrosocial theorists argue, the urban hydrosocial cycle manifests a process of dispossession and disenfranchisement incumbent on the spatial transformation of water from "nature's water" to water that can hold a "duty" toward humanity and that can become "wastewater" (Swyngedouw 2004). That world-making metabolic process through which humanity engages with waterscapes and is, in turn, changed by its efforts Swyngedouw names “coevolution” (2006).

Focusing on feedback systems between human and water interactions, the hydrosocial cycle identifies the human influence on the hydrologic cycle as part of a dialectical development of waterscapes and social systems (Swyngedouw et al. 2002). Linton (2008) argues for a new way of understanding the study of water outside the scientifically-constructed and abstract parameters of hydrology in order to gain perspective on its connection to “the old, supply-oriented paradigm of water resource management” (p. 642). It follows that redefining the hydrologic cycle to include the challenges of the Anthropocene would entail “the integration of physical, biological, biogeochemical, and human components of a more general ‘global water system’” (p. 645). Published the next year, Budds (2009) identified the limitations of hydrological assessments, drawing on critical geographies of water to describe the hydrosocial cycle as a means of extending the production of knowledge beyond technical experts and “exploring the production and use of hydrological data” (2009, p. 420). Linton and Budds (2014) refined these approaches into a “relational-dialectical” model, challenging humanity’s sovereignty over water by highlighting the *internal* relation between water and social power, thus identifying human-water systems as hybrids of nature and society.

That year, Boelens introduced the notion of “water truths,” ways that societies organize around water and change water by ascribing “different cosmological pathways” that “form a socionatural network traveled by gods and ancestors, engendering the human world” (2014, p. 243). Neoliberal practices deterritorialize the hydrosocial cycle and strip it of the truths that cohere to social practices, altering its socio-natural metabolism and extending it into transnational networks mediated through the global market (Boelens 2014, Bakker 2000, Swyngedouw 2003). Under this neoliberal order, hydrosocial theory posits, the “post-political” rescaling of governmental authority upward to multinationals and downward to consensus-based non-governmental organizations accompanies privatization and deregulation (Bakker 2003, Budds and McGranahan 2003, Castro 2007). Against this tendency, Swyngedouw calls for “a rethinking of the meaning of citizenship to recognize the multiplicity of identities, the rhizomatic meanderings of meanings, practices, and lives” (2007, p. 23). Hence, hydrosocial research demands a transition from technocratic urban policy into more direct, democratic processes involving debate and contention across “multiscalar networks.” (Boelens 2008).

Although Swyngedouw, Boelens, and Kaika provided some of the most important initial pushes, we find Bakker’s early and continued influence from critical geographies of water noteworthy. Boelens appears to be the most published author in hydrosocial studies with 23 articles on the topic. Other key authors in the subfield include Linton, Budds, and Hoogesteger. The prominent position Boelens takes in the literature also helps to determine the most prolific study site—his focus areas become the most studied, particularly Peru with 17 published studies. Swyngedouw’s key study area of Spain comes in second place with 16 published studies. In general, South America is the most studied with 39 in total, most of which come from the Andean region. By comparison, there are 11 hydrosocial studies from Africa and 22 from Asia. As many as 59 articles did not clearly attribute their study to a particular site, many of which preferring to make broader assessments on more theoretical grounds.

Reviewing Hydrosocial Theory

Out of 207 records for hydrosocial theory, according to our assessment, the most frequent foci discernable from abstracts included irrigation (35 articles), scarcity (24), dams (23), groundwater (11), desalination (10), glaciers (7), sanitation (6), and mines (5). While ten articles focused on history, hydrosocial theory as a subfield of coupled human-water research concentrates mostly on contemporary water governance issues [Figure 2]. Roughly one-third of all hydrosocial texts incorporate governance as a key topic. Nineteen of those articles were theoretical interventions, while the rest involved place-based analyses from Canada (Cook et al. 2016; Stevenson et al. 2018) to Spain (Swyngedouw 2007, Sanchis-Ibor et al. 2017, Duarte-Abadia et al. 2019) to Peru (Carey et al. 2012, Yacoub et al. 2016, Mark et al. 2017, Damonte and Boelens 2019).

The theoretical frameworks of hydrosocial studies have drawn extensively from the work of Swyngedouw, Boelens, and Kaika described above, incorporating post-structuralist theory (Hoogendam & Boelens 2019, Valladares and Boelens 2019) with analyses of coupled socio-ecological systems (Lerner et al. 2018, Carey et al., 2012). This context has provided intriguing opportunities for inquiries into “multi-scalar networks” (Hommes et al. 2016, Boelens et al. 2019) and decolonization (McLean 2017, Stevenson 2018, Cavazos Cohn et al. 2019, Duarte-Abida and Boelens 2019). An entire book informed by hydrosocial studies but not included in the Web of Science dragnet, *Negotiating Water Governance: Why the Politics of Scale Matters*, assesses rescaling political power in watersheds, often through the efforts of indigenous groups (Norman et al. 2015).

The usage of scale in hydrosocial theory generally returns to the specific context of multi-scalar networks exposited by Boelens in 2008. These networks can be conceived simply as complex and pluralistic assemblages of social organizations, often including disenfranchised groups organizing in opposition to the state and corporations (Hoogesteger and Verzijl 2015, Stoltenborg and Boelens 2016, Truelove 2019). However, the hydrosocial literature on multi-scalar networks also involves power relations within and between administrative bodies, legal arrangements, and physical structures (Hommes and Boelens 2017). For this reason, multi-scalar networks have been used to describe complex systems with a broad range of variables acting in relation to dynamic power relations that assemble nested hierarchies depending on spatio-temporal conditions. Hommes and Boelens describe multi-scalar networks as comprising "legal-political and social institutions, cultural relations, ideas and practices as well as physical structures and the environment" (2017, p. 72).

In situ, such networks produce "hydrosocial territory," a heuristic most clearly described as "the contested imaginary and socio-environmental materialization of a spatially bound multi-scalar network in which humans, water flows, ecological relationship, hydraulic infrastructure, financial means, legal-administrative arrangements and cultural institutions and practices are interactively defined, aligned and mobilized through epistemological belief systems, political hierarchies and naturalizing discourses" (Boelens et al. 2016, p. 2). Hydrosocial territories have been used in a number of ways throughout the hydrosocial literature. Wilson's 2014 qualitative study of the indigenous Koyukon Athabascan people's lifeways in Ruby, Alaska, draws on the theoretical development of territory in hydrosocial literature to explore the issues of sovereignty and traditional lands in the context of indigenous governance. She found that the Koyukon gained hegemony through both demands for state recognition and by practicing an alternative water monitoring program outside of recognition. Similarly, Peloso and Harris use semi-structured interviews to analyze the potential for a participatory water governance that takes into account “existing social networks and community governance mechanisms” in Ashaiman, Ghana (2017, p. 24). They concluded that “modern water” is not as effective as bundling water with social welfare to produce participatory governance through different approaches to socio-institutional arrangements. Using survey data pertaining to decision-making around water use in urban Australia, Farrelly and Brown (2014) took a path analysis toward understanding more mixed water infrastructures incorporating water recycling technologies and altering the “hydrosocial contract” to include more civic participation. Their results suggested that diverse infrastructure development could enable “co-governance, co-design, and co-management” of complex water systems.

Amid the multi-scalar networks that produce hydrosocial territories, perhaps the most prevalent analytical heuristic in the literature is that of Foucault’s “governmentality.” Governmentality involves the linkage between mentality and government, the rational underpinnings of that bind society and political sovereignty, and is understood in different ways by hydrosocial theorists (Foucault 2011). Vallardes and Boelens understand governmentality as emerging through four inter-related “arts of government” (Foucault 2011, p. 261): the regime of Truth, of sovereign power, of disciplinary power, and of neoliberal power (Vallardes & Boelens 2019). Based on these “arts,” power comes not just from the top down but also from the bottom up and horizontally, diffuse and productive. In tandem with governmentality, hydrosocial literature also calls on Foucault's notion of biopolitics based, for instance, "on the categorization, quantification, and knowledge/power formation of urban residents in an attempt to govern their behavior" (Bakker 2014, p. 283). Hence, the biopolitics of water involve its privatization (Bakker 2014), the removal of water management from people with experiential knowledge (Sarmiento et al. 2019), its theft by disenfranchised people (Meehan 2013), its epistemological construction (Hommes et al. 2016), its usage as a productive force (Duarte-Abadia et al. 2019), its administration through large-scale infrastructure programs (Rogers et al. 2016), and the societal rescaling and conflict that emerge around it (Duarte-Abadia & Boelens 2016; Workman 2019).

As a result of the focus on power and scale, we find that hydrosocial studies have traditionally centered on water governance pertaining to general demand, rather than quality, extreme events, and ecosystems services. [Figure 2]. The majority of these studies use content analysis of extant theoretical and legal documents to describe how different places fit or do not fit the conceptual models previously established for hydrosocial territories, waterscapes, and other heuristics for understanding power relations across multiple scales in complex, adaptive human-water systems. As well, we identified 15 articles that discuss semi-structured interviews in their abstracts, while seven abstracts disclose use of ethnographic observation. Four articles utilized survey data. Interestingly, 2019 also saw more quantitative methods used than usual, including groundwater modeling (Castilla-Rho et al. 2019) and system dynamics (Maxwell, Langarudi, Fernald 2019).

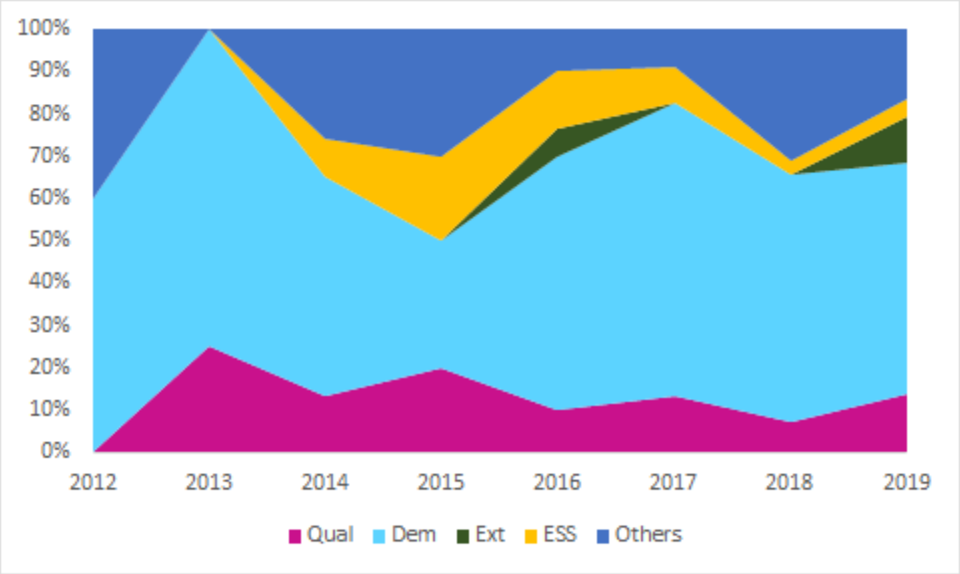


Figure 2: Percent distribution of hydrosocial studies by topic—Quality, Demand, Extremes, Eco-System Services, and Others

Origins of Socio-Hydrology

Cited 578 times since its publication as of January 20, 2020, socio-hydrology's inaugural article by Sivapalan, Savenije, and Blöschl (2012) enjoined hydrologists to expand their analyses of water systems in a fashion that includes human action as "part and parcel of water cycle dynamics" rather than an external force (p. 1271). Importantly, the authors situated their research under Integrated Water Resources Management (IWRM), arguing that "socio-hydrology is the fundamental science underpinning the practice of IWRM" (p. 1271). Perhaps most importantly, the observations of socio-hydrology reject stationary models in favor of explorations of "the co-evolution and self-organization of *people* in the landscape, also with respect to water availability" (p. 1271). Hence, socio-hydrology grew to bolster IWRM with a rapidly increasing theoretical corpus that included the fundamental concepts of co-evolution and complexity amid the co-evolution of human and water systems.

It is important to note that Sivapalan and the other authors of the pioneering socio-hydrology article based their development on prior research, particularly regarding eco-hydrology. Beginning with Frank Geels's 2005 study of the co-evolution of hydrology and Dutch society, the authors call on the sociology of technology and a whole literature of "socio-technological systems," which also influenced hydrosocial theorists (Freeman and Perez 1988, Geels 2005). Similarly, socio-hydrology's innovators call on Kallis' (2011) "vicious cycles" in Athenian water use, which describes "the hydro-environmental geography of Athens" over time as economic investments drove structural changes that correlated with social transformations (p. 801). For his part, Kallis identified a number of similar studies dating back to the early 1990s, placing the marker for socio-hydrology's precursive period further back into the archives (and mingling with hydrosocial theory through socio-technological systems research).

In an interesting reaction to the Sivapalan et al. (2012)'s inaugural "socio-hydrology" article, Sivakumar argued that "socio-hydrology" was "not a new science, but a recycled and reworded hydrosociology" (2013, p. 3788). Referring to the work of Falkenmark and Wildstrand from the late 1970s, Sivakumar insisted that "any new study on the dynamics and co-evolution of coupled human–water systems can only be, at best, an addition to the science of hydrosociology rather than a new science by itself" (p. 3789). Pande and Sivapalan responded indirectly by noting Falkenmark's contributions and calling for their expansion by making "[l]ong-term socioeconomic (such as population, wealth, etc.) and water infrastructure scenarios (e.g., demand projections and water policy)" endogenous to the study of coupled human-water systems (2017, p. 2). Indeed, the concepts presented in contemporary socio-hydrology deserve discussion on their own merits rather than subsumption within the corpus of hydrosocial studies based on the latter's earlier appearance for the following three reasons:

1) Both hydrosocial theory and socio-hydrology have progressed from Falkenmark's late 1970s work in hydrosociology;

2) Socio-hydrology and contemporary hydrosocial theory are discrete subfields of the study of coupled human-water systems with numerous differences;

3) Calling socio-hydrology "hydrosociology" would only instill greater confusion over apparent conflation with contemporary hydrosocial theory, which despite the increasing amount of overlap and synthesis, should still be considered on its own merits.

Having rejected the categorical subsumption of socio-hydrology into hydrosociology or hydrosocial theory, we must further investigate socio-hydrology to understand the challenges of ongoing efforts at synthesizing the research surrounding coupled human-water systems.

Reviewing Socio-Hydrology

While hydrosocial research sometimes includes statistical models, causal feedback diagrams, and contemplation on system dynamics, socio-hydrology tends to incorporate those methods far more regularly [Table 1]. Several review articles of socio-hydrology already exist. Nusser, having first published the term "socio-hydrology" in 2012 without calling for a "new science," produced a brief, approving review of the literature (2017). As well, Xu et al. (2018) offer a generous review calling for the inclusion of a social science perspective without necessarily making a direct link to hydrosocial theory or mapping out a spatial and topical analysis of the research. Other reviews of models and theoretical discourses, such as that produced by Di Baldassarre, Brandimarte, and Beven (2016), offer incisive meditations on uncertainty and precision in socio-hydrology that are often outward-looking but lack specific focus on the other leading school of thought regarding human-water systems.

By contrast, Massuel et al. (2018) call for further interdisciplinary research recognizing that "the hydrological model itself becomes (only) one element in the socio-hydrological approach rather than its end purpose" (p. 2518). Indeed, it appears that the further socio-hydrological analysis develops, the more intellectual space becomes available to address phenomena overlapping with hydrosocial theory, such as the *institutional complexity effect*, whereby "coupled human-water systems often evolve in ways that add more complex infrastructure and governance arrangements to reduce hydrological variability and increase system performance" (Di Baldassarre et al. 2019, p. 6335). Continuing on this theme, Baldassare et al. (2019) call for mixed methods approaches that address the challenge of "different epistemologies, research strategies, and axiologies of qualitative and quantitative approaches," inclusive of "central themes of scholars in critical water studies and political ecology such as the role of ideology, and regional landscapes and the uneven distribution of costs and benefits thereof" (p. 6344). As the International Association of Hydrological Science's current focus on human-water systems vis-à-vis the Panta Rei (Everything Flows) decade of scientific inquiry, the present review hopes to follow this line in the extant research, and to point to novel developments going forward.

According to its inaugural paper, socio-hydrology focuses on three categories: historical socio-hydrology, comparative socio-hydrology, and process socio-hydrology. Excluding review papers and theoretical discourses from our study, we discovered 81 process socio-hydrology articles and 49 comparative socio-hydrology articles, with only 12 historical studies in existence. Authors most central to the field, with the most co-authorships, include Sivapalan, Blöschl, Di Baldassarre, Biglione, and Srinivasan (Xu et al. 2018). The focus on process studies illustrates socio-hydrology's greater investment in practical applications of specific case studies using quantitative methods to solve existing problems. Our Web of Science search found that methods in socio-hydrology draw largely from physical and statistical models, especially system dynamics and agent-based models—with the exception of theoretical and review articles and some 14 articles utilizing sociological methods like interviews, focus groups, and surveys (four of those occurring in the last year).

The majority of socio-hydrological studies come from Asia (28), with nearly half of those coming from South Asia. Only five studies could be located in Africa. The most common focus is flood management and risk (68 articles), with other important topics including drought (29), and groundwater and irrigation (35). Fewer articles focused on governance, with socio-hydrology taking a sharper focus on water management than water governance in most years. One might conclude that socio-hydrology's practical approach tends to be more amenable to the study of water and climate extremes than water use, ecosystem services, or water quality because socio-hydrologists often take more of an engineering approach than a humanistic one. However, there is some annual variation in the number of study topics, suggesting that broader governance problems can also benefit from socio-hydrological approaches [Figure 3]. Moreover, although scholars tend to think of hydrosocial studies as more theory-intensive, socio-hydrology literature involves a higher proportion of articles without case studies, including review articles, discussions on different forms of models, and broader studies across different continents.

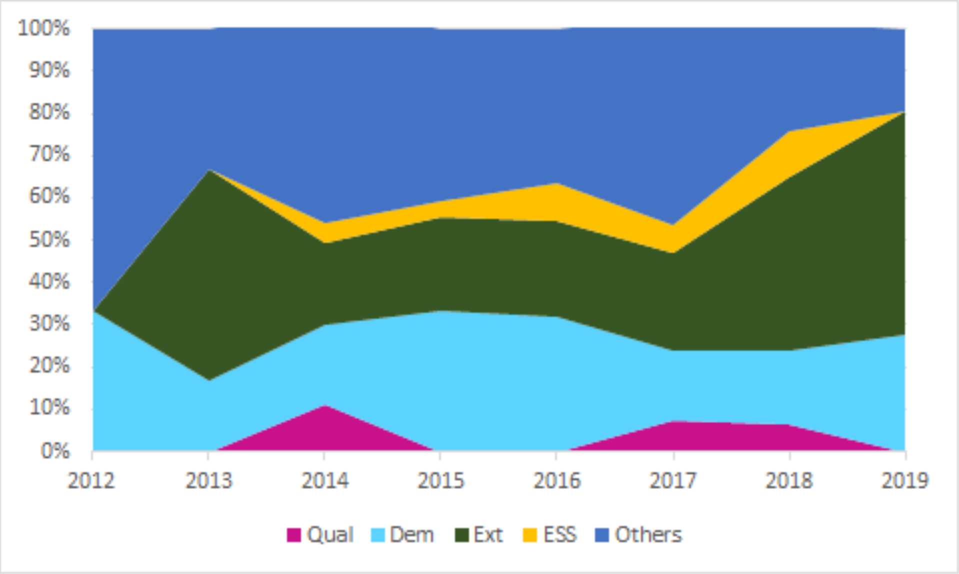


Figure 3: Percentage of socio-hydrology studies by topic—Quality, Demand, Extremes, Eco-System Services, and Others

Despite its impressive focus on quantitative analysis based in complex physical and statistical models, socio-hydrology also incorporates critical analyses of modeling methodology. Srinivasan put the challenges of modeling complex adaptive systems in a manner reminiscent of hydrosocial critique:

> As new technologies develop, users adapt to unreliable water supply. Adaptive responses by humans (acting individually and collectively) in turn may alter the watershed hydrology and consequently water availability. These bi-directional

> feedbacks often result in unexpected emergent behavior. Many water managers fail to account for these complexities (2015, p. 786).

Recognizing the unpredictable nature of such feedbacks, Srinivasan identified three approaches: a “toy” model that is generalizable but not specific, a joint agent-hydrologic model that is accurate for specific, predicted conditions, and a “stylized” model that represents essential characteristics of a system without exact calibration and validation (2015).

An interesting “stylized” model can be found in Ferdous et al. (2018), which attempted to bridge the gap between generic models and specific case studies with what the authors call “socio-hydrological spaces.” Here, the authors hoped to move a step beyond conceptual models by utilizing site-specific narratives to articulate the socio-hydrological space, backed by statistical analysis, without providing a formal model. The authors analyzed socio-hydrological spaces as discrete constructions of human responses to physical phenomena like floods—namely the influence of a population’s choice to “fight” floods by creating infrastructure or to “adapt” to floods by living with them is correlated with property damage and flood impact during extreme events. Using statistical and narrative analysis, the authors showed that the two different groups choosing to “fight” or “adapt” could be empirically understood as distinct, and those who “adapt” experience less damage. Thus, the authors contest that they can better discern co-evolved human systems that maintain adaptive approaches to hazards from those that are less adaptive. Indeed, lessons from socio-hydrological spaces can also be applied to hydrosocial territories in order to create comparative studies of multiscalar networks in different sites and their capacities to “fight” or “adapt” to different modes of governance and forms of hazards.

Sociological methods are becoming increasingly important but remain less commonly used than physical or statistical modeling in socio-hydrology. Houston et al. engaged a survey of residents in Newport Bay Estuary to examine correlations between “nonspatial perceptions of dread” and a spatial understanding of areas prone to flooding (2019, p. 347). In their study of riparian farmers in Tunesia, Ogilvie et al. deployed both questionnaires and semi-structured interviews, mixing quantitative and qualitative methods in a “multi-scalar interdisciplinary approach” to understanding diversification of agricultural practices and resilience to drought (2019, p. 17). Similarly, Nüsser et al. (2019) used field surveys and interviews, along with remote sensing, to assess the efficacy of artificial glaciers in Ladakh, India, in hydrological terms and according to smallholders’ perceptions. It should be noted that the use of these sociologically-based methods often correlate to theoretical overlap with hydrosocial theory.

Meanwhile, some argument exists within the socio-hydrological literature over the nature and importance of quantitative modeling methods. Bekchanov, Sood, and Pinto (2017) argued that Water Economy Models can help drive ecosystem services with the addition of more precise economic data. Rather than critique the usage of models the authors favor them as neutral tools to infer water consumption in such a way as to help steer policy depending on the quality of data. In an important rejoinder to the discussion across sub-fields, Melsen, Vos, and Boelens claimed that models are “uncertain, subjective and a product of the society in which they were shaped” (2018, p, 1435). While their work is largely associated with hydrosocial theory, the authors’ intervention in the subfield of socio-hydrology indicates important shared values in the midst of difficult methodological problems.

In their response to Melsen et al. (2018), six socio-hydrologists including Sivipalan and Blösch stated, “[w]hile we reiterate that, despite acknowledged shortcomings, the enterprise of integrating societal feedbacks into hydrological models is beneficial in prediction and adaptive management, we also agree with the sentiments of the authors” (Srinivasan et al. 2018, p. 1444). As recent modeling efforts become even more refined and complex, for instance incorporating machine learning to simulate adaptive irrigation (Mewes and Schumann 2019), efforts to broaden socio-hydrology beyond modeling have also advanced. For instance, Borga et al. (2019) worked to impliment interdisciplinary collaboration to create post-flood surveys that include eyewitness interviews along with physical data, and Kam et al. (2019) used Google Trends to study drought awareness in California from 2011-2017. Along with this apparent agreement about broadening methodological approaches, we also found areas of study that appear to integrate hydrosocial theory and socio-hydrology in new ways, for instance with hydoeconomics (Jaeger et al. 2017, Müller and Levy 2019). It would appear that the two subfields uncovering coevolutionary dynamics of human-water systems are themselves evolving together through the exchange of ideas and productive critiques.

Bridging the Gap

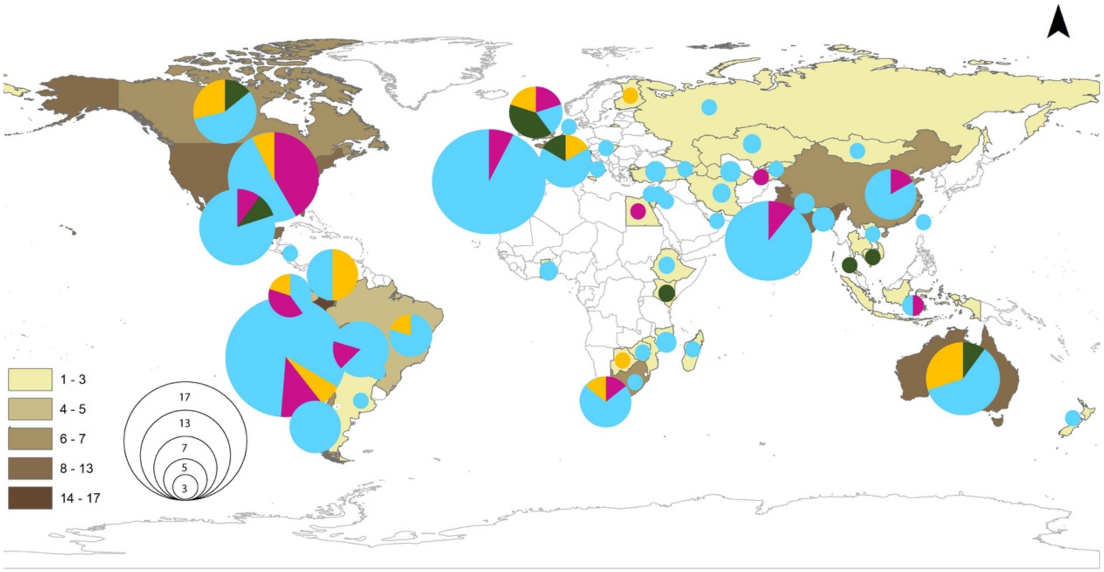
These recent developments elucidate how socio-hydrology, understood as a “positivist” science by Pande and Sivapalan (2017), can also extend to other approaches that also offer generalizable results. Here, positivism, or (post)positivism, may not preclude the materialist or even post-structuralist approaches of hydrosocial theory. Socio-hydrology can also take biocentric perspectives or an approach closer to current fields of thought like Object Oriented Ontology or Assemblage Theory that identify human action as an important causal agent among others in environmental change (e.g., DeLanda 2016). The point of socio-hydrology, then, is not necessarily anthropocentric but an effort to make short- and long-term human behavior endogenous to a hydrologic system in approximately the same way hydrosocial theorists ideate the hydrosocial cycle.

Indeed, socio-hydrologists have mulled over and incorporated the implications of the same foundational theories as hydrosocial studies, such as Actor-Network Theory (ANT). In their call for the inclusion of ANT progenitor Bruno Latour's theoretical insights regarding networks in agriculture archaeology in order to show "how human agency shapes relationships and institutions," Ertsen et al. revealed how cross-fertilization between theoretical approaches between socio-hydrology and hydrosocial research has been put in practice (2015, p. 1381). Similarly, Lane drew extensively on Latour and his associate Michel Callon to promote "greater public involvement in scientific practice" as a way of improving the translation of science into policy in flood risk management (2014, p. 935). Yet, it is not merely the usage of ANT that aligns hydrosocial and socio-hydrological theory but their shared interest in challenging the limits of even the most up-to-date models in describing complex and unpredictable socio-natural systems to extend empirical research designs with broader, systemic assessments.

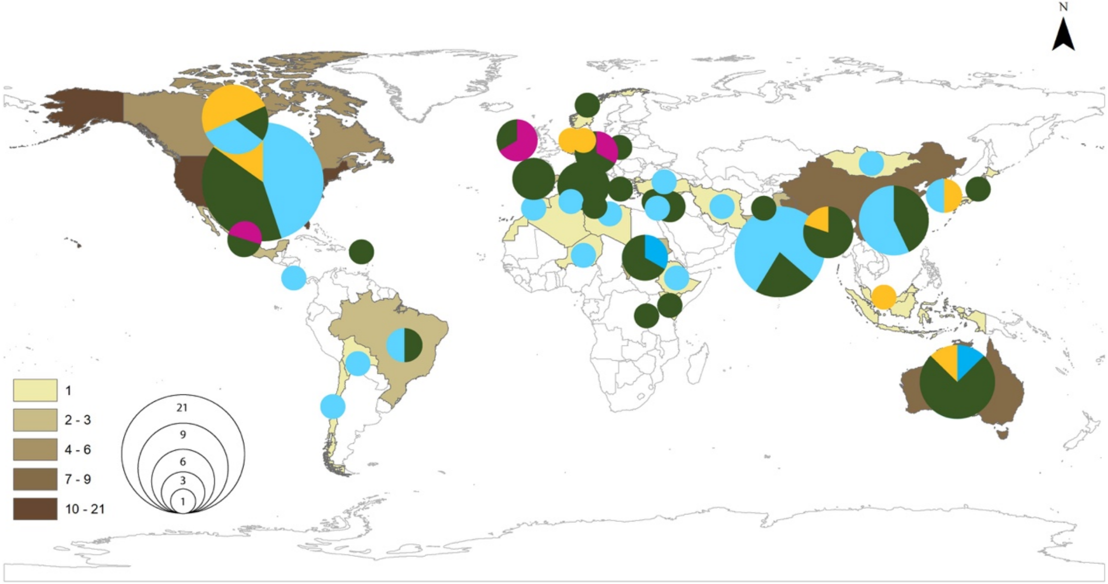
Epistemological studies, more clearly at the bedrock of hydrosocial theory, are also increasingly vital to socio-hydrology – a tendency that explicitly involves integration with hydrosocial theory (Di Baldassarre et al. 2019, p. 6344). For example, Wescoat

(2013) examined the “duty of water” – a discursive construct familiar to hydrosocial researchers – through an epistemological approach to the fundamental assumptions made by British irrigation engineers and planners who helped set the standard for US water systems in the west. Similarly, Strickert et al. (2015) also called for the usage of Cultural Theory in ideating societal conflict and risk pertaining to drought. Van Loon et al. (2016) described human action as an important driver of climate change, calling for definitions of drought to include differentiation between human-modified drought and other drought conditions. Moreover, Callegary et al., in identifying “the utility of social science in applied hydrologic research,” also identified multi-scalar networks without naming them, describing complex relationships between stakeholders, transboundary legal arrangements, and institutional frameworks across both local and global scales (2018, p. 60). As well, Mukherji et al. (2019) provided a recent discussion of epistemological understandings of power, politics, and intersectionality in the cryosphere that would be at home in a hydrosocial special issue. The authors also cited researchers in critical geographies of water like Norman and Bakker, calling for greater focus on “socio-political and historical information, governance, legal and institutional frameworks, cultural sensitivity, communication and stakeholder engagement among others” (p. 71). These instances all illustrate tendencies of cross-over that traverse the boundaries dividing subfields, incorporate different, intersecting disciplines, and implement new critical developments. Perhaps the ongoing tendencies toward integration manifest a partial result of a process of critique and learning undertaken between subfields that draws them into a multi-part assemblage focusing on different, complimentary systems with broad and perhaps increasing overlap.

Further evidence of this overlap, or emergent syntheses, between hydrosocial theory and sociohydrology can be found in more recent, innovative approaches. Investigating the power relations within stakeholder relations relative to groundwater contamination, studies in the new subfield of socio-hydrogeology merge socio-economic assessment and hydrogeology, leading to the identification of important variables otherwise ignored (Re 2015, Re et al. 2017). Similarly, Di Pelino et al. (2019) argue for a coupled human-water approach to public health, which fuses the coupled-systems approach of socio-hydrology, socio-hydrogeology, while "disaggregating into specific elements and behaviours and avoid over-generalization" in the hydrosocial fashion, as well (p. 7). This ecohealth approach, the authors explain, would offer a "more comprehensive understanding of human health within the context of environmental issues" (p. 8). Socio-hydrology and hydrosocial theory are already engaging in a process of interfacing while maintaining unique traits and producing new and fascinating currents that will continue to contribute to the fecund discussions producing new and interesting subfields beyond the Panta Rei period.



Figures 4 & 5: Top map showing distribution of hydrosocial studies; bottom showing socio-hydrology studies via Jan 2020 topic search using Web of Science. Extremes (green), Demand/Use (blue), Quality (purple), and Ecosystem Services (yellow).



Even the spatial distribution of studies seems to indicate a certain symmetry. While hydrosocial studies are concentrated in Europe and Latin America [Figure 4], socio-hydrology is strongest in Asia [Figure 5]. While socio-hydrology incorporates more research from Northern Africa, hydrosocial studies tend to fall in sub-Saharan Africa.

Indeed, the maps of the two studies are symmetrical in compelling ways. At the same time, we can see that there is a considerable lack of forays into water quality and ecosystem services, indicating perhaps an avenue for expansion in future collaborative studies.

Although they seem quite different, then, our study found that hydrosocial research and socio-hydrology share many of the same common presuppositions, inclusive of a conscientious understanding of coupled human-water systems based on the impetus to promote egalitarian resource management by integrating multifarious stakeholders into the planning and implementation of policy. Socio-hydrology appears to deploy more quantitative methods, using suites of statistical and physical models to understand potential scenarios, but Srinivasan's (2015) development of "stylized models" provides an invitation to hydrosocial researchers to mix their methods. As well, hydrosocial approaches may develop and cross-pollinate with socio-hydrological research across different scales in order to produce still more robust and useful research. Furthermore, hydrosocial theory's reliance on marxian political economy remains malleable given its heterodox form, and calls for a multiplicity of epistemological engagements with different systems, not to be seen as a limitation but as a wellspring for future discussion and vigorous debate among analysts of human-water systems for which historical socio-hydrology could provide a significant source.

Conclusions

Our review of the 419 articles from socio-hydrology and hydrosocial or hydro-social studies suggests that the two subfields have grown closer together and are adapting to critiques, although the publication outlets remain different. Hydrosocial studies increasingly emerge from a diverse array of sites, gathering localized observations through rigorous qualitative and empiric methods, while socio-hydrology's openness to assessing the implicit biases in hydrological modeling and navigating theoretical nuance invites active cross-fertilization of methods and theories. As well, a number of overlapping positions can clearly be seen:

1. The conceptual exploration of socio-hydrological spaces, hydrosocial territories, and waterscapes can offer possible transdisciplinary syntheses of practical solutions and theoretical outlooks regarding perceptions of risk, resilience, and adaptivity.
2. The joint recognition that humans must be considered endogenous to an understanding of a hydrological system that we impact moves in tandem with systems analyses that appreciate feedbacks and "metabolic" processes, opening opportunities for studies that incorporate quantitative and qualitative methods.
3. Situated epistemologies produce conditions of power and scale that impact hydrosocial/socio-hydrological systems, while the collaboration of hydrosocial and socio-hydrological studies can help develop conscientious solutions to complex problems in both the short and long term.

Socio-hydrology and hydrosocial theory stem from different ways of reconciling old development regimes to transformative, emergent scientific approaches. While hydrosocial theory has evolved from fields like urban political ecology, it is by no means restricted to those roots, employing a more rhizomal distribution across disciplines. Similarly, socio-hydrologic research looks to myriad places to test different strategies for managing water in ways that align with complex, adaptive, and dynamic ecosystems amid climate change in the Anthropocene. Indeed, we point not only to collaboration across disciplines but to deeper integration between them through the development of more holistic studies that might be seen as an overlapping set in a Venn Diagram. Such studies model scenarios involving the implications of power relations for coupled human-water systems across multiple scales to identify practical solutions to extant problems without losing sight of their boundary conditions (Evers et al. 2018). Thus, we do not seek to promote subsumption but rather applaud the ongoing assemblages of methods and epistemological approaches that harmonize the different subfields into compelling and robust studies without losing their integral distinctions in keeping with what Rusca and Di Baldassarre call "interdisciplinary resource geography" (2019, p. 8-10)

Further research might extend the contemporary trends into a more integrated approach, using subfields of hydrosocial studies and socio-hydrology through the oft-neglected lens of exurban political ecology, which will help provide some insight into the population trends and the responses of watershed ecosystems on which they depend to climate change (McCarthy 2002, McKinnon 2016, McKinnon et. al. 2017). Here, the "stylized" model may offer the greatest opportunity for hydrosocial scientists to use their understanding of power relations toward producing sound, practical proposals for hydrosocial territories while engaging with the dynamism of complex, adaptive systems (Milly et al. 2008).

In turn, by making research more sociologically oriented, with rigorous applications of qualitative methods, socio-hydrologists can make their interests more widespread. Furthermore, by branching out and gaining insight from within socio-ecological systems, socio-hydrologists will have a better opportunity to share and enrichen their ideas, particularly regarding IRWM. Socio-hydrologists may be wise to publish more in social science journals and solicit water resources management articles from social scientists interested in pressing water issues. Finally, greater collaboration with social scientists, which offers transformative frameworks for modeling and translating research material to various stakeholders, would help bridge the translation gap between science and policy (Xu et al. 2018). Indeed, the progress in both socio-hydrology and hydrosociology is encouraging. As climate change produces new and difficult problems, adaptive research communities have drawn these distinct subfields closer together, resulting in a vital cross-pollination that contains transformative potential for future scholars and practitioners to explore together (Ajibade and Adams 2019).

Table 1: List of Agent-Based and System Dynamics models used in coupled human-water systems science

Agent Based Models	Study Area	Problem	System Dynamics	Study Area	Problem
Abebe et al. 2019	Sint Maarten	Flood risk management	Barendrecht et al. 2019	Dresden	Flood Settlement
Farjad et al. 2017	Alberta, CA	River flow modeling	Borgomeo et al. 2018	Bangladesh	Water Poverty Trap
Klassert et al., 2015	Amman, Jordan	Water consumption	Duran-Encalada et al. 2016	MX-US border	Population and consumption
Walker et al. 2015	Theoretical	Human-water systems	Elshafei et al. 2015	West Australia	Water balance co-evolution
Tesfatsiona et al. 2017	Squaw Creel, Iowa	Climate and decision making	Feng et al. 2018	Hehuang, China	Power generation & water supply
Bakarji et al. 2017	Theoretical	Decision support	Gober & Wheater 2015	Saskatchewan	Irrigation and water security
Aerts et al. 2018	Review	Disaster Risk Reduction	Gunda, Turner & Tidwell 2018	New Mexico	Acequia water management
O'Connell & O'Donnell 2014	Israel/Palestine	Floods, virtual water	Jeong & Adamowski 2016	South Korea	Irrigation and SWAT model
Wens et al. 2019	General	Drought risk perception	Liu et al. 2015	Tarim River, China	Socio-economics and resources
			Mehta et al. 2014	Bangalore, India	Urban metabolism and Enviro Justice
			Pande & Savenije 2016	Global	Water metabolism
			Roobavannan et al. 2018	Review	Generalization of system dynamics
			Srinivasan 2015.	Chennai, India	Consumer wells, dynamic infrastructure
			Turner et al. 2016	New Mexico	Acequia water management
			Wheater & Gober 2015	Saskatchewan	Non-stationary and vulnerability analysis

			Xu et al. 2018	Theoretical	Systemic risk with adaptive governance

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Chapter 2: Collaborative Management and Adaptive Transformation in an Exurban Hydrosocial Territory

Abstract: Exurban areas at the interface of rural and urban face economic and ecological hazards accompanying urbanization and climate change. While some posit that collaborative watershed councils can promote viable bioregional alternatives to impasses across federal and state scales, others remain skeptical of rescaling as a way of promoting neoliberal hegemony. In this qualitative study of a watershed group in a hydrosocial territory, I assessed stakeholders' perceptions of economic and ecological hazards, analyzing their diverging understandings of the potentials for resilience and transformativity. Forty-two semi-structured interviews and participant observation of monthly meetings were conducted from August 2017 until April 2020. Using a theoretical synthesis of Exurban Political Ecology, hydrosocial studies, and resilience theory, I found that collaborative watershed practices help align varying approaches together under the common interests of sustainability and resilience. However, stakeholders remain conflicted about the implications of resilience either as an effort to return, or "bounce back," to a prior condition or an effort to "bounce forward" toward transformative adaptation. This research contributes to the literature on Integrated Water Resources Management, showing that collaborative water management can successfully draw together disparate stakeholders for the purpose of specific projects, but the complex process of negotiating different stakeholders' values and renders a broader vision of socio-ecological change somewhat elusive.

Introduction

Exciting developments in Exurban Political Ecology (EPE) over the last ten years have produced innovative ways of understanding socio-spatial change (Chase 2015; Hiner 2016a; Hurley, Macaroni, and Williams 2017; McKinnon et al. 2019; Oteroand Nielson 2017). As populations increase and disperse in manifold ways and to myriad places throughout the country, EPE seeks to understand power relations in complex systems at the urban-rural interface. These advances occur in tandem with shifting ecological dynamics pertaining to climate change, which adds to the political tensions layers of spatial transformations in exurban areas (Bastian et al. 2014; Linkous 2017; Olson 2016; Tilt and Cerveny 2016). By interviewing stakeholders in the exurban hydrosocial territory of Hood River, Oregon, this study analyzes local perceptions of hazards and adaptive capacity in terms of both climate and population changes in the area.

Understanding these perceptions helps further discern not only the challenges facing exurban "waterscapes" but also the efficacity of different ways of responding to those challenges. Thus, this paper attempts to answer the questions:

- What are the challenges that the area's stakeholders (water managers, policy makers, conservationists, orchardists, federal agencies) perceive in terms of population and climate change in Hood River, and do they feel prepared to meet the challenges?
- Does the adaptive capacity of the region indicate transformative capabilities?

By answering these questions, this study fills a gap in the existing literature on EPE with regards to resilience in human-water systems. This research is important because it draws attention to the hazards facing water resources in exurban areas as a result of climate change and urbanization processes, as well as the work of collaborative groups in promoting transformative adaptations to changing conditions.

Literature Review

I utilize an integrative theoretical framework of EPE (Walker and Fortmann 2003), hydrosocial territories (Boelens et al. 2016), and transformational adaptation theory (Ajibade and Adams 2019). Each of these theoretical frameworks provides a body of important literature with crucial gaps that this integrated framework seeks to fill. This synthesis of approaches helps craft a coherent, heuristic theoretical framework suited to the demands of Hood River but generalizable across different watershed-dependent exurban areas. It also involves aspects of an interlocking literature that have yet to be fully developed and applied in qualitative studies.

Exurban places are defined by their place on the threshold between rural and urban, making them particularly fascinating case studies for “First World Political Ecology” (Angelo and Wachsmuth 2015; Johnson and Schultz 2011; MacGregor-Fors 2011; McCarthy 2002). EPE often focuses on relations between long-time rural residents and “amenity migrants” seeking calmer lives free from the hustle and bustle of urban metropolises, remote from the city but not entirely removed from the city’s conveniences (Cadieux and Hurley 2011; Finewood 2012; Gosnell and Abrams 2011; Lekies et al. 2015; Walker 2011). Describing tensions between old and new-comers, rural and urban livelihoods, productivist and post-productivist economies, EPE tends to study tenuous negotiations of multi-scalar networks (Perreault 2003) amid diverging processes of urbanization and ruralization (Cantor 2020).

Hydrosocial territories are described as "*the contested imaginary and socio-environmental materialization of a spatially bound multi-scalar network in which humans, water flows, ecological relationship, hydraulic infrastructure, financial means, legal-administrative arrangements and cultural institutions and practices are interactively defined, aligned and mobilized through epistemological belief systems, political hierarchies and naturalizing discourses*" (Boelens et al. 2016, p. 2). Although hydrosocial theory examines the same type of multi-scalar networks as EPE, studies synthesizing the two are a relatively recent development. In particular, Cantor (2020) reconciles the two fields through an analysis of "hydrosocial hinterlands" comprising flows through which urban and rural co-construct and change one another. As well, McKinnon et al. (2019) discuss sustainability in terms of the tacit tensions of exurban processes, noting that EPE often focuses more on amenity migrants than other stakeholders and community members. The present study extends Cantor's discourse of hydrosocial territories in exurban areas, while also moving beyond the "amenity migrant" to study those who actively participate in producing hydrosocial territories.

In exurban areas, various stakeholders develop de-centralized and non-linear collaborations. To reconcile conservation and production with in-migrants seeking both growing economies and ecological recreation, some stakeholders look to non-linear development strategies that draw from *in situ* social networks rather than top-down, technocratic administration (Abbruzzese and Wekerle 2011; Hartman and De Roo 2013;

Martin et al. 2019; Tilt and Cerveny 2016). Such efforts look to the integration of Adaptive Management and Integrated Water Resources Management to ameliorate conflict through the implementation of “participation, democracy, deliberation, diversity, and adaptability,” using incentive-based resource management mechanisms like ecosystem services (Engle et al. 2011; Jewitt 2002). Through these challenges, exurban areas can act as socio-ecological petri dishes for an “other” form of governance that takes place in a watershed (Mckinnon and Hiner 2016). To minimize the risk of stalemate (Boucquey 2017; Hurley and Walker 2004; Walker 2003), both environmentally and politically, exurban planners focus on adaptation to existing hazards and resilience to potential hazards amid large-scale transformation (Alberti and Marzluff 2004; Craig and Ruhl 2019; Morehouse et al. 2008).

Goals of such collaborative management and planning often attempt to balance participants’ social and economic class with lifestyle benefits (Bastian et al. 2014; Locke and Rissman 2015). Different actors representing alternative narratives, interests, and needs instantiate “mutually constitutive” scales both endogenously and exogenously as competition and collaboration are negotiated with regards to both internal and external boundaries (Hoogesteger, Boelens, and Baud 2016). Thus, stakeholder’s identities and sense of place, bound to both the water resources and to one another (Hurley and Arı 2018), constitute multi-scalar networks in hydrosocial territories as complex adaptive systems defined by the coevolution of humans and water resources (Boelens et al. 2016; Cook, Hall, and Larson 2012; Walker and Hurley 2004).

While the literature on sustainability, resilience, and transformational adaptation appears robust, few if any studies focus on its implementation in the study of exurban hydrosocial territories. Previous studies conceptualized the role of watershed groups in rural areas (for instance, as Community-Based Water Resource Management) rather than to discern how and why they function in relation to resilience or transformational adaptation (Habron 2003; Lurie and Hibbard 2008). Exurban development remains a relevant subject to pursue, given global growth patterns and trends in political economy, and many exurban areas lie within waterscapes defined by multi-scalar networks. As such, it becomes imperative to analyze forms of collaborative watershed management and stakeholder engagement in the context of resilience and transformational adaptation to perceived hazards posed by development and climate change.

Site Selection: Hood River, Oregon

Hood River is an example of an exurban community, lying just 60 miles east of Portland, Oregon. The county comprises a rural valley and peri-urban city in the shadow of Mount Hood to the south where the Hood River begins. Because of anthropogenically-caused climate change and exurban growth, the Hood River Valley faces water management challenges linked to development and climate change. Hood River County is drained by the Hood River, which flows north from Mt. Hood about 25 miles to meet the Columbia River at the City of Hood River, containing a population of about 8,000 residents. With a broader population of approximately 23,000 residents, the population is predominantly white, although the percentage of Hispanic or Latino people has increased over the past two decades (from 25% in 2000 to an estimated 32.1% in 2019) (US Census Bureau 2019). The population of Hood River County is projected to increase to nearly 35,000 people by 2050, a 50% rise from 2019 (Ruan et al. 2016).

The population of the basin increased steadily with agricultural productivity, as growing orchards brought in more migrant labor, leading to a burgeoning Latino community. In the 1980s, tourism from wind surfers at the famed “Bridge of the Gods” drew more in-migrants, making it more amenable to a relaxed, exurban lifestyle. While in-migrants drawn by recreation brought a liberal tendency with them, the tech industry rapidly grew into a profitable multinational enterprise. At time of writing, the local tech mogul, Collins Aerospace, had just merged with Raytheon, making one of the area’s top employers among the largest defense contractors in the U.S. This shows that the progressive politics of the Watershed Group are part of a complex socio-spatial phenomenon produced by metabolic processes of urbanization and ruralization that stem from dynamic technological modes involved in the accumulation of capital (Ross and Cantor, forthcoming).

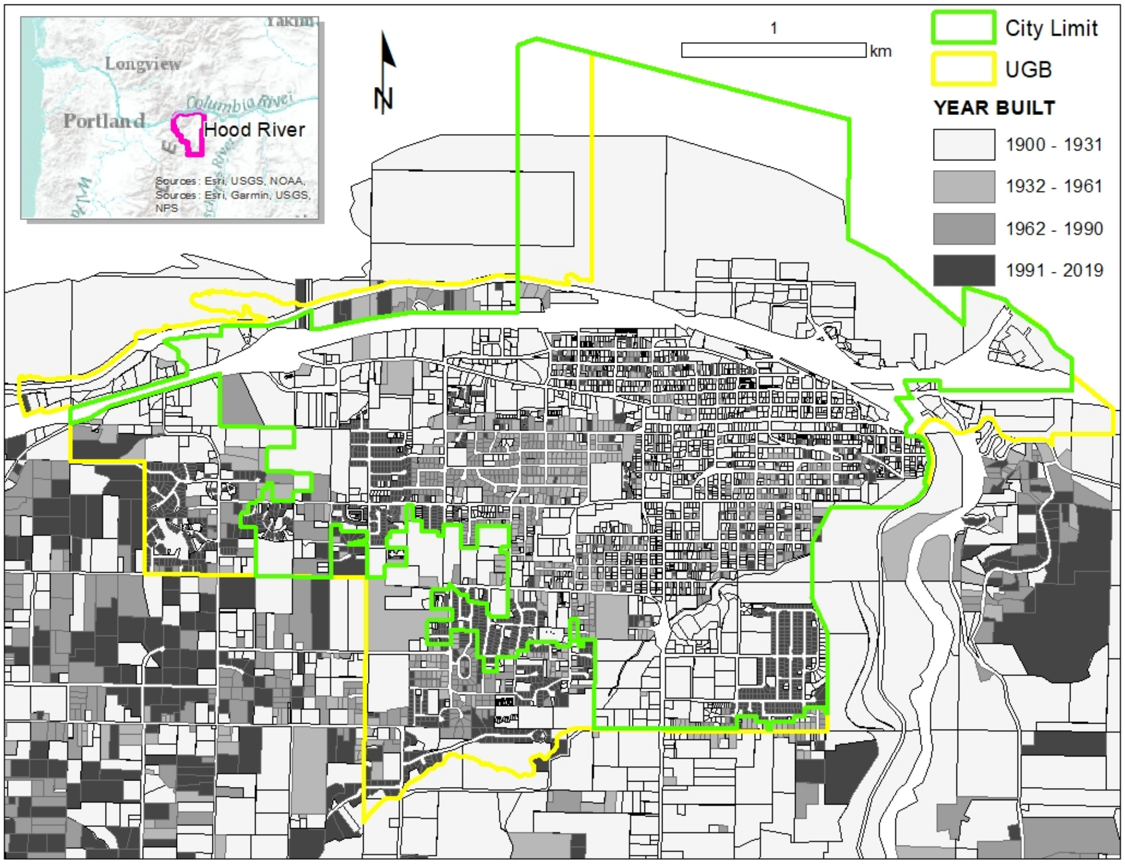


Figure 5: Hood River City Limits and Urban Growth Boundary given taxlots by year built up to 2019

The recreation and tech boom added to concern over the loss of farmland and tradition to urbanization practices. Meanwhile, the retreating glaciers that feed Middle Fork of the Hood River drove farmers and conservationists to collaborate on new efforts to improve ecological and economic sustainability (Bureau of Reclamation 2015; Salminen et al. 2016). At the same time, stakeholder groups involved in the Hood River hydrosocial territory face added challenges of urban development on irrigation district land beyond the Hood River city limits [Figure 1]. Thus, Hood River lies at the intersection of two hydrosocial problems: retreating glaciers caused by anthropogenic climate change and urbanization processes that threaten wetlands and alter the urban-rural relationship in the valley.

The Hood River Watershed Group emerged in the 1990s out of efforts of the local Soil and Water Conservation District and associated farmers, conservationists, and regulatory agencies to resolve the most pressing hydro-social problems in the area. As the state government established the Oregon Watershed Enhancement Board to fund local joint agricultural and conservation efforts, watershed councils formed around the state based on collaborative resource management strategies. The Watershed Group drew together stakeholders from agriculture to conservation and habitat restoration interests, developing a political strategy distinct from the Conservation District. The watershed group can, then, be seen as an effort to rescale resource management from federal agencies to local stakeholders. Yet tensions still exist among stakeholders over the prioritization of hazards and the potential to meet the increasing challenges.

Methodology

Study Design and Data Collection

Semi-structured interviews were conducted to understand the perception of risk and resilience by members of the watershed group. Examples of studies utilizing such methods include papers on farmer adaptations to water shortages in Kenya (Kulecho and Weatherhead 2006), perceptions of water quality among farmers in Jordan (Carr, Potter, and Nortcliff 2011), and responses to water shortage in Southern Spain (García-Vila et al. 2008). The semi-structured format helps maintain a standard interview guide, but affords the opportunity to ask questions that arise from the interview subject’s responses, as noted in other studies of risk perception (Ainuddin and Routray 2012; Bye and Lamvik 2007; Knudsen and Gron 2010). I also conducted participant observation, which offers a chance to engage in the reality of the observed phenomenon, for instance, attending and participating in meetings, visiting subjects on site, and going to functions (Bernard 2006).

Interviews included considerations about water use, water management, climate change, and urbanization. I included questions about Hood River's relationship with nearby Portland, Oregon, as well as their perceptions of contemporary changes, hazards, and threats. My research questions issued from an effort to discern the diffusion of different opinions on hazards pertaining to climate and development across scales, the efficaciousness of collaboration, different styles of integrated management, and varied perceptions of inter-subjective community-forming practices associated with water management. I sought, as well, to understand different stakeholders' understanding of the watershed group, itself, as well as its mission of social outreach and resilience to climate change. These questions helped me ascertain the way watershed group members and their immediate community understand their relationship to water and place in a changing, complex environment [Appendix B].

I conducted 42 separate interviews with 32 individuals associated with water use and management in the Hood River Valley. To recruit subjects, I used snowball sampling to attain the most representative total sample of interconnected social networks within discrete stakeholder groups (Noy 2008). I categorized the 32 subjects by ascertaining their closest association to water issues. While overlapping associations occurred, I designated six stakeholder groups: water managers, conservationists, tribal representatives, farmers, policy makers, and local business interests [Table 1].

To focus on collaborative exurban management, I interviewed stakeholders involved and invested in watershed management who may have had peripheral relationships with the Watershed Group but whose interests nevertheless impacted and were impacted by watershed management. To avoid a skewed sample, I made extra effort to interview subjects who are not merely frequent meeting attendees by locating businesses involved in watershed-based activity and reaching out to local water-policy makers. Interviews ranged from half an hour to two hours and were largely conducted at frequent meeting places and public places in Hood River, such as on-site in farms and in private residences, places of business, at the local library, and at local coffee shops.

Participant observation of eight monthly meetings and events from April 2019 to April 2020, during the planning of the Hood River Watershed Group's new Action Plan, supplemented the semi-structured interviews, providing richer background information on internal dynamics. My regular involvement in the group likely had little impact on their goals, since my behavior largely consisted of taking notes and carrying on cordial conversations. However, it did bring me a more robust understanding of the nuances of intentionality, ideology, and discursive strategies deployed in collaborative organizing.

Table 2: Characteristics of interview subjects grouped by stakeholder identity, gender, crossover membership with other stakeholder groups, and membership in the collaborative Watershed Group or the Hood River Forest Collaborative (StewCrew).

Stakeholder group	Interview Subject	Date of Interview	Followup Interview	M/F	Crossover Groups	Collab
Water Managers	Subject 2	7/2/2019	1/15/2020	F	Con	Y
	Subject 6	7/15/2019	1/15/2020	F	Con	Y
	Subject 7	7/17/2019		F	Con	Y
	Subject 8	7/17/2019	1/15/2020	M	Con/Grow	Y
	Subject 13	10/8/2019		M	Con/Grow	Y
	Subject 23	12/2/2019		F		Y
	Subject 31	2/20/2019		M		Y

	Subject 32	2/22/2019		M		Y
Conservationists	Subject 5	6/6/2019	1/15/2020	M	WM	Y
	Subject 12	9/17/2019	1/24/2020	M		N
	Subject 14	10/22/2019		M		N
	Subject 22	11/25/2019		M	WM	Y
	Subject 16	10/22/2019		M		Y
	Subject 17	10/23/2019		M		Y
	Subject 20	11/5/2019		M		N
	Subject 21	11/13/2019		M		Y
Local Business Interests	Subject 1	6/29/2019	1/15/2020	M	WM	Y
	Subject 11	9/17/2019	1/28/2020	F		N
	Subject 18	10/30/2019		M		N
	Subject 19	10/30/2019		M		N
	Subject 27	1/22/2020		M		N
	Subject 28	1/22/2020		M		N
	Subject 30	1/30/2020		M		N
Local Industry (Growers/Logging)	Subject 4	7/3/2019	1/27/2020	M	WM	Y
	Subject 15	10/22/2019		M	Con	Y
	Subject 24	12/6/2019		M	Con	Y
	Subject 25	1/22/2020		M		Y
	Subject 29	1/27/2020		M		Y
Tribal Representatives	Subject 3	7/3/2019	1/23/2020	M	Con/WM	Y
	Subject 26	1/22/2020		M	Con/WM	Y
Policy Makers	Subject 9	8/7/2019	2/4/2020	F	Con/WM	Y
	Subject 10	9/17/2019	1/29/2020	F	WM	N

Data Processing and Analysis

I used Trint to transcribe all interviews and deployed an inductive analysis to draw out leading themes and codes (Fletcher and Shaw 2011; Palys and Atchison 2012).

The software Atlas.ti was used for data processing, focused coding, memo-writing, and visualization (Basit 2003). This inductive approach means that the process of ascertaining the most important codes and their meanings relies on the raw data, rather than a preconfigured analytical framework, to understand ways identities are constituted and differentiated from one another (Thomas 2006).

It became particularly important to code for the importance of ideas such as resilience and collaboration among the interview subjects, as well as development and climate change [See Appendix A]. I created three code groups, including indicators for exurban development, hazards, and the Watershed Group. The hazard perception group included key issues like natural disasters, climate change, and concerns about glaciers, while the exurban development group included such frequently-discussed topics as amenities, planning, housing, and infrastructure. Lastly, the Watershed Group code group incorporated issues directly pertaining to the organization, inclusive of some of the codes belonging to the prior two categories, as well as separate codes pertaining to Watershed Group business and dynamics. The different understandings of situational shifts among the Hood River population was also approached in relation to the value placed on collaboration by different groups and stakeholders. To quantify the interests and priorities of different stakeholders, I used a weighted ranking system in which a subject's first hazard priority is considered 1 point and the second priority is considered 0.5 points. This system helped rank the concerns among different stakeholders, providing insight into the needs and demands that factor into the Watershed Group's decision-making process.

Understanding the Watershed Group

The Hood River Watershed Group functions as a facilitator of both community and resources within the community. Meetings offer an opportunity to see guest presentations by scientists from federal agencies and local consulting firms about relevant matters. Its capacity to connect scientists, regulatory agencies, and lay participants in the hydrosocial network makes the Watershed Group a “boundary organization” that can both integrate different scales and “jump scales” to work with other groups without having to subsume them under its umbrella (Guston 2001). In this way, federal and local scales intersect at the watershed, creating an important interface not only between urban and rural but between science and local water use.

Those involved in the group tended to appreciate the meeting process, governed by a double-consensus system where the totality of votes at two different meetings are required to approve any initiative, as a useful community-forming tool. One interview subject called it an “open forum”:

> “It's not just stuffy staff meetings, so to speak. You've got people coming in that are concerned citizens bringing their ideas, bringing their knowledge and then also participating... They're getting out, educating people and then also getting projects on the ground, leveraging a lot of the money that’s in the basin to apply for additional grant money. So they're bringing a lot of money into the basin and really facilitating a lot of these projects. So they've been real key in the basin and especially with some of the grants that they received.” (Interview 3, 28:01)

The description of the meeting space as free from stuffy staff meetings evokes an air of normalcy and friendliness confirmed by participant observation at meetings and events. The establishment of community around the coupled human-water system is, in turn, viewed as one of the major accomplishments of the group:

> “I think one of its biggest accomplishments and ongoing work is really getting a hold of these folks saying we’re not talking to each other, and getting to know

> each other as people and building that, therefore, building trust between those organizations where there obviously—certainly if we go through climate change, there's going to be more disagreements between some of these entities… And so you have a diagram where we can overlap and arc together and then start to diverge. But knowing folks as individuals working together on the parts you kind of work together on kind of helps you ride out some of the other stuff without it breaking the relationship" (Interview 9a, 17:22).

Hence, the Watershed Group formed a point of origin for my study, but not the entirety thereof. In short, the Watershed Group could be seen as the most important hub in the multi-scalar network that I studied, but not the only node in the broader "hydrosocial hinterland" (Cantor 2020).

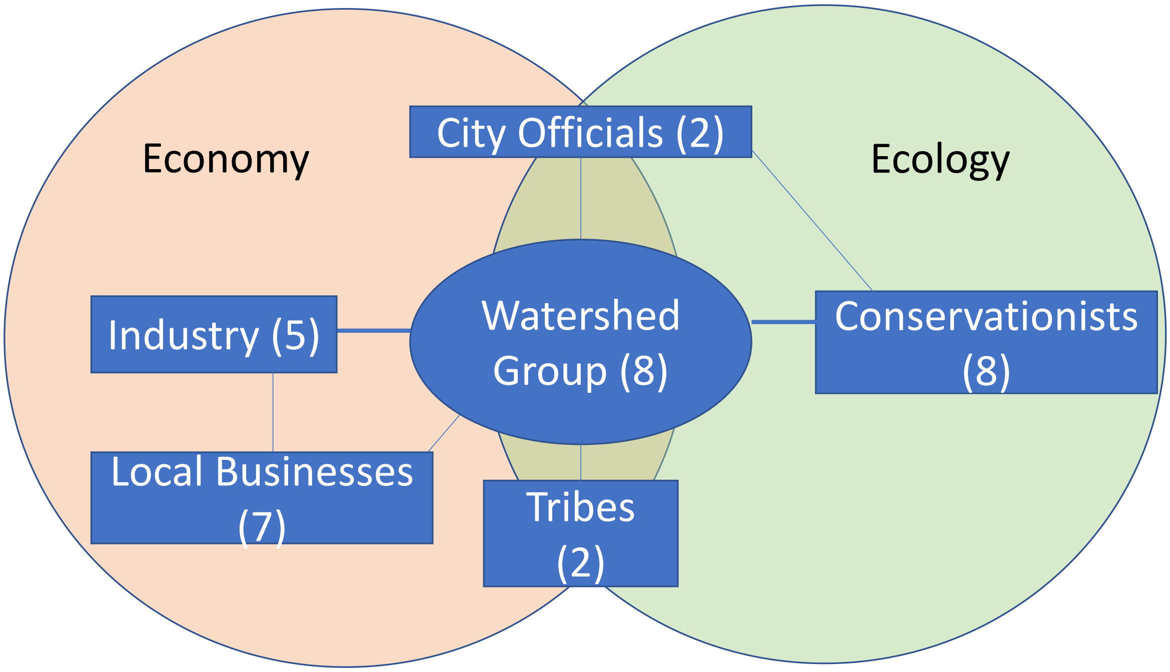


Figure 6: Diagram showing the connectivity of different stakeholders through the Hood River Watershed Group based on 32 interview subjects. Lines with more weight indicate larger member cross-over between sectors.

Primary Hazard Concern: Climate Change

Climate change was the most significant concern among all interview subjects [Figure 3]. However, development was also an important, if secondary, hazard. Studying the stakeholders' understanding of development and climate change together, then, illustrates how complex issues are approached in exurban places.

Interview subjects were nearly four-times more concerned about climate-related hazards than non-climate related hazards like housing or out-migration, although that may be partly due to the sample's focus on stakeholders directly focusing on ecological issues. At the same time, some of the climate focus overlaps with the issues of population and development, while most interview subjects commented on the problems of exurban tensions between urban and rural issues.

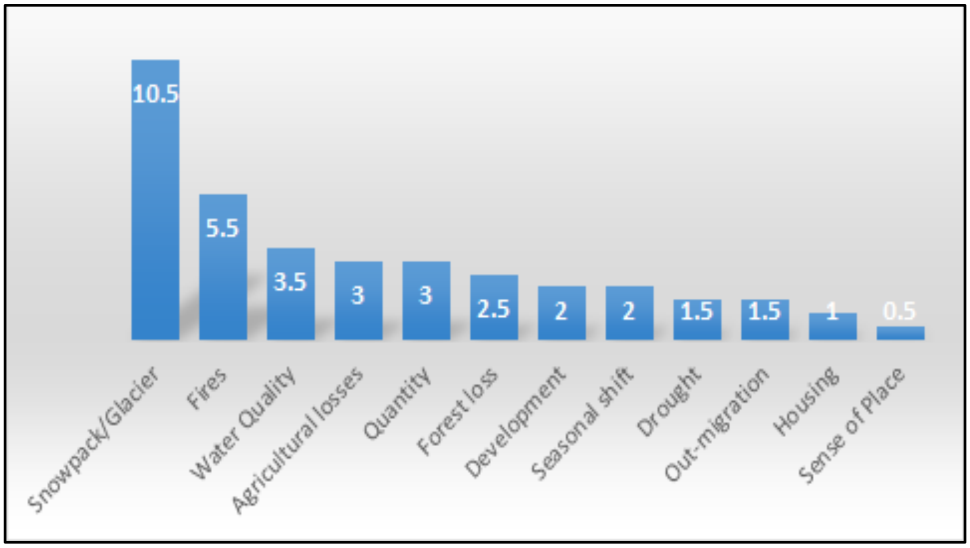


Figure 3: Hazard priorities according to interview subjects

Some interview subjects noted that climate change will produce unpredictable outcomes, but they agree that climate change will likely cause earlier peaks in the annual hydrograph, leading to longer summers and placing more of a burden on farmers during the later part of growing season. The loss of glaciers and snowpack would mean the loss of water storage for the summer, so the Irrigation Districts join together in the Watershed

Group to apply for grants to fund projects that will build more reservoirs and enhance existing ones (Bureau of Reclamation 2015).

Melting glaciers and snowpack concerned the highest number of interview subjects (37%), all of whom assessed that most residents of the valley recognize the priority of conserving water. Small businesses were most represented in concerns over forest fires, likely because they stand to lose the most in the event of a decline of tourism and recreation activities. Industry actors were the top group concerned with forest loss, as the timber companies have a vested interest in maintaining healthy stocks of forests for future harvests. Tribal stakeholders voiced the most concern over water quality, along with city officials, due to their interest in salmon habitat. While more subjects (5) viewed water quantity as a priority than did development (3), fewer prioritized it above all other issues, giving development a higher score.

While some offer a note of sadness at losing beautiful water features as a result of infrastructure, 73% of those concerned about vanishing snowpack and glaciers promoted piping irrigation ditches in order to reduce the amount of water lost to seepage or evaporation, as suggested by Watershed Group interest in preventing agricultural losses. Inclusive of those concerned about agricultural losses, instream water quantity, and seasonal climate shifts, some 59% of the concerned interview subjects recommended water infrastructure to conserve water. By working together to conserve water at the irrigation turnouts, farmers can satisfy the needs of the tribes and conservationists who want more in-stream flows to enhance habitat for salmonids. Infrastructure, then, promotes harmony and a shared sense of purpose within the group. Infrastructure projects can lead to social fragmentation and authoritarian polity (Brown 2013; Mullenite 2019), and when fragmentation does not occur as a result of rescaling power for infrastructure projects, the enfranchisement of variegated systems of privatization can still ensure that multinational actors exploit local populations' efforts (Bakker 2013; Norman and Bakker 2009). Yet in some cases, farming communities leverage state engagement to further mutually beneficial infrastructure projects without losing their autonomy in water management. (Fischer 2017). At the same time, such counter-hegemonic reversals, which in some cases appear post-neoliberal, can manifest "conservative tendencies beneath their communitarian discourse" (Perreault 2008). In the case of Hood River, "downscaled" water management has led to a set of common, integrated goals, if not a common sense of purpose, as it pertains to climate change.

Secondary Hazard Concern: Development

As well as issues related to water availability, quantity, and quality as they pertain to climate hazards in the Hood River basin, development presents clear problems for people connected to the Watershed Group. The building of subdivisions and new homes in the valley threatens important wetlands that maintain riparian habitat, while development outside of the city limits and low-income housing within the city are also perceived as infringing on irrigation districts and parks, respectively. Participants in the hydrosocial territory are, then, engaged not only in issues of irrigation and instream water but also exurban growth as well. Those hoping to develop in the city to fill housing demand meet resistance from conservationists, leading them to pursue development further up the valley where farmers and conservationists hope to maintain water access and wetlands. Whereas when confronting climate change, different stakeholders bring different opportunities for resilience to the table, the fractious complexity at the political intersection of land, water, and society renders collaboration more difficult when it comes to development.

To some, Hood River's growing population presents the need to develop residential buildings and subdivisions, which can create land use problems with regards to conservation of farmland and biodiversity—especially when occurring in the irrigation districts. Talking about dynamics within the City of Hood River, one interview subject spoke about a "divide, if you will, between the rich and the poor": "There's those people in this community with a lot of money they can afford to buy second homes and they do it. And the rents go up. And then there's all those folks who work in the service economy. Having to work two, sometimes three jobs and they can't afford a place to live" (Interview 19, 11:46). Here, housing scarcity fosters tension between stakeholders by constituting an economic axis that distinguishes rich from poor and forces new construction beyond the city limits.

This contrast between rich and poor is partially layered onto a spatial dimension determined by competing values between rural and urban residents. Since Hood River grew as a timber county, taxes from logging helped buoy the budget. However, as timber interests faded, property taxes remained relatively low, leading to budget shortfalls for services. Two bond measures that promised to raise property taxes in the county faced defeat at the hands of interests often perceived to be rural. "When I moved here, I thought for sure people would rather maybe support bond measures and stuff more," one interview subject told me. "It's a very rural [versus] urban thing" (Interview 6, 6:29). Not all opponents of affordable housing live in the more rural part of the valley, and vice-versa, but some of those who do tend to speak to values and interests associated with its rural constituents (e.g., preservation and tradition), thus drawing spatial and economic arrangements into a fractionally-aligned system.

While conservationists may work to protect riparian integrity in the valley and compensate for a lack of tax-born funding, some have also worked to block a local low-income housing development on the site of a local park, bringing the ire of younger interview subjects who cannot afford to live in Hood River. According to one interview subject, “The Morrison Park stuff is definitely a very interesting kind of partnership between the folks that are against government subsidy, affordable housing—that conservative / liberal thing—and very green liberals [who think] ‘Every tree is sacred and cutting down a tree to develop housing is bad’” (Interview 9, 32:38). Although conservationists seek to limit it, the lack of low-income housing may contribute to trends of development outside of the city on irrigation district land, impacting wetlands.

People displaced from the city might find cheaper land further up the valley, leading to the conversion of farmland and, in some cases, development on ecologically sensitive areas. Some developments carry forward on smaller swales or water features that go unnoticed until built over. “You know, there's not there's an awareness so that we don't get calls about, oh, well, another wetland,” another Watershed Group member explained. “You know, people are going, you know, this little swale or this wetland, they may or may not even know it. Probably don't even realize that it’s what they’re doing is, you know, filling a wetland, you know?” (Interview 7, 25:24). One interview subject noted the combination of a land squeeze and new developments:

> “I think the closer you get to town, there's definitely talk. There's a building pressures and any little orchard that's kind of still in town or right next to town is definitely under threat... In fact, there's a there's a new development going it potentially going in right down my street. And if it goes in as planned, it would totally change the nature of our little neighborhood into a 25 unit, a high-end housing place.” (Interview 6, 14:31).

In-migrants hope to buy farmland to build properties and develop hobby farms or smaller gardens, but find it difficult to locate an unprotected area. A Watershed Group member explained, “Land is hard to come by here that doesn't have like a wetland on it or a creek or something” (Interview 6, 24:06).

At the same time, pressure is building to keep farmland. As one long-time farmer put it, “They don’t make land anymore. And in my opinion, I really don’t want to lose good farming land… You can’t reclaim foundation, right?” (Interview 4, 14:29). Thus, concern over exurban development is closely intertwined with the perception of farmland as imperiled, which climate hazard perception heavily reinforces.

Table 3: Topics of contention over urbanization process (low-income housing) in Hood River

Aspect	**Actors**	**Position 1**	**Position 2**
Economic	Rich and Poor	Wealthy keep property values high	Poor seek place to live in Hood River
Cultural	Rural and Urban	Profitable farming becomes more difficult; strong traditional opposition to taxes	New taxes will bring new services and could free up budget for affordable housing
Ecological	Green liberals and Housing Advocates	New housing will destroy valuable parks and green spaces	Housing in the city might mean less commuting and traffic in city
Social	Residential water users and Irrigators	Expansion outside of the Urban Growth Boundary is necessary	Water provisions for residential areas could promote more development on farmland

Territorial	Farmland and Development	Farmland produces food for people, and development removes farmland	People want to live near farms that they view as panoramic and peaceful.

The economic aspect of agricultural precarity tied to a lack of low-income housing also involves farmworkers pushed further up the valley to find cheaper houses. One former farmworker told me, “I know it’s not just the Latino community, but in general. The society is becoming an artist town and there is a lot more people moving. And because of the cost of housing, it's increasing and low-income people as well as the Latino… We can’t afford to live in town. So a lot of these communities have been displaced from downtown” (Interview 12, 11:24). Amid the tense climate provided by the Trump Administration’s harsh immigration policies, unsettling the Latino community causes consternation among farmers. “Today, we're pretty dependent on the Hispanics,” one farmer told me. “If we don't have them, that that's almost like not having water or not having sun” (Interview 4a, 28:18). Thus, a feedback loop can emerge where rejection of taxes in rural areas and housing by conservationists backfires by pushing out farmworkers and poor people, causing development on wetlands and creating difficulties for orchards, thus driving an already complex multi-scalar system into further challenges.

The sense of scarcity of land and the impacts of development on water feeds into a felt frustration over unwanted transformation. “Ag is still a big thing,” one person who has lived in the area for decades told me. “But in terms of the town, the tourism, the recreation and the tourism that are associated with it have really overtaken it. And then in addition to that, as people move here, the prices have skyrocketed. And part of that is coupled with California… [A] small little house down there, that's worth a bundle and come up here and own a number of acres and a big old place, you know, and that, you know, I mean, that happens everywhere" (Interview 8, 22:11).

Most describe the City of Hood River as an evolving place as a result of in-migrants, as perceptions of farms blend into the panoramic scenery of tourism. The farmland may be appreciated, but as a novel driver of tourism rather than a world-class commercial producer of pears. "It's beautiful. It's stunning," one local resident told me. "And you get this sense, not only are there these natural areas that are all around us, but these orchards, this productive farmland, which has its own entity, is providing us not only with jobs and the money and revenue and all of that, but it's keeping families going and keeping communities alive at the same time… It's just this beautiful agricultural bounty that we have here." This subtle movement of farmland into a spectacle—a useful part of a romanticized, bucolic waterscape—boosts the value of properties in Hood River without contributing to agricultural production. Hence, the farms themselves engage with the networks comprising productivist and post-productivist economies. Yet residents are keenly aware that the intrinsic connection between the sense of place that drives exurban growth and Mt. Hood's dramatic glaciers and snowpack could cause cascading problems in terms of agricultural failure due to water shortages, a steep decline in the economic benefits of in-migration and tourism, and a movement out of the exurb.

Resilience and Transformation: Triangulating Hazard Management

The looming problem of climate change and the issues of development and conservation of farmland described above converge with stakeholders' perceptions of resilience to hazards. Stakeholders generally believe that their efforts to build storage and infrastructure will stave off the worst hazards of climate change and maintain the present course of agricultural production. However, the implications of climate change seem more difficult to solve when coupled with exurban development.

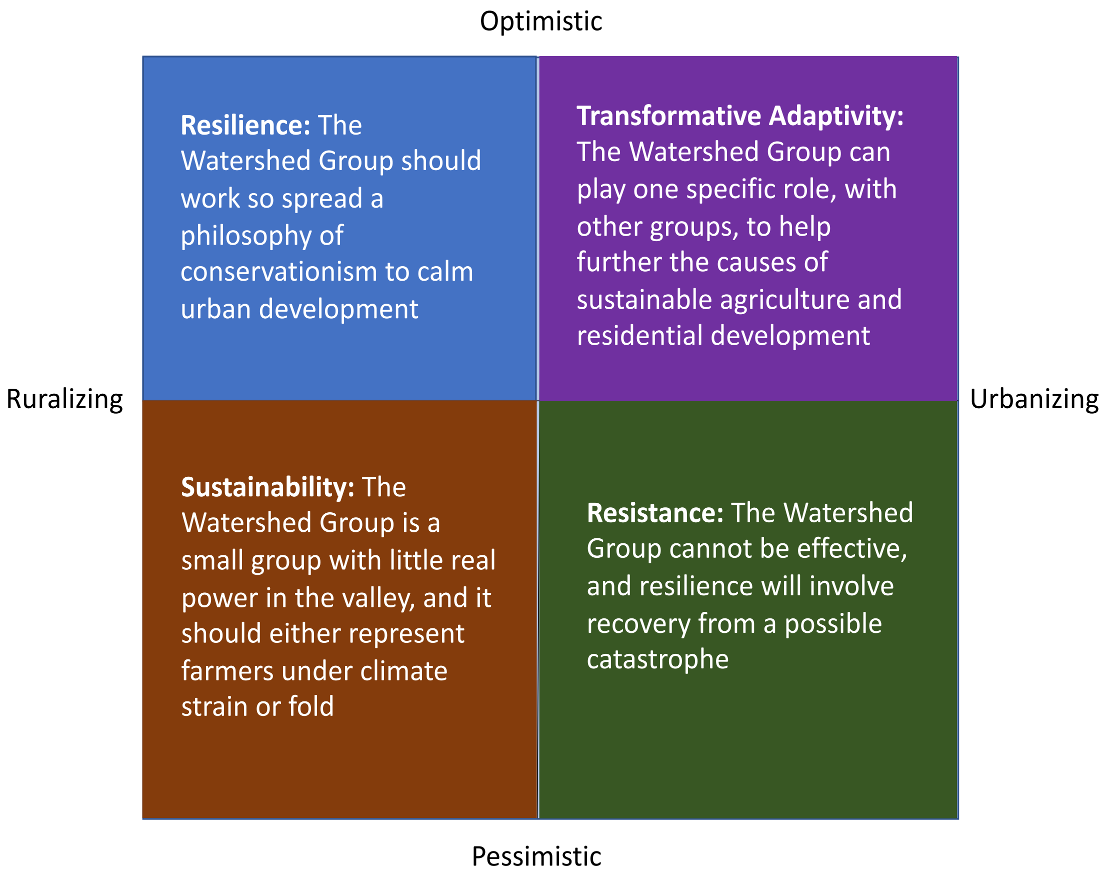
The question of community resilience for the watershed, then, remains one of triangulating the hazards of climate change with the interests of growth and development. I found a radical vision for transformative adaptation connects the waterscape of rural and urban development in the exurban area to other watersheds in the region. However, the potential for large-scale transformative multi-scalar networks goes largely unexplored, as groups still struggle for funding within their own local purviews. I noted four different understandings of transformativity relative to stakeholders' relationship to exurban development and the outside world: Resisters, System Sustainers, Bounce-Forwarders, and Bounce-Backers [Figure 4].

Resisters and Unwanted Transformation

The Watershed Group cannot do enough to stem the onslaught of climate change in the basin. This opinion sees ecological catastrophe as immanent, and views liberal efforts to conserve parks over low-cost housing as senseless in light of the massive potential impacts of climate change. However, it is not entirely defeatist in that it views the climate-caused catastrophe as an opportunity that might nourish deeper community bonds. This understanding most closely approximates "resistance" to the hazard, because it does not affirm a way of maintaining the system or adapting to prevent crisis.

Unwanted transformation indicates that resilience might be impossible, and that a system change may happen regardless of socio-cultural change in the area. With the decline of logging, the rise of recreation and tech, the subsequent increase in housing values, and the recession of glaciers and snowpack, a lingering doubt remains over the capacity to scale back ongoing changes perceived as negative by many long-time residents. One resident active in a collaborative group compared the situation to the eruption of Mt. St. Helens:

> "You saw what happened after St Helens. There was an incredible amount of resilience in those systems in the face of climate change... Maybe, you know, we might be a total regime shift, right? We might see an event that could actually result in, you know, us transitioning from sites dominated by particular species to having a totally new kind of set of conditions." (Interview 24, 6:54).



Resilience: The Watershed Group should work so spread a philosophy of conservationism to calm urban development

Transformative Adaptivity: The Watershed Group can play one specific role, with other groups, to help further the causes of sustainable agriculture and residential development

Sustainability: The Watershed Group is a small group with little real power in the valley, and it should either represent farmers under climate strain or fold

Resistance: The Watershed Group cannot be effective, and resilience will involve recovery from a possible catastrophe

Figure 4: Diagram showing different positions respective to urbanizing and ruralizing trends in accordance with their optimism or pessimism regarding climate change and residential development in Hood River.

According to this approach, transformativity comes from a traumatic event, and the Watershed Group cannot accomplish enough to stave it off. Belief in unwanted system change does not seem like the dominant mood, but it does issue from lingering concerns about the potential risk of farm loss and decline of recreation resulting from climate hazards.

One interview subject opined, however, that such an economic plight could help bring people together in the basin toward a sense of shared purpose. A transformation that the Watershed Group could help create might occur due to “some sort of reactionary thing where, you know, we have three years of bad drought in a row and nobody has any water and farms are going belly up and people aren’t coming to the area to recreate because there's no snow and things of that nature” (Interview 3, 26:21). In this sense, unwanted transformation could pave the way for an ensuing socio-political transformation. However, interview subjects remained divided on the kind of transformation they hoped to see.

System Sustainers

The Watershed Group should not endeavor to meddle in issues of development, and should remain concentrated on issues directly related to the watershed, say System Sustainers. This group does not view exurban development as positive, and does not support reaching out to attempt to make development more ecological. Instead, it seeks to stop development *and* short-term property rentals, while focusing matters of resilience on irrigation and biodiversity restoration. In this view, valley residents can maintain a traditional way of life, with political and economic power remaining in the agricultural areas.

Bounce-Backers: Resilience

Some who view negatively the current conditions of housing prices, traffic, and a shift of priority from the valley to the recreation industry in the city highlight the potential for a bounce-back to simpler times. The Watershed Group can work with locals to spread a philosophy of conservation of natural resources based on a simpler time in the past, say "Bounce-Backers" who hope for system-wide resilience. This group of people from different stakeholder groups wish that exurban development could be "done right," following ecological ways of growing the area for future generations without changing the lifeways and character of the area.

One interview subject put their objection to transformations caused by the recreation industry in philosophical terms:

> "My issue with the whole recreation side of things is the idea that, 'OK, we don't want to destroy and take and, you know, rip up and get the natural resources or whatever, but we want to take the beauty of it and the ability to interact with it and monetize it'. Or the [idea that] 'This is worth saving, because it's valuable to me to be able to walk around or ride my bike in it or swim in it or whatever.' […] So I feel like, reaching out, I would like to help imbue, just through my own philosophy and attitude about things, the attitude that things are important just because they are, and because they're part of nature and not because of our interaction with them" (Interview 8a, 46:39).

This interview subject seemed to hope that broader political change could occur within the valley to bring civil discourse away from economic and proprietary gain and toward a more rustic vision of the way things were and how to protect them. However, the subject voiced concern about political change and the potential for divisiveness: “I worry about turning it into a similar to political sort of involvement stage, you know, where it's like, OK, you say one thing wrong or you say this and you get pounded, you know, because you spoke out of turn or you said something off the cuff that was not quite correct, whether it be politically correct or factually correct” (Interview 8a, 48:33).

This desire for a return to past, simpler ways of life, and an appreciation for nature in-and-for itself, can adapt to a number of political positions in the area. For instance, the rejection of building new low-income housing in parks or beyond the city limits might fall under the rubric of environmental conservation and reduction of issues associated with urbanization (Cantor 2020). In this sense, bouncing back does not challenge socio-economic norms or political power structures. Instead, it seeks to expand the existing norms of conservation to the developing areas.

“Bounce Forwarders”: Adaptive Transformation

The effect of different discursively-produced political identities on climate risk perceptions and water governance preferences indicate some constitutive ideas and concepts. Indeed, while their different ideas contribute to some creative tension within the Watershed Group, their independence also brings the group its richness and capacity for negotiation, collaboration, and productivity. In this sense, collaborative management is developed through ongoing discussions about larger-picture strategy amid a practical movement toward accomplishing shared goals.

The Watershed Group can help facilitate ongoing transformation in the area by advocating for ecologically-minded development, “bounce-forwarders” proclaim. This group, most closely identifiable as oriented toward adaptive transformation, hope to see the area rejuvenated by development for lower-income people, as well as ecological conservation, and adaptive measures to ensure the continued productivity of agriculture. This alternative form of transformation, which would encourage “moving forward” through the present changes, involves building more housing, infrastructure, and transit to-and-from Portland in order to bring down the cost of living and make more people’s lives easier. Some argue, for instance, that residential developments would consume less water than irrigated farmland, making carefully planned expansion a potential conservation measure that could lower the cost of living and make the exurban community more accessible.

While this approach may irk some stakeholders, there is a prevalent sense that development is inevitable at the same time, hoping to influence its progress rather than attempt to prevent it. Outreach on this level would include fostering broader community with businesses in the city in order to connect people on a watershed scale that bridges the urban-rural gap. The draw-back to such endeavors appears to many the lack of resources to carry the project. “It's a ‘Catch 22’ situation,” one conservationist noted. “I think one potential result of getting more people and more businesses involved is getting a bigger budget, getting people to contribute money. But it's hard to go out and do that if you don't have the resources to do that” (Interview 5, 16:28). So, while adaptive transformation would shift some of the balance of power in the area to the urbanizing areas, it is more difficult, because of problems of resource allocation.

It is difficult to gauge which vision is the most prevalent, because most stakeholders recognized the different possibilities and did not necessarily favor one or the other, although the more pessimistic idea of unwanted transition is less popular. At a meeting I attended, some disagreement emerged over plans for outreach, with some expressing feelings about the need for the Watershed Group to remain focused on the needs of water providers in the valley rather than consumers in the city. “I just think it's hard to have the bandwidth to do everything,” a Watershed Group member told me in an interview held afterwards. “And so I think what it's going to be is maybe connecting with some of the groups that are already working downtown, because you can’t have it all (Interview 6, 27:52). In this vision of transformation, the Watershed Group members “jump scales,” shifting from watershed scale to occupying rural and/or urban roles and back in order to cover different sides of the problems without making the Watershed Group, itself, into an organization that confronts all of the hazards as a totality (Bulkeley 2005; Cox 1998).

Connecting Climate to Development in Adaptive Exurban Transformation

The visions of transformation promoted by different hydrosocial stakeholders at varying times point to tensions between ideas rather than specific stakeholders or groups. The leading concern among stakeholders is the decline of glaciers and snowpack levels for varying reasons, and their different perspectives render collaboration easier. At the same time, stakeholders are also concerned about exurban development, but their different perspectives render collaboration more difficult. All stakeholders hope to participate in establishing the watershed as vital to the sense of place in the area, with some viewing the growth of tourism as inimical to the authenticity of that experience. At the same time, the interviewed recreation industry representatives held the Watershed

Group’s efforts in high esteem and expressed a willingness to engage with their outreach efforts. There appears, then, an opportunity to increase efforts by the Watershed Group to establish broader connections to the more urban stakeholders in order to improve the experience of a sense of place connected to a shared vision of collective transformation.

To consider how the stakeholders can combat climate change more broadly, some contemplate linking together different watershed councils in a kind of federated approach to water management on a bioregional scale to overcome the perceived failure of federal environmental policy and the limitations of watershed-based localism (Interview 24, 09:28). “Currently, I mean, we have environmental groups that are tackling really important issues, but nobody is working on the [bigger] issues like what is the future of that private industrial forest land and how are we going to hold it?” one Watershed Group member explained. “It’s a pretty small base, relatively speaking. It's really diverse and really cool. There's a lot smart people here, like there's a potential to make this a model of resilience for the Gorge and probably for the country. But solving that part of the problem is a huge piece of this that I don't feel like anybody is really solving” (Interview 24, 39:33). A broader, interconnected approach to a self-managed and decentralized climate policy would manifest many key traits of complex adaptive systems in hydrosocial territories, rescaling power from top-down hierarchies to collaborative management practices involving multiple stakeholders with different interests (Gray 2007; McGinnis, Woolley, and Gamman 1999).

At the same time, exurban development remains controversial. Most see the current situation as an urbanizing transformation that lacks real controls. Norms are changing such that the trusted and traditional ways of land use regulation can impugn development, while newer systems of tourism can infringe on the older, agrarian interests. Yet some insist that the two can complement one another, as with the agricultural “fruit loop” tourism circuit (Interview 10, 20:41). Still, some view “new-comers” as dismissive of agricultural investment in the community and understand the Watershed Group a part of the rural side in the perceived rural-urban division (Interview 15, 3:16).

Development, tourism, and the amenity economy are largely felt as contributing much-needed capital to the economy, but as secondary to the agricultural contributions. The advance of climate change augurs a situation wherein different adaptations might ultimately lead to trouble for some regional actors, and tensions arise as to who will feel the brunt of it. “There has to be winners and losers,” one interview subject told me. “I mean, you know, it is really hard. I mean, we’ve got to come up with a thing that sort of moves this along in a moderate way that everyone can kind of live with” (Interview 8, 25:04).

While it is clear that most stakeholders view the receding glaciers as the leading hazard, the four contending ways of pursuing that mission remain contentious. Those who view mitigation as partially effective at best do not have a diminished view of the hazards. To the contrary, they view the hazards as overwhelming, requiring an approach that connects to other groups outside of the Watershed Group’s purview—hence, their frustration. At the same time, those who seek to “bounce back” to a more bucolic way of life in which the new-comers abide by a pace of development set by stringent land rules and a deliberate conservationist agenda remain somewhat more optimistic about the Watershed Group’s ability to leverage the political balance of power. Lastly, those who hope to “bounce forward” are more connected to the metro area and do not necessarily view the Watershed Group as capable of extending itself to a holistic solution on a watershed scale that bridges city and valley, seeking perhaps to shift the balance of power.

As with other exurban areas, questions of landscape in Hood River traverse different interests resolved through actors and actor groups to oppose those of perceived competitors (Cook, Hall, and Larson 2012). Issues of multi-scalar landscapes and waterscapes are broached by non-linear processes of community mediation as represented by the Watershed Group (Hartman and De Roo 2013). In this respect, the Watershed Group presents different approaches to transformative adaptation, where a more-pessimistic form of *resistance* manifests in the notion of post-catastrophe return, while *resilient* thinkers hope to reset an already-transforming system to an older time that might have better communitarian systems in place to meet future challenges, and those looking to a *transformative* approach conceive of adapting to present transformations while implementing measures that would make current dynamics more amenable to change and ready for future hazards (Matyas and Pelling 2015; O’Brien 2011). These approaches do not negate the practical processes of the Watershed Group but are alive as part of the developing expression of nonlinear hydrosocial management—a facilitator rather than an authority in the traditional sense of water management regimes (Lansing 2003).

Conclusion: Exurban Collaboration in Hydrosocial Systems

This study shows that the politics of exurban waterscapes involve a continued negotiation of multi-scalar hydrosocial territories to address leading problems.

Collaborative watershed management in exurban areas will continue to act as a kind of facilitator of different stakeholders in the public interest, but the question of dissensus regarding long-term goals should not be neglected in light of present strategies, as the two are closely intertwined. It will be vital for collaborative groups to continue to foster interesting dialogue regarding stakeholder interests across multiple scales remains an important aspect of the art of compromise.

While most of the literature on exurban areas focuses on divisions and conflict, this study shows that collaboration can successfully knit stakeholder interests into practical advances. At the same time, the distance from traditional water management renders collaborative organizations susceptible to critique. Projects typically succeed when they fall into line with the organizational protocols and goals of large donors, which often include federal and state agencies. Hence, groups that form a channel through which funding can be administered to projects determined necessary by the whole group may simply manifest an effective scalar modulation of larger state authority. While this is successful on the one hand, it does not necessarily challenge more overarching systems of authority and power (Swyngedouw 2000; 2004).

However, this exurban case indicates the extent to which policymakers who hope to improve residential capacity through urbanizing processes are beholden to countervailing hegemony. Perhaps this tension could be ameliorated with increased outreach to rural areas. Similarly, by reaching out to local social groups, businesses, and policymakers in exurban areas, hydrosocial management could promote a form of growth that encourages respect for agriculture as well as equitable conditions for all residents in an exurb. At the same time, exurban collaborative management can continue to pursue its current course of improving irrigation infrastructure, but necessary efforts to address the hazards of climate change in a deeper way will require more participation of not just irrigation district representatives but farmers, themselves.

Along with its unifying goals, collaborative management meets some tension in efforts to formulate a shared vision of exurban transformation. The competing trends of urbanization and ruralization that inhabit exurban hydrosocial territories are thus involved in a contentious multi-scalar interplay that will continue to define developments as the region meets the future challenges of climate change. At the same time, the Hood River Watershed Group and groups like it can play an important role in addressing the hazards presented by anthropogenic climate change and uneven development by bringing together communities based both on consensus and dissensus.

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Chapter 3: Exploring Irrigators' Resilience to Climate Change in a Glacier-Influenced Watershed using System Dynamics

Alexander Reid Ross and Heejun Chang

Abstract: This paper uses a System Dynamics model to create a "stylized" understanding of a watershed-dependent socio-hydrological system. Climate scenarios are used to grasp the impacts of different climatological forcing on downstream agricultural systems, along with glaciers on which they depend. Adaptive measures are incorporated, including a water bank and infrastructure improvements. A drought scenario includes an iterative balancing system to test how farmers can respond to low-flow years by maintaining instream flows for endangered fish habitat while minimizing losses to irrigation water. This research finds that resilience to climate change in a socio-hydrological place may indeed prove feasible, using a multi-tiered approach that resolves problems of irrigation loss and incorporates conservation methods. Without those methods, however, this model indicates that collaboration between interests seeking irrigation water use and those seeking to maintain instream flows will ultimately become impossible. As a socio-hydrologic model, this effort emphasizes the coevolution of socio-hydrological systems, showing how feedback cycles involved in testing adaptive capacity to climate change can improve community resilience and advance cooperative, integrated water management.

Introduction

Adapting human systems to the crises of climate change today is a top priority for people around the world. Whether in terms of human rights, national security, or biodiversity, the task of confronting the hazards caused by climate change manifest a shared global challenge (Busby 2008; Driscoll et al. 2012; Levy and Patz 2015). To address these pressing issues, scholars increasingly group human-natural systems in coupled studies (Liu et al. 2007). They comprise a large body of research from understanding ancient socio-ecological systems to gaining new perspectives on how they can adapt to future scenarios (Cote and Nightingale 2011; Leeuw and Redman 2002; Longo et al. 2016). As water issues involve some of the most urgent of the hazards portended by climate change, socio-hydrology is fast becoming one of the most important avenues in this tendency of scientific study for the future of humanity (Pande and Sivapalan 2017; Sivapalan, Savenije, and Blöschl 2012).

Socio-hydrology includes three main branches: process, historical, and comparative (Sivapalan, Savenije, and Blöschl 2012). More studies focus on process socio-hydrology, working to understand the functioning of contemporary systems and how they might change over time. Yet research in historical and comparative socio-hydrology manifest important contributions to the apprehension of the co-evolution of human-water systems and the differences between them. Practical applications in process socio-hydrology are the most prolific, likely because they stand to most directly impact policy approaches to systems facing current stressors or hazards. The present study is part of this growing literature locating specific sites facing major threats and developing methods of improving their adaptive capacity.

Located in the transition zone between the high, desert plateau of Eastern Oregon and the orographically-inclined temperate rainforest of the Western Cascades, Hood River faces an uncertain future of climate impacts. To further understand and articulate the processes and probable outcomes of hydro-climatic changes in the basin, as well as their concomitant effects on local agricultural producers, we created a System Dynamics model (SDM) of crucial aspects of the socio-hydrological system as it pertains to irrigation. Gaging alternative future scenarios helps deepen our understanding of potential capacity of local residents to adapt to those circumstances, while gaining a sense of which adaptations might have the best impact on the coupled system, itself.

Literature Review

Socio-hydrology often involves the utilization of different kinds of models for understanding and projecting the evolving nature of the coupled human and water systems at a longer time scale rather than simulating a snapshot of the future (Srinivasan et al. 2017). These models, while imperfect, can offer holistic insight into the functions of system dynamics as humans make their footprint on their environment and vice-versa (Troy, Pavao-Zuckerman, and Evans 2015). Socio-hydrologists use statistical methods and SDMs, in particular, to understand the impacts of different scenarios and adaptive policy changes in human-water systems.

In their study, Tian et al. (2019) use a statistical analysis to assess patterns of asymmetric water consumption during dry periods, discerning an “upward spiral” of human water consumption that a “new vision for water resources planning” could ameliorate. Studies using SDMs include the reuse of urban wastewater for irrigation in South Korea (Jeong and Adamowski 2016), the comprehension of population rise and water resource demands in Ghana (Kotir et al. 2016), and glacial contributions to an agricultural basins Iran (Ghashghaei, Bagheri, and Morid 2013). Other SDMs creatively engage with mutualist approaches to agricultural systems (Turner, Tidwell, et al. 2016), power generation (Feng et al. 2016), socio-economic development (Song et al. 2018), and saltwater intrusion (Lauriola et al. 2017).

No studies in socio-hydrology yet model glacial influence on irrigation systems in light of climate scenarios using SDMs. While Kotir et al. (2016)'s study illustrates the influence of climatological systems on variability in water availability for industry, it does not include a cryospheric component or a basin-scale analysis. On the other hand, while the important research by Ghashghaei, Bagheri, and Morid (2013) does include cryospheric modeling on the basin scale, it lacks an integrated agricultural component. Similarly, Jeong and Adamowski (2016) combine a mechanistic physical model with human behavioral elements like land use change, but their model describes an urban geography distinct from the questions of instream flows and canal losses that concern irrigation districts. Some studies do research cryospheric influence in irrigation systems (Carey et al. 2017; Nüsser, Schmidt, and Dame 2012), but not with SDMs. Thus, the present article, using an SDM to analyze the functioning of irrigation systems located in a glacially-influenced watershed threatened by the impacts of climate change, is a novel contribution to the literature.

SDMs are among the most frequently used in socio-hydrology, along with agent-based models, because they articulate feedbacks within coupled systems that exhibit "big problems" of human-water coevolution (Sivapalan 2015). More specifically, SDMs can provide heuristic pedagogical tools to show how human behavior can and will impact the development of water systems, and how variability functions within a temporally-specified system (Schlüter et al. 2012; Sivapalan 2015). As well, SDMs can offer long-term path analyses that avoid the mistakes and "back-firing" feedback of short-term planning (Turner, Menendez, et al. 2016).

Developed by MIT scientist Jay W. Forrester in the 1950s and subsequently taken up by General Electric and ensuing fields like industry, military strategy, agriculture, biology, and ecology, SDMs use diagrams based on inter-connected differential equations to exhibit the internal functions of a complex system expressed both graphically and quantitatively (Gustafsson 2017). Described as stock-and-flow systems or causal feedback loops, SDMs can represent essential relationships as they change over time based on alterations or perturbations at different points. Hence, uncertainty can be incorporated within non-linear systems to produce a general model that examines how human interactions with environmental change can determine future conditions (Barlas 2009).

At the same time, Sivapalan (2015) notes that such models come with important qualifications: "The conceptualization, quantification and measurement of all variables, especially social variables, suffer from scale issues, a result of discrepancies between the scales at which they may be measured and the scales at which they are modeled". Modelers often have to make important tradeoffs between precision, generality, and realism in defining the spatio-temporal boundaries of a system and its intended effects (Troy, Pavao-Zuckerman, and Evans 2015). To negotiate uncertainty in physical models while articulating more nuance than a conceptual model, Srinivasan (2015) offers a "stylized model" as a "simplified representation of the real world that aims to replicate the essential dynamics observed in one or more study sites, but does not attempt to calibrate and validate every variable."

As “promising explorative tools that can help explore socio-hydrological dynamics and contribute to theory development,” stylized models have been used to examine feedback systems in flood risk (Ciullo et al. 2017; Di Baldassarre et al. 2015), conceptualize the dynamics of ancient systems (Kuil et al. 2016), and model the potential effects of climate extremes like droughts (Di Baldassarre et al. 2017). Stylized SDMs, like the present effort, can then work under the assumption that while some of the variables may not be immediately verifiable, the trends modeled do present a heuristic, exploratory opportunity. If stylized models do not validate important variables, however, they are not useful, and this study recognizes those limitations by ensuring the necessary steps to validate all critical variables.

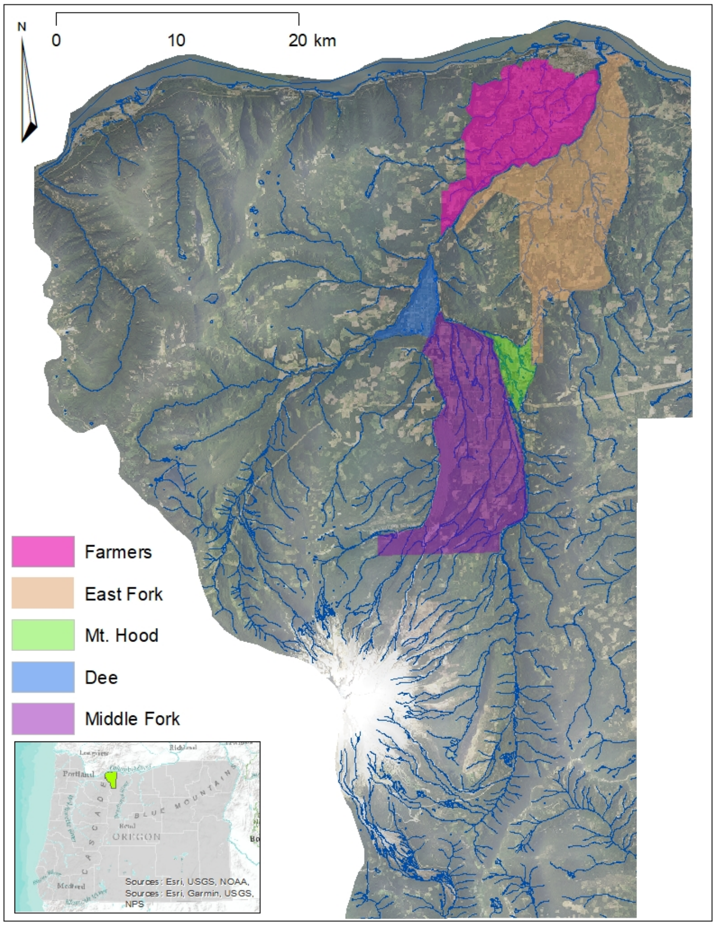

Figure 7: Irrigation districts distributed through the Hood River Valley

Site Selection

Located in the Columbia River Gorge that cuts through the Cascade Range on the Oregon border with Washington, Hood River relies on discharge from glaciers and snowpack for late-summer flows that nourish once-flourishing salmon runs and provide valuable water to farmers during the crucial months of the growing season. About 1,248 km^2, the Hood River basin incorporates five irrigation districts [Figure 1], producing close to $100 million in commodity sales annually. However, observations record the glaciers are receding, while median snowpack levels reflect earlier peaks and sharper declines (Bureau of Reclamation 2015; Fortner et al. 2009; Frans et al. 2016; Jackson and Fountain 2007; Nolin et al. 2010). For farmers, this means losing water during an important time and potentially having to switch orchards to vineyards or other less water-intensive products.

For local Native American tribes, the loss of streamflow could mean the complete collapse of already-teetering salmonid runs, leading to cultural and economic impoverishment. Because of its unique place in the middle of the Cascades range, the western part of Hood River feels the orographic effects of the mountains' "rain shadow" more than the eastern part, which is generally drier. This unique geographical feature makes Hood River vital habitat for four threatened fish species considered threatened in terms of the Endangered Species Act (Bureau of Reclamation 2015; Salminen et al. 2016). These steelhead, bull trout, cutthroat trout, and spring Chinook require higher flows to ensure cooler water temperatures in order to swim up the Hood River and find spawning grounds. Since native people rely on the salmon for their livelihood and maintain water rights for in-stream flows to continue their traditional practices, water quantity becomes not just a moral issue but a potential legal quagmire (Galbreath et al. 2014). For local businesses that rely on recreation both in the form of farm tours and hiking around the glaciers, as well as some white-water kayaking, climate change will also present major problems.

Other studies have been conducted to examine the retreat of glacial mass balance on the mountain (Fortner et al. 2009; Jackson and Fountain 2007), as well as glacial contribution, and potential loss thereof, to the Hood River (Nolin et al. 2010). Indeed, such studies have contributed to a larger field of research on glacial vulnerability in the

Pacific Northwest and broader U.S. (Frans et al. 2018; McCabe and Fountain 2013). However, studies regarding the potential impacts of retreating glaciers on the human systems that rely on them in the Mount Hood area have not been published outside of local reports.

Methods

Data Acquisition

Hood River is one of the most instrumented streams in the U.S. As a result of the Hood River Watershed Group's efforts, as well, there have been several studies of water quantity and availability conducted in the area (Bureau of Reclamation 2015; Christensen and Salminen 2013; Salminen et al. 2016). These studies and data installations proved instrumental in specifying a "stylized" SDM to assess irrigation systems' adaptive capacity to climate change in Hood River [Table 1]. Using a "stylized" approach enables an overview of a larger system involving multifarious nodes with built-in algorithms to allow for uncertainty and sensitivity analysis.

Table 4: Data sources for SDM.

Variable	Data source	Dates used
Streamflow	USGS Tucker Bridge (14120000), Middle Fork above West Fork, East Fork above Main Stem, West Fork near Dee	1979-2005
Precipitation (Rain/Snowfall)	CMIP5/MACA simulated historical data, Climate Mapper Tool; GridMET	1979-2005

	(45.3965N, -121.6894E) observed historical data	
Glacial discharge / ddf	Nolin et al. 2010	2010
Snowpack	Government Camp GVT60	2020
Irrigation withdrawals	Christensen and Salminen 2013	2013
Temperature	CMIP5/MACA simulated historical data, GridMET observed	1979-2005
Infiltration	Tang 1996; Suecker et al. 2000; Stähli et al. 2004	1996-2004
Irrigation losses	Interviews with water managers, Christensen and Salminen 2013	2013, 2020
Climate change scenarios	CMIP5/MACA toolkit.climate.gov	2020
Potential Evapotranspiration	CMIP5/MACA simulated historical data, GridMET observed	1979-2005

Observed precipitation, temperature, potential evapotranspiration, and mean monthly temperatures data were generated from daily data gathered from the GridMET point (45.2965N, -121.6894E), located in the seasonally recurring snowpack near the Coe and Eliot glaciers that feed into the Middle Fork Hood River. GridMET provides a basin-wide, elevation-corrected climate grid for the study area at a 4km^2 scale. These observed historical temperatures and precipitation from 1950-2005 were used to calibrate the model, along with average monthly snowfall estimates provided by the weather station at Ski Bowl Summit (GVT60). Simulated historical conditions were generated using CMIP5 models to create a Base scenario. I relied on CMIP5's 2050 and 2080 scenarios under the RCP 4.5 conditions and RCP 8.5 conditions, representing reduced carbon emissions in the former case, and continued emissions in the latter, for calibration and scenario analysis, while reducing snowfall by an estimated 20% during the RCP8.5

condition in accordance with the simulated drop in precipitation. CMIP projections were obtained using simulated daily data from MACA version2 METdata and bcc-csm1-1, which uses the r1i1p1 ensemble, available through the NW Climate Toolbox (Hegewisch et al. n.d.).

Streamflow data were coupled with data on irrigation withdrawals at different points to measure the impacts of agriculture on streamflow (Christensen and Salminen 2013). I used a three-tiered conceptual model [Figure 2] to show feedbacks between irrigation districts and streamflow in my model. While the schematic shows in detail the specificity of the irrigation system, to avoid over-complicating my model, I simplified my model's representation of the system by only showing the diversions that comprise the majority of the district (e.g., although the Middle Fork Irrigation District maintains water rights for some streams that flow from the East Fork, they only amount to 17 cfs, so they were not factored in).

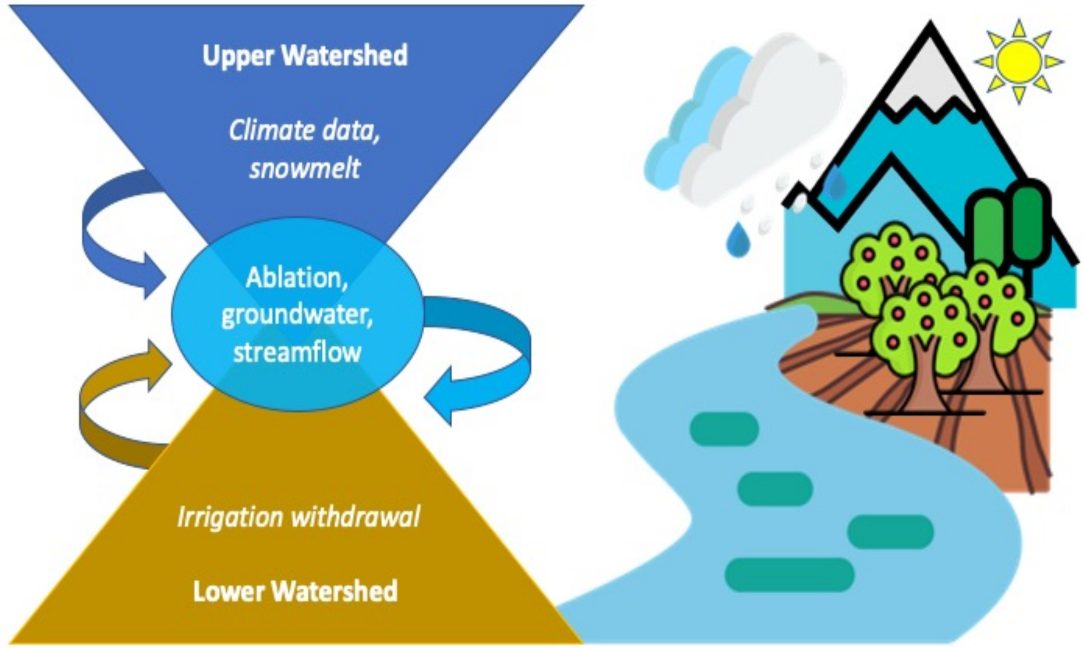

Figure 8: Conceptual, three-tiered model of the system dynamics of the Hood River watershed

Because the model utilized a monthly time step in order to understand nuanced changes on an inter-decadal scale, the results can be generalized in accordance with a stylized model. Not all parameters are validated—for instance, groundwater was not validated because groundwater data are sparse and groundwater modeling is not the main goal of this model. Capable of telling an alternative story about what happens in the basin given different climate scenarios, this model is also used to explaining why, what changes might occur to meet the demands of those new challenges, and what the results of those changes might be.

Model Construction and Parameterization

The SDM of the Hood River was divided into three sections (and one subsection) to fully explicate how the parts intersect. The first section comprises the climate, including the primary model drivers—snow and temperature—and their impacts on the snowpack and snowmelt. The second section involves the effects of precipitation, glacial melt and groundwater flows on upper-basin streamflow. As a subsection between the first and second section, a glacial ablation model was included. Lastly, the model uses real irrigation withdrawal data in order to ascertain, finally, the downstream flows of the mainstem through the city and into the Columbia. By experimenting with different irrigation water withdrawals under different “water bank” scenarios, as well as irrigation infrastructure upgrades, we can see the feedback within a human-water systems and model the outcomes of agricultural changes on streamflow.

The first section of the model includes average monthly snow and rainfall (“seasonal variability” and “snow” parameters), as well as empirical monthly average temperatures, as Lookup Tables. Lookup Tables bring an internal validity to the model logic, insofar as they represent actual diurnal variability without inference or interpolation. However, a simple parabolic wave lacks the exactitude of the actual monthly measurements provided by Lookup Tables. A degree day-factor equation following Nolin et al. (2010) (4.4 mm per degree Celsius over zero per day) was then used to track the extent of melt from the snowpack. [Figure 3].

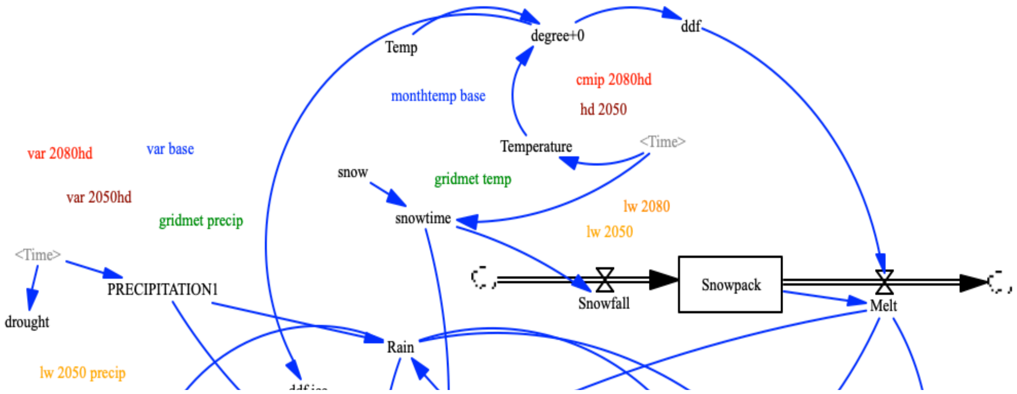

Figure 3: Top third of the SDM showing different scenario sets of “lw” (Less Warm, RCP4.5), hd (Hot/Dry, RCP 8.4), and GridMET (simulated observed data)

The second part of the model, which includes upland flows, adds the hydro part to the hydro-climate SDM. As the melt flows from the snowpack, it is multiplied by the area of the sub-basin and the percentage of snowpack in the sub-basin by area. Thus, the linear measurement of snowmelt (i.e., the length of estimated water content of snow in millimeters over an area) is transferred into a cubic measurement of water volume. A similar function is applied to the rain that flows into the watershed, with some losses to percolation in the groundwater estimated in correspondence with other studies about runoff and infiltration in similar coniferous forests and alpine and sub-alpine watersheds in Guangzhou, China (Tang 1996), the Colorado Rockies (Suecker et al. 2000), and Southern Switzerland (Stähli et al. 2004) [Figure 4].

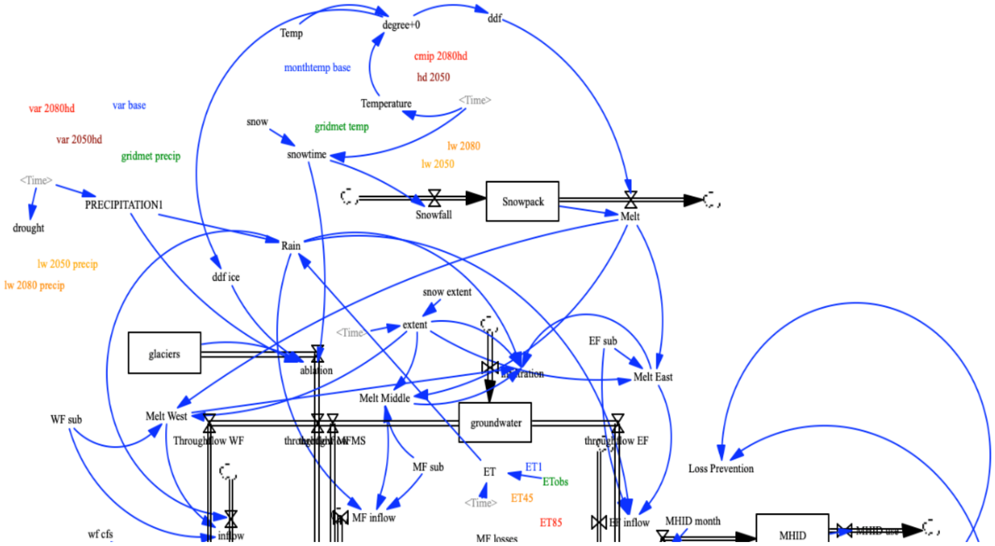

Figure 4: Middle portion showing glacial discharge, evapotranspiration (ET) under different scenarios (base, observed, RCP4.5 and RCP8.5) and groundwater infiltration.

The glacial modeling relies on a similar degree-day factor equation as the snowpack equation (7.1 mm per degree over 0 per day), multiplied by the glaciated area of the relevant sub-basins as described by Nolin et al. (2010). A feedback loop exists as well between the glaciers and the ablation rate, derived from an earlier study that found glacier discharge drops in an approximately 1:0.9 ratio with glacier retreat. Hence, as the glaciers decline, so does their contribution to runoff (Nolin et al. 2010) [Figure 5].

A groundwater stock is also added as a conceptualization of the volume of water stored under the surface. The groundwater comprises infiltration from percolation of snowmelt, as well as rain across the span of the sub-basins. Water then moves from the groundwater stock into the streams via throughflow, becoming the baseflow for each tributary, as well as the mainstem, itself. The amount of throughflow was determined by examining observed streamflow data contributed by local consultants. Since the flow meters at Tucker Bridge, West Fork near Dee, and East Fork above the Mainstem provide the best locations for identifying flow levels on the sub-watershed scale, they were used to estimate the throughflow. The average annual nadir of streamflow during the dry season, at which point no rain or snow could have influenced the streamflow, was located and used to approximate throughflow (Bureau of Reclamation 2015). As well, an evapotranspiration variable is developed using simulated scenarios from MACA to modify rainfall.

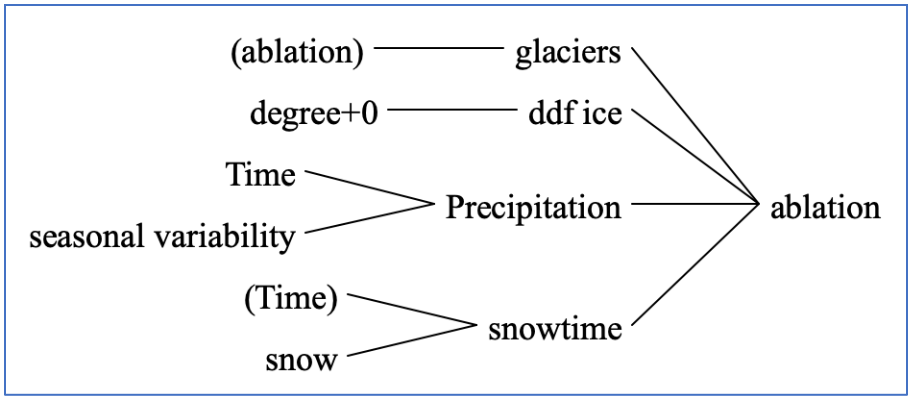

Figure 5: Causes tree for glacial ablation showing feedback. DDF Ice indicates the degree-day factor at which ice melts per degree above zero Celsius per day

The final segment of the model lies in irrigation, where the irrigators' withdrawals impact the streamflow [Figure 6]. Here, the tributary streams function as stocks in the same way as one might take a snapshot of a stream at a given time. There is water entering from runoff of snowmelt and rain, as well as throughflow. The stock empties immediately, and the flow, itself, is imagined as a fairly stable result of the general process of motion. Monthly measurements for irrigation withdrawals function on the outflow portion of the process in the same way as earlier Lookup Tables. Because farmers do not pull water out of the stream during the rainy season, actual monthly irrigation averages are used, providing different values for different months instead of averaging annual totals across 12 months. By using a Lookup Table with specific mean monthly water usage averages, the model gains a closer reflection of the naturally occurring socio-hydrological system, as opposed to seasonal or annual scale, and shows correlation between streamflow and shifts in precipitation and temperature [See Appendix E for full list of equations].

Such influences are important when experimenting with feedbacks between watershed-irrigation systems after the watershed model is complete, and while calibrating it. First, the irrigation districts are allowed to take as much water as their water rights demand, even if it leaves the stream with a negative flow. This helps us understand where, when, and how shortfalls in the water budget can be found, as well as the approximate quantity needed to return to necessary values. Second, a tool is included to incorporate infrastructure improvements, vis-à-vis loss prevention. Next, a balancing loop is included consisting of two intertwined feedbacks: first, comprising the balance mechanism's apprehension of the stream's shortfall and concomitant substitution of that water from the irrigation flows. Thus, in the initial model, farmers may withdraw beyond the needs of instream rights. However, in subsequent scenario modeling, shortfalls (in the East Fork) are accommodated with sustainability measures like the balancing tool.

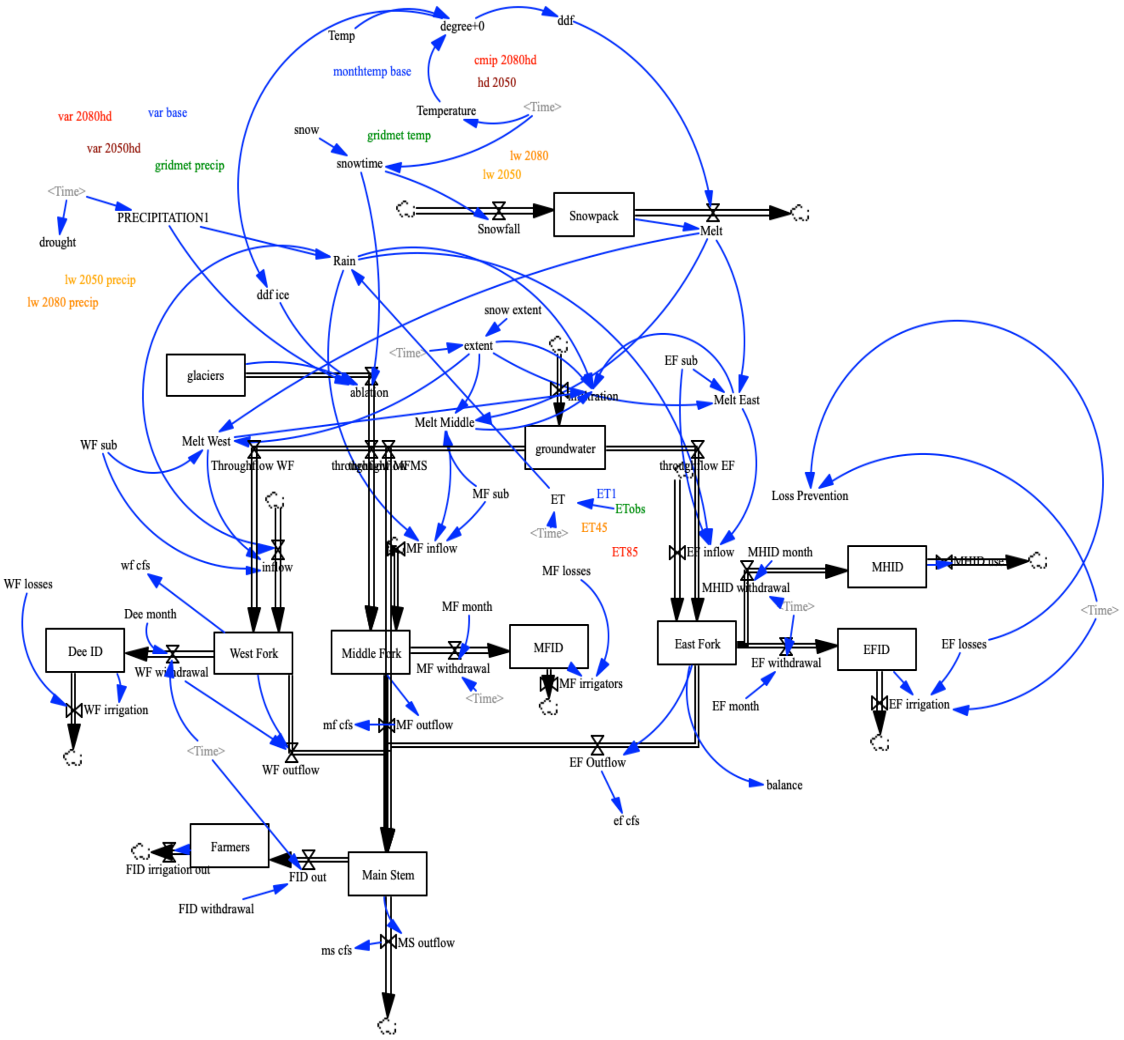

Figure 6: Entire SDM of Hood River Valley irrigation system

Specification and Tuning

As mentioned above, the model logic is largely driven by a two-sided movement. Firstly, climatological forcing of mean temperature and precipitation drives streamflow scenarios on a monthly scale in the first, top-down movement. Secondly, irrigation parameters are determined reflexively according to farmers’ needs and instream requirements in the bottom-up movement. The data for model specification was found at the sources disclosed above, while the equations for degree-day factor modeling were largely derived from an earlier study of the glaciers (Nolin et al. 2010), which is validated by another article on glacier contributions using a different isotope-based method (Frans et al. 2016). Based on studies of snowmelt and infiltration in other alpine and sub-alpine basins tested using sensitivity analysis, it is estimated about 15% of melt would enter streams directly, with the rest entering groundwater through infiltration or sublimating back into the atmosphere (Stähli et al. 2004; Suecker et al. 2000).

While the model uses metric units, it includes conversion variables to easily show conventional American measurement of cubic feet per second. In order to prevent variables from falling into negative numbers, I created algorithmic “if then else” functions that ensure zero as the lowest numeric possibility for variables other than temperature. For all Lookup Tables, a shadow variable of Time was modulated by 12 steps (i.e., 12 months in a year) using the Modulo function.

Verification and Validation

Internal model parameterization, specification, and logic were tested using different simulations at first that did not rely on pre-determined climate scenarios. The model was initialized in steady state using observed data to determine its functioning, and then temperature, precipitation, and snow levels were altered in accordance with the simulated historical data and climate scenarios from CMIP5. Through this iterative process, and using the Nash-Sutcliff Efficiency (NSE) to ascertain model accuracy, errors were corrected, ensuring the dynamics represented gave a precise record of the basic system, as well as results that could be validated through assessment of other studies.

Verification in steady state took place by returning to observed flow levels from flow meters, snowpack levels from SNOTEL stations, and glacial runoff from Nolin et al (2010) to ascertain the proximity of model outcomes to ensure that the model logic produced outcomes falling within a viable range of probability. A regression model used to assess correlation between modeled mainstem streamflow using observed climate data and observed streamflow produced an NSE of 0.643 [Figure 7, Appendix D]. The correlation is particularly strong during the summer flows, which are especially important for irrigation season. Other modeled predictions in basin studies conducted by federal agencies, local consultants, and the Watershed Group were also used to assess my results by comparing them to other results produced through alternative methods.

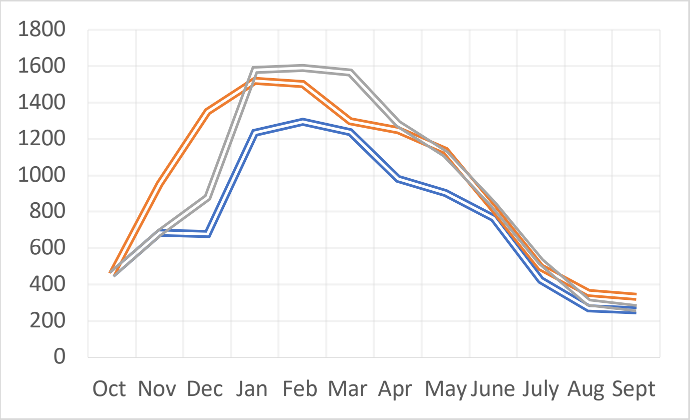

Figure 7: Observed streamflow (orange) and modeled streamflows in cfs using observed climate data (grey) and simulated historical climate data (blue).

Sensitivity Analysis

Lastly, sensitivity analysis was used on the rate of melt per day per degree over zero— Degree Day Factor (DDF) variables—to test their validity in relation to other variables, as well as the sensitivity of the whole system to them. Because these figures derived from normalized equations across different glacierized mountain basins, they represent an estimate rather than an exact quantification. Hence, observations were made of the response of each function to reasonable variations in DDF, for both snow and ice to document a plausible range of effects given each scenario. I then compared my model results using DDF combinations of ice and snow melt rates to the observed average monthly base flow at Tucker Bridge.

As seen below [Table 2], the averaged 4.4 and 7.1 values for snow and ice DDF used by Nolin et al. (2010) produced different R^2 values, revealing that a sensitivity analysis could be used to tune the model [Table 3]. The snow DDF of 2.5 on the lower range of the scale provided a higher R^2 value when coupled with a 7.1 for ice, suggesting that a 9.1 ice DDF would over-estimate glacial contributions. The same was true with the 4.4 snow DDF, bringing an adjusted R^2 value of 0.83. At the same time, an ice DDF of 11 offers only a slight reduction in streamflow, but comes closer to accuracy in modeling glacial discharge. Using a DDF of 2.5 (snow) and 11 (ice), then, enables my model to predict upwards of 84% of simulated historic streamflow and comes within 86.5% of glacial discharge per Nolin et al. (2010), suggesting that it would provide a reasonable stylized comparison [full table at Appendix C]. The same sensitivity analysis was used for infiltration rates and streamflow, due to the effects of generalization across different soil types. Since the Base simulation revealed that increased infiltration does not improve the model's fitness, I maintained the ratio of snowmelt flowing directly into streams at 0.25 and rainfall at 0.15 [Appendix D].

Table 5: Sensitivity analysis of Degree Day Factor (DDF) snow and DDF ice (snow&ice), reporting R^2 values correlating to simulated streamflow and actual monthly flow at Tucker Bridge (2015).

	DDF 4.4&7.1	**DDF 2.5&7.1**	**DDF 4.4&9.1**	**DDF 2.5&9.1**	**DDF 4.4&11**	**DDF 2.5&11**
R	0.913	0.918	0.912	0.918	0.913	0.919
R^2	0.833	0.843	0.833	0.844	0.833	0.844
Adj. R^2	0.816	0.827	0.816	0.828	0.816	0.829

Table 6: Comparison of glacial runoff DDF to determine model fitness

	August-September Discharge	Percent Difference
Nolin et al. 2010	4290000	–
Base (DDF 7.1)	3036460	-29.22%
Base (DDF 9.1)	3827310	-10.79%
Base (DDF 11)	4558000	+6.25%

Scenario Testing

To test the boundaries of the system, I introduced a perturbation of zero rain for a year under Hot/Dry conditions. The water managers must make a decision to risk a lawsuit and maintain their irrigation withdrawals on the East Fork or to sacrifice some of their yield for the good of the salmon by returning water to the stream. The irrigators decide to undertake an iterative process, agreeing upon a bare minimum streamflow of about 75 cfs for these trying times. Every time the water level drops below 75 cfs, farmers decide to make necessary changes to draw the level back up. I also modeled other downstream feedbacks, returning irrigation losses instream through hypothetical infrastructure improvements, and through a Water Bank system derived from participant observation of Water Group meetings. The Water Bank scenarios are created by removing a given percentage of irrigation withdrawals from the East Fork Irrigation District, thus returning the flows to the stream, while infrastructure improvements are created as a variable turning irrigation losses back into streamflow.

Results and Discussion

Findings

My findings suggest two major issues. Firstly, snowpack will decline and peak earlier, shutting of late-summer streamflows. Secondly, glaciers will continue to recede at a faster pace, with ablation increasing at first but declining as glacier volume retreats. These two phenomena will represent a challenge to sustainability for irrigators who live downstream and rely on late-summer snowpack and glacial discharge.

A decrease in precipitation and increase in temperatures cut snow accumulation down considerably on the mountain. Modeled snowpack based on observed historical climate data found 1.22 meters, or about 48 inches of SWE accumulation peaking in the month of May. While this number lies in the lower half of Mt. Hood snow years since 1980, it is just 8% over the median for the decade of the 2010s—1.13 meters (44.5 inches). Simulations of 8.5 and 4.5 RCP showed substantially diminished snowpack with very little deviation between them, accumulating to approximately 0.27 meters (10.6 inches) in December, and then declining to virtually nothing by June [Figure 8].

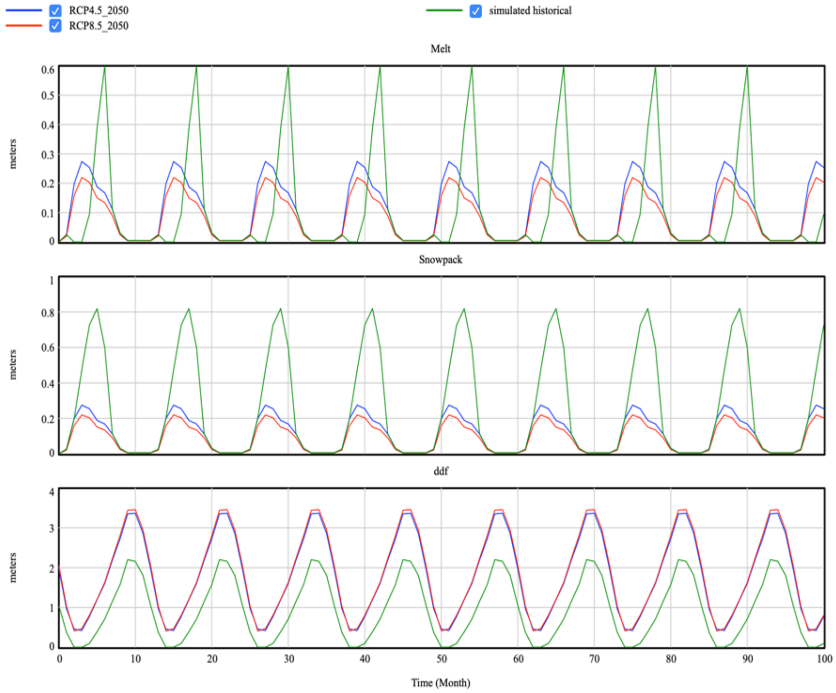

Figure 8: Causes strip for snowmelt in terms of Snow Water Equivalent

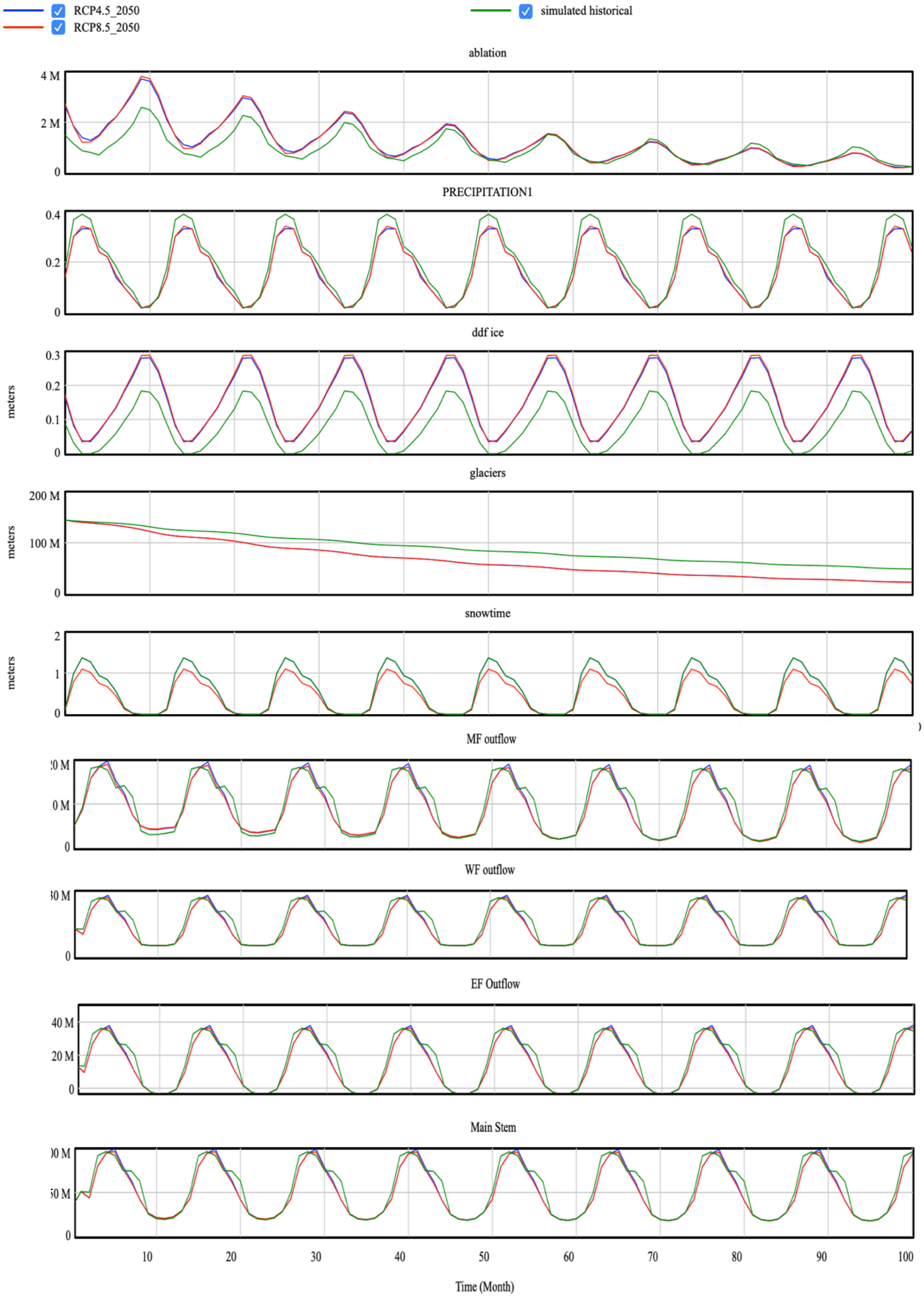

Figure 9: Modeled glacial retreat, ablation influence, precipitation, and streamflow for Base, RCP4.5 and RCP8.5 scenarios in the Middle Fork, West Fork, East Fork, and Mainstem

While warmer temperatures may bring increased melt to the glaciers, the reciprocal decline in glacier discharge resulting from a reduction in the glacier will counteract the higher discharge's modest influence on streamflow under 2050 conditions for either RCP scenario. Secondly, climatological forcing of temperature and precipitation cause streamflow to peak up to three months earlier (in January instead of March or April) and decline faster. These combined issues will lead to a decline in available irrigation water in summer.

Although glaciers are steadily declining, shortfalls are projected to occur most sharply for the non-glacier influenced East Fork Irrigation District, with flows in the dry season dipping down to zero given current irrigation withdrawals [See "EF Outflow," Figure 9]. These findings are also consistent with those of the Hood River Water Conservation Strategy (Salminen et al. 2016), As with all other streams, the East Fork peaks higher than the Base scenario, but declines more rapidly, causing a decrease of about 222.6 cfs during the dry season. Without resolution, this scenario would likely lead to adjudication over who obtains water—conservationists and tribal interests for instream flow or farmers for crops. To avert that socio-hydrological disaster, the Watershed Group is attempting to address the potential hazard with resilience strategies. However, shortages of instream flow will be particularly troubling, because the East Fork has fewer opportunities for storage due to its more rugged geomorphology. As well, the East Fork loses more water to evapotranspiration, due to its position on the sunnier eastern side of the transition zone and the extent of logging in the West Fork.

Resilience Strategies

Irrigation infrastructure is a hydromorphogenic in the sense that it produces and is produced by both management and waterscape, making it an important actant in human-water systems (Mollinga 2013). Assessing the water issues confronting the East Fork Hood River, three strategies came to the fore during the interviews of the Hood River Watershed Group and its participants: water storage, irrigation infrastructure improvements, and water banking. However, since there is no location feasible to construct a viable water storage facility, two options remain. The first options is irrigation infrastructure improvements—especially piping canals that lose water to both evaporation and overflow. The second option involves "water banking," through which different farmers agree to fallow their land every year to ensure water use reduction. The final option is implementing a balancing feedback mechanism, which adapts to lower river flows by automatically lowering irrigation consumption in real time. Each of these would play distinct roles in the social relations of the basin.

Instream feedback from irrigation infrastructure

"Sustainable intensification" to "tap the unused potential in existing agricultural schemes" includes piping ditches and represents one method of posing resilient systems (Khalifa et al. 2019, pg. 153). To examine and test the potential strategies for sustainable intensification, I honed in on the East Fork Irrigation District in particular, and built in a toggle for irrigation losses. Based on previous reports in the region, I determined that East Fork irrigation district losses, resulting from evaporation on open canals, amounted to upwards of 21 cfs historically (Salminen et al. 2016). To model new infrastructure that would feed irrigation savings back into the stream given water-conserving pipelines, I included an Irrigation Savings variable that channels the losses back instream. This feedback mechanism returned enough water to maintain low flows. However, instream water levels fail to satisfy minimum requirements of 150 cfs during the dry months if the irrigation districts continue to fulfill their water rights. (Christensen and Salminen 2013). As Meehan (2014) shows, an assemblage of objects such as infrastructure pipes can produce power—in this case, indicating that creating resilience to climate change can manifest a powerful act of collaborative water management.

Water banking system

Another option confronting the Hood River Watershed Group involves "water banking," a system in which an alternating set of farmers allow their fields to go fallow, or grow less water-intensive crops, such as hay, during the season, in exchange for compensation from a general fund. As Parramond (2016) illustrates, water banking can develop out of collaborative social relations. Doing this would enable water to go back into the stream, theoretically resolving some important habitat conservation issues. To model these scenarios, I reduced the East Fork withdrawals by 10% (WB1), 20% (WB2), and 30% (WB3) in three different simulations using the Hot/Dry scenario as the base. While these scenarios did not have significant impacts on streamflow during the rainy and snowy seasons, they did save a significant amount of water during the critical dry season [Figure 10]. In October, when the instream water right is 150 cfs, however, the highest Water Bank savings, plus savings from infrastructure improvements, is 43.62 cfs [Table 4]. In this way, water banking could prove a highly effective way, with infrastructure improvements, to return instream flows given an RCP8.5 simulation, thereby meeting more of the habitat requirements for the East Fork Hood River.

Table 4: Savings in irrigation water in cfs due to different initiatives to improve resilience under the RCP8.5 climate conditions

	Infrastructure Savings	**Inf + WB1**	**Inf + WB2**	**Inf + WB3**
August	20.32	29.62	38.92	48.22
September	20.95	31.54	42.08	52.62
October	21	28.54	36.08	43.62

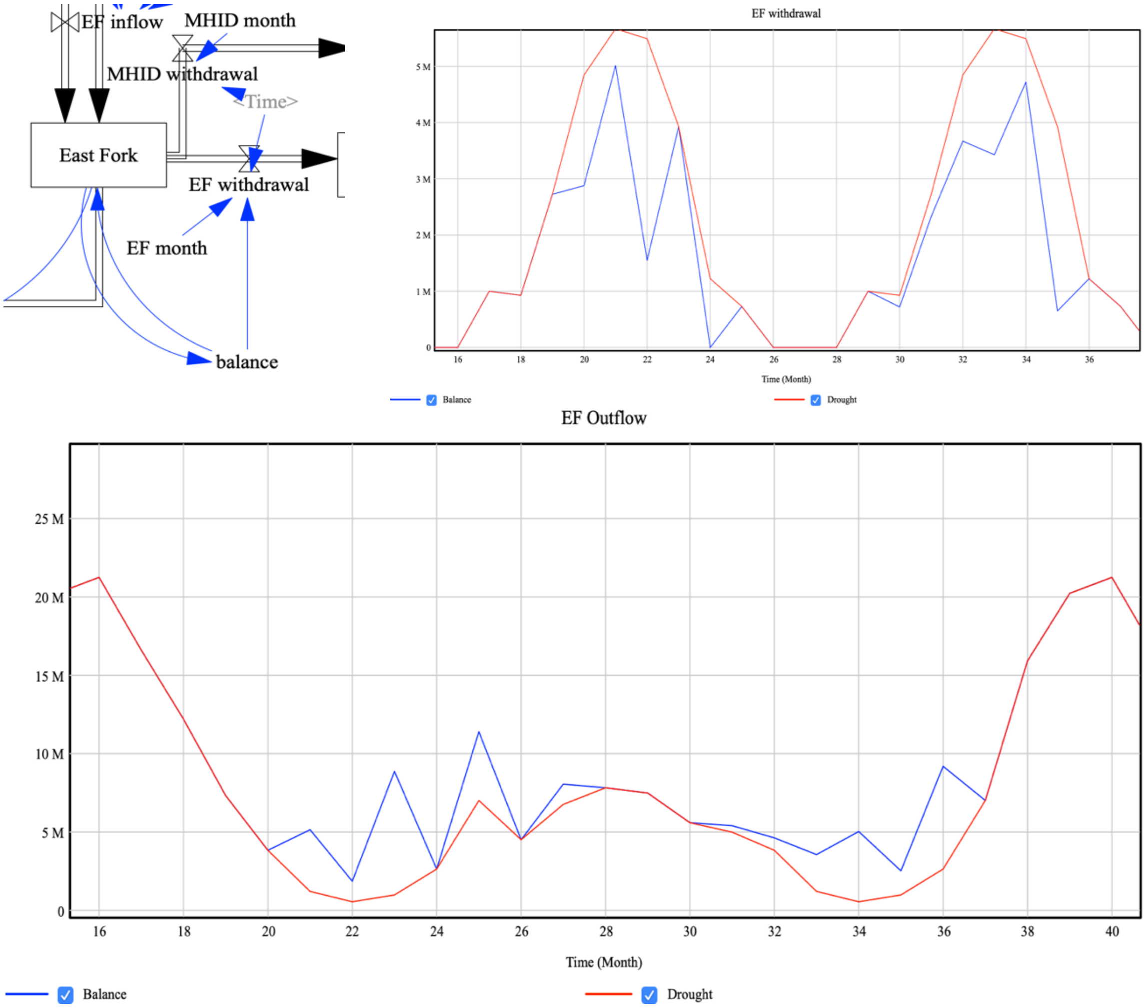

Figure 9: Inclusion of a balancing feedback loop for drought response (left) keeps water instream to protect habitat (center, in meters^3) by shaving off a small portion of irrigation withdrawals (right, in meters^3).

Hazard Modeling: Drought

Using the method outlined above, inducing a drought by interrupting precipitation for the wet season, I simulated a perturbation to see how the system could respond reflexively. The balancing dual-feedback loop is inserted to return irrigation withdrawals instream in response to shortfalls of 75 cfs the farmers sacrifice to keep the minimum flows going, while most of their water rights continue to go toward crops. As Baños et al. (2019) observe, drought can significantly damage a place's draw to tourists, while tourism and in-migration can make drought more difficult to contend with. Although the process outlined above causes shortfalls as farmers take time to calculate the needs, it enables quick responses that could better navigate the nuances of the conditions than simply depressing all irrigation by a given percentile (particularly in the event that water banking is already in play) [Figure 10]. This would diminish the negative feedbacks that resonate on broader economic levels.

Conclusions

The SDS developed in the present study provides a valuable tool to determine how and why adaptive strategies can be taken to make coupled human-water systems more resilient. SDMs provide a key resource for showing both how physical systems function in tandem with human interaction and how feedback mechanisms can improve conditions in coupled systems.

It is important to note the limitations of such models. Firstly, they rely on forcing mechanisms that cannot integrate granular data to the extent that larger, more dataintensive climate models can do. We rely on climate selection criteria that generates likely parameters based on prior occurring iterations, which may prove unpredictable in the future. Furthermore, the differences in modeled scenarios from wetter to drier issue from our uncertainty regarding the future of climate change.

At the same time, two lessons emerge from the modeling process, which are paradoxically also part of the first premises of its initial stages. Firstly, the coupled human-water systems can be projected for either prevention of worst case scenarios or addressing them in the safest most efficient ways possible. Secondly, while accuracy is at a premium in modeling specificity, the lack of specialized, continuous data cannot preclude efforts to address system dynamics in general. Thus, "stylized" models offer excellent means of planning for complex hazards and aligning stakeholders behind new ways of addressing them.

While this model's simulations do not match perfectly the actual flows in the Hood River system, it can approximate that system's functions, and in return, offer different ways of viewing the watershed. It is a useful beginning point to which other attributes modeling agent behavior and the influence of outreach on conservation could be added at a later time. Water quality can also feature into broader system dynamics, as weakened glacial structure could also lead to collapse of the glacier, leading to flooding including potentially dangerous sediment. As well, decline in hyporheic fauna would threaten microinvertebrate specialists, and downstream temperature change based on less glacial influence could lead to warmer water and reduced salmonid habitat. The glacier's discharge will likely become increasingly sedimentary as it retreats. Thus, the present model provides a template that can be used for further studies on the impact of the reduction in glacial ablation on the Middle Fork Irrigation District in terms not only of quantity but also quality.

By utilizing the “hard path” approach of incorporating supply-side sustainable intensification through infrastructure, as well as “soft path” solutions that moderate water use, areas like the Hood River Valley can work to adapt to climate hazards (Medeiros and Sivapalan 2020). The main question that arises is, then, after saving the water for instream habitat conservation, will other problems arise, and who will be able to counter them? Will turning flows back to the streams lead farmers to tap wells that will draw from throughflow?

While tribal actors may be pleased by efforts to put water back into streams, irrigation district managers will have a difficult time selling the idea to their constituents. SDMs can provide important tools to work through these questions, and expand adaptive capacity, as well as community awareness, for socio-hydrological systems, but collaboration will involve more complex social processes. Discontent among farmers could also create larger economic problems, leading some local businesses to oppose adaptive measures, while others may support keeping water in streams for fishing or boating purposes. These issues will be part of an iterative process of “scale jumping” and stakeholder discourse as hazards come to bear on the watershed.

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Conclusion

This dissertation has marked a new synthesis of theoretical and methodological approaches. Focused on a critical interface of multifarious scales, it reckons with complex systems in transformative circumstances during which societies attempt to reckon with both human and natural forces. Through these efforts, it locates difficult tensions within the process of transformation resulting from climate change and population increase. Although collaboration prevails to improve conditions for endangered species and farmers in the valley, fewer compromises present themselves for the trends of urbanization.

Indeed, for most people in the valley, the retreat of the glaciers and snowpack represents an imminent threat to their livelihoods. Meanwhile, population growth in the city can bring more revenue to those owning summer homes, small businesses, and recreational enterprises, but bears with it significant challenges as well. It would appear, then, the promotion of collaborative water governance represents a safe ruralizing tendency within an exurban place caught in a knot of urbanization. However, collaborative rescaling of water governance is also effective, because it draws together conservationism and liberal ideals that emanate from the same metabolic process causing urbanization. Therefore, controversy over urbanization does not exist in a wholly different system but in dialectical relation to socio-political trends bringing about collaborative water management.

An uneven landscape emerges in which rural and urban scales correspond in relation to water interests, while diverging in relation to public interest in affordable housing. The rural and moneyed interests are perceived by housing advocates to hold hegemony over the urban in countywide ballots, while urban residents who hope to maintain a calmer, bucolic lifestyle oppose new developments on environmental grounds. This appears to manifest the contradictions of maintaining peaceful simulations of rural living with amenities that attract urbanites who also care about the environment—a veritable tradition in Oregon summed up in former Governor Tom McCall's famous declaration, "I urge [visitors] to come and come many, many times to enjoy the beauty of Oregon. But I also ask them, for heaven's sake, don't move here to live."

Through qualitative methodology, the interests, fears, and values of people related to water governance in the Valley appear to support calls for resilient systems to the perceived threat of anthropogenic climate change. At the same time, qualitative methods show that real measures could hold significant value by contributing to reinforcing system resilience, if not transformation. While these changes may not suffice, as some stakeholders interviewed admitted, to compensate for all of the losses brought by climate change, hope persists that adaptation will prevent loss in quality of life.

In using these methods and their related subfields—hydrosocial theory and socio-hydrology, respectively—in one combined study, this dissertation shows how discrete approaches to human-water systems can complement one another. On one hand, qualitative methods can reveal hazard perceptions, which provide an indication of lines of inquiry that will yield the most helpful results for the local community. As well, engagement with stakeholders through the modeling of system dynamics can prove useful in developing the most effective model. In this way, quantitative methods become integrated with the qualitative through an iterative process wherein the researcher gains qualitative insight into the formulation of the problem, produces a model to benefit the community, and is supported in this process by feedback from the community.

With this mixed-methods study, we might understand the conclusions of this dissertation as revealing a more systematic intertwining of the premises of hydrosocial theory and socio-hydrology based on a tacit reconciliation of systems science as it pertains to the study of resilience. In particular, the fundamental assumptions of co-evolution that underlie both sides of human-water systems studies emanate from a basic understanding of societies as linked together with their ecological conditions through social relations of production. As a process rather than a static production, these complex, adaptive human-water systems form assemblages of human and non-human actants bound to transformation, whether wanted or not.

Exurban America especially values quality of life, and whether transformation renders that quality exclusive to those lucky enough to enjoy it or opens up a more inclusive, adaptive model remains to be seen. Exurbia is characterized as a place for repose and relaxation as well as fun and excitement; a place based on the morals of hard work combined with the pleasures of craft and skill; a place for quietly taking one’s time, intimately engaging in a supportive and inclusive community, and developing one’s understanding of the world through a simpler way of life. Yet its participation in the world’s complexities, production of drones and agricultural commodities, development of tourism and recreation industries, all intrude on the simplicity of the exurban narrative.

As this study has shown, understanding systems through a geographical lens that uses mixed methods with an interdisciplinary focus in order to ascertain how human-water systems interact, coevolve, and provide new paths to transformative adaptation to social and climate change. The development of systems science toward such dialectical assessment of social and material conditions offers fascinating insight into the interplay of multiplicity and singularity in complex systems. However, this study was limited by Covid-19, such that the final integration between the quantitative and qualitative feedback became impossible. Future studies would complete this iterative process to include the community not only in the development of the problem but also the suite of responses. While this study did utilize ethnographic participant observation to outline and calibrate those responses in the SDM, future studies could integrate methods and subfields further by closing the feedback loop. Follow-up work will include the convening of a workshop with the Watershed Group following the relaxation of stay at home orders in order to discuss the viability of the solutions presented in this dissertation.

This study has provided vital conclusions that indicate further potential for the design and development of future studies. Because approaching coupled human-water systems science using a synthesis of contemporary sub-fields offers an opportunity to understand complexity through mixed-methods studies, future studies might construct similar research designs that use complementary sub-fields to build situated knowledge. Since exurban areas such as Hood River confront multifarious challenges from urbanization and climate change, which they can ameliorate through multi-scalar collaboration and adaptive system dynamics, further projects might integrate Agent-Based Models with the execution of strategies developed through qualitative problem formulation and quantitative modeling of solutions and scenarios. Lastly, that coupled human-water system dynamics modeling shows that Hood River (and exurban areas like it) may be able to “bounce forward” through climate hazards, but only through the implementation of preparatory measures, studies developing spatially explicit models of land use change caused by exurban development could indicate trends that help guide positive adaptation.

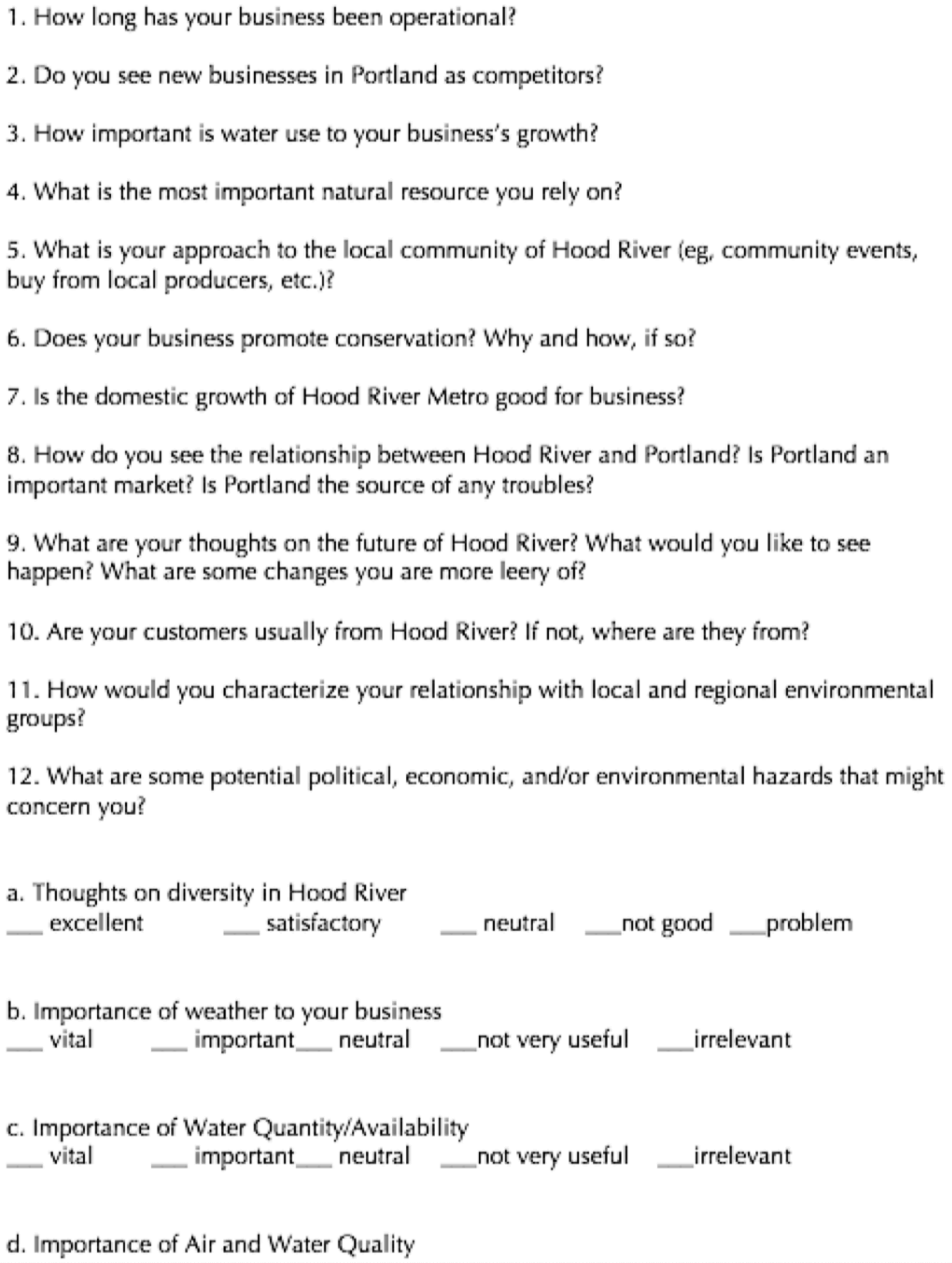
Returning to Thales, it would appear water and place offer the simplest, perhaps most essential, social relationship for the continued development of humanity. The role of water in the production of human society and sense of place (and vice-versa) may offer a key link in an ongoing process through which society transforms to meet the most pressing challenges of the 21st Century. Developing sound methods and innovative approaches grounded in local collaboration will prove most important in pursuit of that adaptive transformation.

Appendix A: Codebook

Code	Code Group 1	Code Group 2	Code Group 3
Agriculture			Watershed Group
Amenities	Exurb		
Beer	Exurb		
City	Exurb		
Climate Change		Hazards	
Community	Exurb		Watershed Group
Commuting	Exurb		
Conservation			Watershed Group
Development	Exurb		Watershed Group
Earthquake		Hazards	
Energy			Watershed Group
Exurb	Exurb		
Farmland		Hazards	Watershed Group
Fires		Hazards	
Fish		Hazards	Watershed Group
Forest			Watershed Group
Funding			Watershed Group
glaciers		Hazards	Watershed Group
Hazards			Watershed Group
Housing	Exurb		
Infrastructure	Exurb		
Locals	Exurb		
New-comers	Exurb		
Perception	Exurb		
Planning	Exurb		
Portland	Exurb		

Race	Exurb		
Recreation	Exurb		
Resilience			Watershed Group
Rural v urban	Exurb		
Shortage		Hazards	Watershed Group
Skiing			
Snowpack		Hazards	Watershed Group
Taxes	Exurb		
Tech	Exurb		
Tourism	Exurb		
Traffic	Exurb		
transformation			Watershed Group
Tribes			
UGB	Exurb		
Water quality		Hazards	Watershed Group
WG: business			Watershed Group
WG: dynamics			Watershed Group
WG: outreach			Watershed Group
Wine	Exurb		

Appendix B: Interview Guide



1. How long has your business been operational?

2. Do you see new businesses in Portland as competitors?

3. How important is water use to your business's growth?

4. What is the most important natural resource you rely on?

5. What is your approach to the local community of Hood River (eg, community events, buy from local producers, etc.)?

6. Does your business promote conservation? Why and how, if so?

7. Is the domestic growth of Hood River Metro good for business?

8. How do you see the relationship between Hood River and Portland? Is Portland an important market? Is Portland the source of any troubles?

9. What are your thoughts on the future of Hood River? What would you like to see happen? What are some changes you are more leery of?

10. Are your customers usually from Hood River? If not, where are they from?

11. How would you characterize your relationship with local and regional environmental groups?

12. What are some potential political, economic, and/or environmental hazards that might concern you?

a. Thoughts on diversity in Hood River
___ excellent ___ satisfactory ___ neutral ___not good ___problem

b. Importance of weather to your business
___ vital ___ important___ neutral ___not very useful ___irrelevant

c. Importance of Water Quantity/Availability
___ vital ___ important___ neutral ___not very useful ___irrelevant

d. Importance of Air and Water Quality

Appendix C: Regression Tables

Modeled mainstem streamflow based on alternating DDF variables and simulated historical data

	DDF 4.4/7.1	**DDF 4.4/7.1**	**DDF 2.5/7.1**	**DDF 4.4/9.1**	**DDF 2.5/9.1**	**DDF 4.4/11**	**DDF 2.5/11**
0	456	456	456	456	456	456	456
1	953	684.912	684.912	684.912	684.912	684.912	684.912
2	1350.5	670.485	670.485	673.737	673.737	676.826	676.826
3	1519.5	1231.94	1231.94	1233.06	1233.06	1234.13	1234.13
4	1500.4	1294.75	1294.75	1294.72	1294.72	1294.7	1294.7
5	1297.5	1238.59	1238.59	1238.57	1238.57	1238.54	1238.54
6	1247.6	1007.4	980.638	1007.66	980.903	1007.91	981.154
7	1134.8	995.453	899.945	996.585	901.077	997.655	902.147
8	819	843.215	762.747	845.278	764.81	847.226	766.758
9	496.5	335.838	418.544	339.174	421.879	342.316	425.022
10	353	262.807	262.807	267.299	267.299	271.514	271.514
11	333.6	247.401	247.401	253.559	253.559	259.309	259.309
R		0.91271141	0.91811622	0.91243608	0.91845243	0.91271141	0.91876885
R^2		0.83304211	0.8429374	0.83253959	0.84355486	0.83304211	0.8441362
Adj. R^2		0.81634632	0.82723114	0.81579355	0.82791035	0.81634632	0.82854982

Appendix D: Snowmelt Sensitivity Analysis

Mainstem streamflow based on alternating rain coefficient using observed historical data

	Observed	0.15	0.1	0.2	0.175
0	456	456	456	456	456
1	953	684.912	684.912	684.912	684.912
2	1350.5	772.679	645.736	899.621	836.15
3	1519.5	1310.26	1006.31	1614.21	1462.23
4	1500.4	1313.55	1006	1621.09	1467.32
5	1297.5	1291.65	988.605	1594.69	1443.17
6	1247.6	1073.58	841.184	1305.98	1189.78
7	1134.8	944.002	743.464	1144.54	1044.27
8	819	733.653	608.898	858.408	796.031
9	496.5	523.441	480.14	566.741	545.091
10	353	339.41	338.644	340.175	339.792
11	333.6	282.97	282.97	282.97	282.97
R		0.93310297	0.93664737	0.92526366	0.92911791
R^2		0.87068115	0.87730829	0.85611284	0.8632601
Adj. R^2		0.85774926	0.86503912	0.84172412	0.84958611

Appendix E: Equations

The following are the equations for Warm/Hot scenario including the drought function and the Balancing variable. They generally reflect the alternative scenario equations.

(01) ablation=
IF THEN ELSE(glaciers<=ddf ice , 0 , ((30*ddf ice)+PRECIPITATION1+snowtime
) * (50.6*10000))*(glaciers/1.44317e+08)

(02) balance=
IF THEN ELSE(EF withdrawal>0 , IF THEN ELSE(East Fork > 5.8e+06 , 0 , 5.8e+06
-East Fork) , 0)

(03) cmip 2080hd(
[(0,0)-(11,30)],(0,17.01),(1,9.1),(2,5.14),(3,4.94),(4,7.6),(5,10.48),(6,
13.49),(7,18.05),(8,23.02),(9,28.11),(10,28.4),(11,24.15))

(04) ddf=
(30*(0.0044 *"degree+0"))
Units: meters

(05) ddf ice=
IF THEN ELSE("degree+0">0 , (0.011*"degree+0") , 0)
Units: meters

(06) Dee ID= INTEG (
WF withdrawal-WF irrigation,
1e+06)

(07) Dee month(
[(0,0)-(11,1e+06)],(0,223250),(1,0),(2,0),(3,0),(4,0),(5,223250),(6,372083
),(7,446500),(8,930208),(9,930208),(10,930208),(11,930208))

(08) "degree+0"=
IF THEN ELSE((Temperature-Temp)>0 , Temperature-Temp , 0)
Units: Celcius

(09) drought=
IF THEN ELSE((Time < 36 :AND: Time > 24) , 0 , 1)

```
(10)    East Fork= INTEG (
                EF inflow+throughflow EF-EF Outflow-EF withdrawal-MHID
withdrawal,
                        1.4e+07)


(11)    ef cfs=
                (EF Outflow*35.3147)/2.628e+06
        Units: cfs

(12)    EF inflow=
                (Rain*EF sub)*0.15+(Melt East)+Loss Prevention
        Units: m3

(13)    EF irrigation=
                EFID-EF losses(MODULO( Time , 12 ))


(14)    EF losses(
                [(0,0)-(11,5e+06)],(0,0),(1,0),(2,0),(3,0),(4,0),(5,0),(6,0),(7,1.563e+06
        ),(8,1.563e+06),(9,1.563e+06),(10,1.563e+06),(11,1.563e+06))


(15)    EF month(
                [(0,0)-
(12,9e+06)],(0,1.74621e+06),(1,1.04183e+06),(2,0),(3,0),(4,0),(5,1.4288e+06
        ),(6,1.32462e+06),(7,3.89199e+06),(8,6.92074e+06),(9,8.09653e+06),(10,7.8435
1e+06
        ),(11,5.61101e+06))


(16)    EF Outflow=
                East Fork


(17)    EF sub=
                2.8e+08
        Units: meters

(18)    EF withdrawal=
                EF month(MODULO( Time , 12 ))*0.7
```

(19) EFID= INTEG (
EF withdrawal-EF irrigation,
1.04e+07)

(20) ET=
ET85(MODULO(Time , 12))

(21) ET1(
[(0,0)-(11,60)],(0,0.0584),(1,0.0247),(2,0.017),(3,0.0169),(4,0.0285),(5,0.0565),(6,0.0861),(7,0.13),(8,0.1481),(9,0.1796),(10,0.1572),(11,0.1111))

(22) ET45(
[(0,0)-(11,10)],(0,0.0655),(1,0.0274),(2,0.0187),(3,0.0194),(4,0.0303),(5,0.0586),(6,0.09126),(7,0.13734),(8,0.1632),(9,0.1968),(10,0.1738),(11,0.1192))

(23) ET85(
[(0,0)-(11,10)],(0,0.0671),(1,0.0283),(2,0.0194),(3,0.0203),(4,0.0329),(5,0.0626),(6,0.0945),(7,0.1419),(8,0.178),(9,0.2065),(10,0.1864),(11,0.1246))

(24) ETobs(
[(0,0)-(11,60)],(0,0.0544),(1,0.0204355),(2,0.0144),(3,0.0165822),(4,0.0282725),(5,0.0576),(6,0.0857893),(7,0.129926),(8,0.147479),(9,0.178868),(10,0.158475),(11,0.1051))

(25) extent=
(snow extent(MODULO(Time , 12)))*0.2

(26) Farmers= INTEG (
FID out-FID irrigation out,
1e+07)

(27) FID irrigation out=
Farmers

```
(28)    FID out=
                (FID withdrawal(MODULO( Time , 12 )))


(29)    FID withdrawal(
                [(0,0)-
(11,1e+07)],(0,3.13294e+06),(1,7.18864e+06),(2,6.69749e+06),(3,7.717e+06
        ),(4,8.33466e+06),(5,8.2528e+06),(6,9.27231e+06),(7,7.79142e+06),(8,8.05188e
+06
        ),(9,8.08164e+06),(10,7.91793e+06),(11,6.87609e+06))


(30)    FINAL TIME  = 100
        Units: Month
        The final time for the simulation.

(31)    glaciers  = A FUNCTION OF( ablation)
        glaciers= INTEG (
                IF THEN ELSE( ablation > glaciers+glaciation , 0 , glaciation-ablation ),
                        1.44317e+08)
        Units: meters

(32)    gridmet precip(
                [(0,0)-(11,10)],(0,0.2569),(1,0.5053),(2,0.505),(3,0.5),(4,0.399),(5,0.3775
        ),(6,0.2848),(7,0.199),(8,0.1487),(9,0.0487),(10,0.0446),(11,0.111))


(33)    gridmet temp(
                [(0,-5)-(11,20)],(0,4.308),(1,-0.98),(2,-3.3),(3,-2.98),(4,-3.22),(5,-1.748
        ),(6,-0.003),(7,3.341),(8,6.589),(9,11.97),(10,12.31),(11,9.504))


(34)    groundwater= INTEG (
                infiltration-throughflow EF-throughflow MF-throughflow MS-
Throughflow WF-
        throughflow MS,
                        1e+12)


(35)    hd 2050(
                [(0,0)-(11,30)],(0,15.6),(1,7.82),(2,3.1),(3,3.53),(4,6.1),(5,9.15),(6,12.36
        ),(7,16.89),(8,21.27),(9,26.11),(10,26.23),(11,22.36))
```

(36) infiltration=
((Rain*0.7)*9.33e+08)+(((Melt East*0.5)+(Melt Middle*0.5)+(Melt West*0.5)
)*extent)

(37) inflow=
(Rain*WF sub*0.15)+(Melt West)
Units: m3

(38) INITIAL TIME = 0
Units: Month
The initial time for the simulation.

(39) Loss Prevention=
EF losses(MODULO(Time , 12))

(40) lw 2050(
[(0,0)-(11,30)],(0,14.91),(1,7.34),(2,3.45),(3,3.18),(4,5.83),(5,9.04),(6,12.13),(7,16.58),(8,20.64),(9,25.42),(10,25.54),(11,21.69))

(41) lw 2050 precip(
[(0,0)-(11,10)],(0,0.14),(1,0.3),(2,0.33),(3,0.33),(4,0.24),(5,0.22),(6,0.14),(7,0.1),(8,0.061),(9,0.02),(10,0.03),(11,0.06))

(42) lw 2080(
[(0,0)-(11,2000)],(0,15.47),(1,7.94),(2,3.9),(3,3.73),(4,6.36),(5,9.5),(6,12.64),(7,17.05),(8,21.44),(9,26.1),(10,26.36),(11,22.42))

(43) lw 2080 precip(
[(0,0)-(11,30)],(0,0.15),(1,0.3),(2,0.32),(3,0.33),(4,0.24),(5,0.22),(6,0.14),(7,0.1),(8,0.06),(9,0.02),(10,0.03),(11,0.06))

(44) Main Stem= INTEG (
throughflow MS+EF Outflow+MF outflow+throughflow MS+WF outflow-FID out-MS outflow
,
3.3934e+07)

```
(45)    Melt=
                IF THEN ELSE( Snowpack-ddf<=0 , Snowpack  , ddf )
        Units: meters

(46)    Melt East=
                (Melt)*0.25*(EF sub)*extent
        Units: m3

(47)    Melt Middle=
                (Melt)*0.25*(MF sub)*extent


(48)    Melt West=
                (Melt)*0.25*(WF sub)*extent
        Units: m3

(49)    mf cfs=
                (MF outflow*35.3147)/2.628e+06
        Units: cfs

(50)    MF inflow=
                (Rain*MF sub)*0.15+(Melt Middle)
        Units: m3

(51)    MF irrigators=
                MFID-MF losses


(52)    MF losses=
                0


(53)    MF month(
                [(0,0)-
(12,4e+09)],(0,2.22506e+06),(1,2.59714e+06),(2,3.05108e+06),(3,2.99899e+06
        ),(4,3.09573e+06),(5,3.3041e+06),(6,3.19247e+06),(7,3.25201e+06),(8,4.13756e
+06
        ),(9,4.72545e+06),(10,4.33105e+06),(11,3.54967e+06))


(54)    MF outflow=
                Middle Fork


(55)    MF sub=
```

```
          2.8e+08
     Units: meters

(56) MF withdrawal=
          (MF month(MODULO( Time , 12 )))


(57) MFID= INTEG (
          MF withdrawal-MF irrigators,
               2.225e+06)


(58) MHID= INTEG (
          MHID withdrawal-MHID use,
               372000)


(59) MHID month(
          [(0,0)-
(67,800000)],(0,37208.3),(1,0),(2,0),(3,0),(4,0),(5,89299.9),(6,230691
     ),(7,528358),(8,751608),(9,558124),(10,297666),(11,208366))


(60) MHID use=
          MHID


(61) MHID withdrawal=
          (MHID month(MODULO( Time , 12 )))


(62) Middle Fork= INTEG (
          (ablation)+MF inflow -MF outflow-MF withdrawal+throughflow MF,
               5e+06)


(63) monthtemp base(
          [(-0.1,-2)-(11,20)],(0,7.97),(1,2.84),(2,-0.028),(3,-0.176),(4,0.72),(5,2.937
     ),(6,5.358),(7,8.722),(8,11.92),(9,16.68),(10,16.36),(11,13.696))


(64) ms cfs=
          (MS outflow*35.3147)/2.628e+06
     Units: cfs
```

(65) MS outflow=
Main Stem
Units: m3

(66) PRECIPITATION1=
var 2080hd(MODULO(Time , 12))*drought

(67) Rain=
IF THEN ELSE((PRECIPITATION1-ET)>0 , (PRECIPITATION1-ET) , 0)
Units: meters

(68) SAVEPER =
TIME STEP
Units: Month [0,?]
The frequency with which output is stored.

(69) snow(
[(0,-0.3)-(12,20)],(0,0.127),(1,0.9906),(2,1.3716),(3,1.27),(4,0.9398),(5,0.8382),(6,0.5588),(7,0.1524),(8,0.0254),(9,0),(10,0),(11,0))
Units: meters

(70) snow extent(
[(0,0)-(11,10)],(0,0),(1,0.1),(2,0.7),(3,0.85),(4,0.8),(5,0.7),(6,0.5),(7,0.25),(8,0.1),(9,0.05),(10,0),(11,0))
Units: percent

(71) Snowfall=
(snowtime)*0.2
Units: meters

(72) Snowpack= INTEG (
IF THEN ELSE(Snowpack+Snowfall-Melt<=0 , 0 , Snowfall-Melt)
,
0)
Units: meters

(73) snowtime=
snow(MODULO(Time , 12))*0.8
Units: meters

(74) Temp=
0
Units: Celcius

```
(75)    Temperature=
                cmip 2080hd(MODULO( Time , 12 ))
        Units: Celcius

(76)    throughflow EF=
                5.20916e+06


(77)    throughflow MF=
                5.20916e+06


(78)    throughflow MS=
                1.11625e+07


(79)    Throughflow WF=
                6.17658e+06


(80)    TIME STEP  = 1
        Units: Month [0,?]
        The time step for the simulation.

(81)    var 2050hd(
                [(0,0)-(11,10)],(0,0.14),(1,0.3),(2,0.34),(3,0.33),(4,0.24),(5,0.22),(6,0.15
        ),(7,0.1),(8,0.06),(9,0.02),(10,0.03),(11,0.06))


(82)    var 2080hd(
                [(0,0)-(11,10)],(0,0.14),(1,0.3),(2,0.34),(3,0.34),(4,0.25),(5,0.22),(6,0.15
        ),(7,0.1),(8,0.06),(9,0.02),(10,0.02),(11,0.06))


(83)    var base(
                [(0,0)-(11,10)],(0,0.1747),(1,0.3652),(2,0.387),(3,0.3674),(4,0.2612),(5,
        0.2342),(6,0.1835),(7,0.1193),(8,0.0849),(9,0.0225),(10,0.0231),(11,0.0649
        ))


(84)    West Fork= INTEG (
                inflow+Throughflow WF-WF outflow-WF withdrawal,
                        1.3e+07)
```

(85) wf cfs=
(West Fork*35.3147)/2.628e+06

(86) WF irrigation=
Dee ID-WF losses

(87) WF losses=
4.80609e+06

(88) WF outflow=
West Fork-WF withdrawal

(89) WF sub=
3.73e+08
Units: meters

(90) WF withdrawal=
(Dee month(MODULO(Time , 12)))