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Vulnerability of water supply from the Oregon Cascades to changing climate: Linking science to users and policy

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ABSTRACT

Despite improvements in understanding biophysical response to climate change, a better understanding of how such changes will affect societies is still needed. We evaluated effects of climate change on the coupled human–environmental system of the McKenzie River watershed in the Oregon Cascades in order to assess its vulnerability. Published empirical and modeling results indicate that climate change will alter both the timing and quantity of streamflow, but understanding how these changes will impact different water users is essential to facilitate adaptation to changing conditions. In order to better understand the vulnerability of four water use sectors to changing streamflow, we conducted a series of semi-structured interviews with representatives of each sector, in which we presented projected changes in streamflow and asked respondents to assess how changing water availability would impact their activities. In the McKenzie River watershed, there are distinct spatial and temporal patterns associated with sensitivity of water resources to climate change. This research illustrates that the implications of changing streamflow vary substantially among different water users, with vulnerabilities being determined in part by the spatial scale and timing of water use and the flexibility of those uses in time and space. Furthermore, institutions within some sectors were found to be better positioned to effectively respond to changes in water resources associated with climate change, while others have substantial barriers to the flexibility needed to manage for new conditions. A clearer understanding of these opportunities and constraints across water use sectors can provide a basis for improving response capacity and potentially reducing vulnerability to changing water resources in the region.

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1. Introduction

Globally, the potential impact of climate change on water resources has been the subject of analysis for over a decade, and the Intergovernmental Panel on Climate Change (IPCC) has recently reported on accumulating evidence that freshwater resources are vulnerable globally (Bates et al., 2008). In the Western U.S., where many of the water supplies are currently over-allocated, water is one of the resources most vulnerable to climate change, as changes in the timing or quantity of streamflow have potential to further stress supplies (Barnett et al., 2005; Bales et al., 2006; Knowles et al., 2006). In particular, summer water shortages are predicted to worsen in response to climate change in many parts of the Western U.S., including the Oregon Cascades (Parson et al., 2001; Mote et al., 2003). Although less than 10% of annual streamflow occurs during July and August in this region, summer flows are particularly important for many of the water users there. At the same time, it is the flow most sensitive to alteration with climate change. As more precipitation falls as rain and snowmelt occurs earlier, a portion of the summer flow is shifted to winter and spring. Summer flows are also more vulnerable to increased evapotranspiration losses with warming.

One of the Cascades rivers where these types of changes are expected to occur is the McKenzie River, which spans an altitudinal range from over 3000 m at its eastern boundary to just over 100 m at its confluence with the Willamette River. The McKenzie provides water for commercial, industrial, and residential uses, and contributes to hydroelectric generation. In addition, it provides habitat for fish, including three federally listed species – bull trout, spring Chinook salmon, and Oregon chub – and recreational activities such as guided fishing on the McKenzie constitute

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important sources of income and employment (Jefferson et al., 2007). The extent to which these water sectors will be impacted by the effects of climate change on streamflow is largely unknown.

Climate-driven changes in water supply and water use in the McKenzie River basin are strongly geographically mediated, with a large degree of spatial and temporal variation in potential changes to this key resource. Mote et al. (2003, 82) note, however, that ''...attempts to characterize impacts and vulnerabilities by jointly projecting climatic changes and other salient trends are in their infancy, and require much more effort'' (exceptions include Miles et al., 2000; Hamlet, 2003; Whitely Binder, 2006). In the case of the McKenzie River watershed, the opportunity exists to advance this type of research by linking projections of the hydrologic response to climate change with information gathered on the human components of that system, including the actors and institutions that use and manage the water supply. Broadly, this paper focuses on the conditions and characteristics that lead to vulnerability among water users with respect to projected changes in timing and quantity of streamflow in the McKenzie River. We examine the role geographic variation in existing water availability and its sensitivity to climate warming may play in determining vulnerability to change, and the degree to which it is accounted for by water managers. Specifically, we address the following questions:

1. How do the spatial and temporal aspects of changes in streamflow interact with, increase, or reduce vulnerability in the human components of the system? And, to what degree do water managers take into account the spatial and temporal aspects of streamflow with respect to predicted climate-driven changes in water supply?
2. What kinds of institutions and information on climate change impacts exist that would influence the existing ability of actors in the McKenzie River watershed to respond to altered streamflow conditions associated with climate change?

We begin with some general considerations about the assessment of vulnerability of human and natural systems to climate change and then summarize recent research in the McKenzie basin that projects distinct geographic differences in the magnitude and timing of streamflow changes due to climate warming. Because this research is both relatively new and posits large differences in response for different parts of the basin, it provides an excellent construct from which to explore the extent to which spatial and temporal aspects of change influence vulnerability in the human system. Using semi-structured interviews, we examine four water sectors and the ways in which they are potentially vulnerable to climate change.

2. Assessing vulnerability of human–natural systems

A great deal of current attention in the area of climate change research is focused on understanding the likely effects on both ecosystems and societies (Eakin and Luers, 2006; Ford et al., 2006, 2008; Franco et al., 2008; Dovers, 2009). This includes attention to where changes are most likely to happen, where they will be most severe, and what kinds of conditions can either attenuate or amplify vulnerability to these changes (Turner et al., 2003; Ford and Smit, 2004; Brooks et al., 2005). However, despite improvements in knowledge regarding biophysical response to climate change, our understanding of how these responses will influence and affect people and societies remains underdeveloped (Ford et al., 2006). As such, where the ability to address human–environmental systems jointly exists, it can provide a more complete picture of likely vulnerabilities to climate change (Turner et al., 2003).

Although there are a number of definitions of vulnerability and its components, most conceptualize it as a function of sensitivity to stresses and the capacity to absorb, cope with, and adapt to those stresses (Mote, 2003; Adger, 2006; Eakin and Luers, 2006; Ford et al., 2006). In this paper, we refer to vulnerability as the extent to which climate change may damage or harm a system, which depends on the system's sensitivity and its ability to adapt to new conditions (IPCC, 1996). Vulnerability can be rooted in the sensitivity and adaptability of either the human or natural components of systems, and ''multiple pathways to vulnerability'' can exist as a result of different combinations of sensitivity and adaptability (Adger, 2006, 268). Sensitivity – or the degree to which a system responds to changes in climate – can be influenced by a variety of characteristics, such as the spatial distribution, timing, and frequency of climate change impacts (IPCC, 1996; Miles et al., 2000; Ford et al., 2008). These characteristics can affect the physical system, as well as influence the extent to which those alterations impact society (Turner et al., 2003; Ford and Smit, 2004). Adaptability – or the degree to which adjustments are possible in ''practices, processes, or structures of systems in response to projected or actual changes of climate'' – involves adjustments in both ecological and social systems in response to climate change (IPCC, 1996, ix). As noted by the IPCC (1996, ix), adaptation can be either anticipatory or reactive and both ecological and social systems ''have capacities that enable them to resist adverse consequences of new conditions or to capitalize on new opportunities.'' In this paper we highlight the component of adaptability consisting of a system's response capacity, with a focus on existing institutions in the human system and awareness of potential impacts and communication of climate change information, which can strengthen adaptability in the human system (Pielke, 1998; Turner et al., 2003; Adger et al., 2005).

In the case of the McKenzie River, current research has provided insight into the characteristics of the natural system that influence its sensitivity and resilience to climate change. Physical science-based research indicates that certain characteristics of the McKenzie River system can attenuate or amplify the effects of climate change on water resources, resulting in some sub-basins being more sensitive to climate change than others (Tague et al., 2008; Tague and Grant, 2009). However, a parallel understanding of the ways in which characteristics associated with the human components of the system – that is, the actors and institutions involved in using and managing the water supply – is currently lacking. Combining physical science analysis of the system with investigation of the human component can provide a better understanding of sensitivity of water users to climate change in this region and the capacity of the coupled human–natural system to respond and adapt (Fig. 1).

3. The geography of Oregon Cascades water resources

The Western Oregon Cascades are the source of streamflow for a series of east–west trending tributaries that flow into the Willamette River. Lowest elevations within the Cascades are rain-dominated but much of the range maintains a winter snowpack. Streamflows throughout this region reflect the dominance of spring snowmelt as a major source of water, although winter rainfall can produce substantial flows. Peak flows and flood events typically occur during warm storm events that fall on existing snowpacks (Moore and Wondzell, 2005). Precipitation generally increases with elevation. The partitioning of precipitation into rain versus snow and the timing of snowmelt also varies along elevational gradients, leading to spatial differences in the seasonal distribution of streamflow. While snow processes are an important control on the seasonal pattern of streamflow, in the

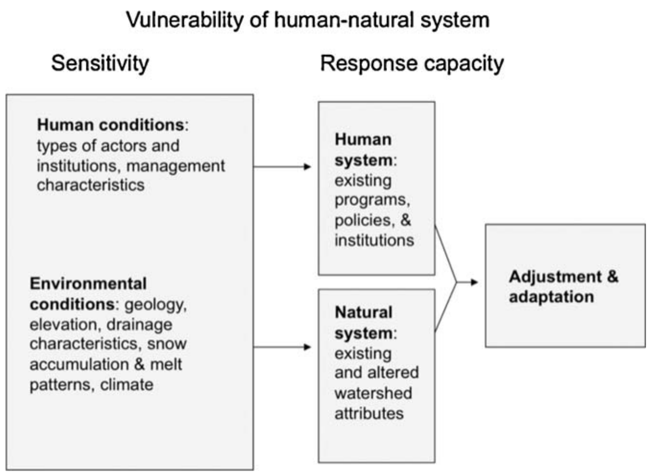

Fig. 1. Conceptual model of vulnerability used to evaluate the human–natural system of the McKenzie River watershed and its vulnerability to climate change effects on streamflow.Adapted from Turner et al. (2003).

Oregon Cascades, geology of the Cascades also plays a key role in shaping spatial-temporal patterns of streamflow.

The Oregon Cascades comprise two distinct geologic units – the High and Western Cascades – with distinct streamflow patterns (Fig. 2). Analysis of historic summer flow patterns within the Oregon Cascades shows that the percent of High versus Western Oregon Cascades in the contributing area of headwater streams is a good predictor of spatial variation in summer streamflow and summer stream temperature (Tague and Grant, 2004; Tague et al., 2007). This empirical relationship between geology and summer streamflow includes a range of elevations and suggests that geologic distinctions are as important as elevation-based difference in snow accumulation and melt as a control on spatial difference in summer streamflow. Analysis based on hydrologic modeling further supports this interpretation (Tague et al., 2008; Tague and Grant, 2009).

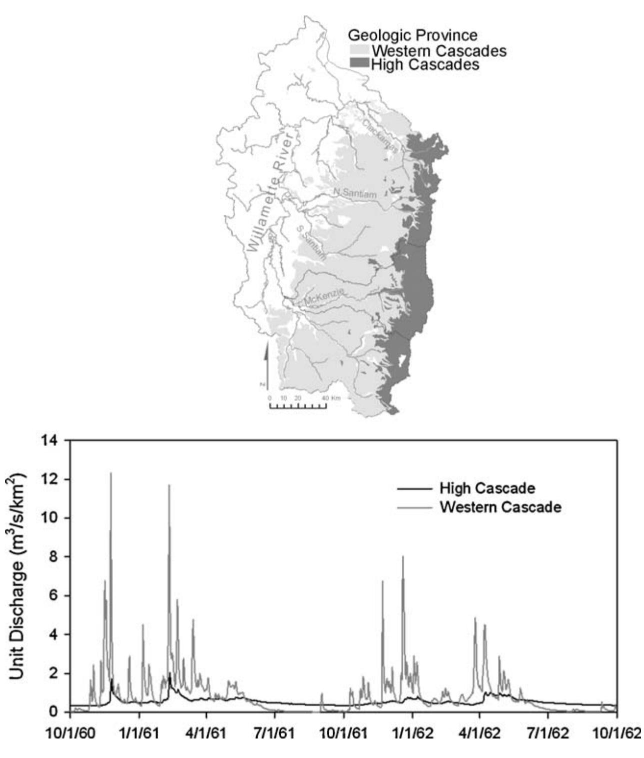

Fig. 2. Flow regimes in the High Cascades (spring-fed) and Western Cascades (surface flow-dominated), Oregon. In the High Cascades, precipitation infiltrates into young lava flows and emerges at large springs. In the Western Cascades, precipitation and snowmelt run off hillslopes directly to stream channels.

Spatial differences in snow accumulation and melt patterns and geologic distinctions also strongly shape how streamflow will respond to a warming climate. Warmer temperatures reduce the amount of precipitation that falls as snow and lead to earlier spring snowmelt. Elevations near the current rain–snow transition line are most vulnerable to this effect (Nolin and Daly, 2006). Streams integrate over a range of elevations but it is clear that streams whose contributing area contains a large proportion of "snow-at-risk" elevation will show greater sensitivity than those at lower elevations. Within the Oregon Cascades, most elevations that are currently snow-dominated are "at risk," in contrast to the Sierras and Rockies where snow at higher elevations is less vulnerable (Nolin and Daly, 2006; Payne et al., 2004; Mote, 2006; Hamlet et al., 2005).

Geology also acts as a first order control on the response of streamflow to climate change. Slower drainage and deep groundwater stores of the High Cascades result in greater summer streamflow but also greater sensitivity of late season flows to changes in inputs as rainfall or snowmelt. Tague and Grant (2009) demonstrate how greater temporal smoothing of inputs, such as occurs in the High Cascades relative to Western Cascades, leads to greater changes in late season flows given the same change in timing of snowmelt. For the High Cascades, this temporal smoothing of streamflow responses to warming reduces the impact of changing snowmelt on winter peak flows but increases the impact on summer streamflow. Tague et al. (2008) applied a hydrologic model (RHESSys) to two McKenzie River watersheds, one dominated by High Cascade geology and the other by Western Cascade geology. RHESSys was also used to examine a hypothetical watershed with High Cascade snow accumulation and melt patterns but Western Cascade geology. This hypothetical watershed was used to investigate the relative effects of differences in geology versus the spatial differences in snow accumulation and melt. Details of model set-up, calibration and verification are summarized in Tague et al. (2008). This model based analysis confirms that spatial differences in geology acts as a first order control on the difference in the sensitivity of Western and High Cascades streamflow to warming, although differences in snow accumulation and melt patterns also contribute to High/Western differences. Model results suggest that reductions in late summer streamflow will be greatest for the High Cascade streams. Hydrologic model results estimate that a 1.5 °C warming (a relatively moderate warming projection for the next several decades in this region (Payne et al., 2004)) will reduce mean August streamflow by approximately 0.46 cfs (cubic feet per second) per mile contributing area for the McKenzie River at Clear Lake, a High Cascade stream, but only 0.08 cfs per mile contributing area for Lookout Creek, a Western Cascade stream. Mile contributing area is used to normalize by watershed area. High Cascade streamflows, in general, are the greater source of streamflow during the summer; thus, their greater sensitivity during the summer will have important implications for water resource management. In contrast, Western Cascade streams will show the greatest changes during the winter months and will be the primary source of increased winter flood flows as more precipitation falls as rain during winter (Fig. 3; Table 1).

Relatively greater summer flows and deep groundwater spring-fed contributions in the High Cascades also lead to colder temperatures in these streams relative to Western Cascade dominated streamflow (Tague et al., 2008). This cold water is critical for aquatic habitat. While higher flows in High Cascades streams to some extent buffer them to warming, predictions of greater reductions in flow in these regions may increase the sensitivity of these streams to warming.

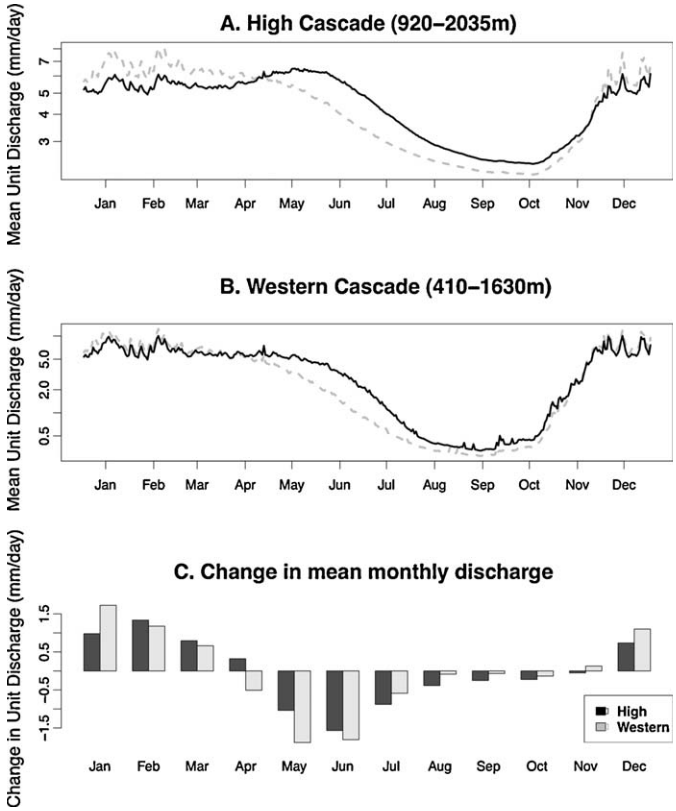

Fig. 3. Projected effects of a 1.5 °C uniform temperature increase on streamflow (mm/day) in the High Cascades (A) and Western Cascades (B), where grey lines represent streamflow under warming, and (C) change in mean monthly discharge (mm/day) in the High Cascades and Western Cascades, Oregon.Figure adapted from Tague and Grant (2009).

In summary, in the Oregon Cascades, a warmer climate will shift the distribution of streamflow in time, with more streamflow occurring during winter and spring and less during the summer (Fig. 3; Table 1). Similar effects of warming on streamflow have been shown using both empirical and model based analysis throughout the Pacific Northwest (e.g. Cuo et al., 2009; Stewart, 2009; Chang and Jung, 2010). Streams within the High Cascade region contribute disproportionately, relative to their drainage area, to system-wide streamflow volumes during the summer (Tague and Grant, 2004). At the same time, High Cascade streams will show greater absolute reductions in summer streamflow (relative to Western Cascade dominated watersheds). Yet, these streams may be increasingly relied upon in the face of summer water shortages. High Cascades streams are also colder and thus are particularly significant as refuges for cold water species under a warming climate. Western Cascade streams dominate flow contributions during the winter, and their fast-draining geology tends to accentuate flood responses, which may increase in a warmer climate (Tague et al., 2008).

Table 1
Type and location of predicted streamflow changes.

Type of change	Portion of watershed
Increased winter flows	High and Western Cascades
Earlier/lower snowmelt-driven peak	Greater change in High Cascades
Reduced late spring flow	High and Western Cascades; timing of peak reduction earlier in Western Cascades
Decreased summer flow	Volume reductions (per area) greater in High Cascades
Minimal snowmelt response	Western Cascades
Earlier and increased intensity of summer drought	Percent reductions in summer flow greater for Western Cascades

4. Approach

A variety of approaches have been used to assess vulnerability, including documenting the ways changing conditions are experienced by a community (Smit and Wandel, 2006). In some cases, "bottom–up" approaches are used, in which researchers seek input from communities on the climatic conditions to which they are most sensitive and their strategies for managing risk (Belliveau et al., 2006; Young et al., 2009). Others have started with a set of climate change scenarios as a basis for "shared learning of both scenario impacts and the regional context on which these impacts would be felt" (Cohen et al., 2006, 333). Our approach resembled that of Cohen et al. (2006), as we sought to understand vulnerability in the McKenzie River watershed by presenting a scenario of regional climate change impacts to stakeholders involved in water use and management and documenting how they expect to experience changing conditions and what factors would facilitate or constrain response to those conditions. There are relatively few studies that take an integrated approach to understanding regional and local impacts of climate change and that engage stakeholders in the process (e.g. Miles et al., 2000; Neilsen et al., 2006; Langsdale et al., 2009), and this study contributes to filling that gap.

Our analysis of sensitivity and adaptability among water users was informed by our knowledge of geographic variation in the projected response of the physical system and focused on features associated with the spatial scale and flexibility as well as the timing and temporal flexibility of water use (Fig. 4). Consistent with past research focused on the links between climate and water resources in the Pacific Northwest, we used a sectoral approach and evaluated impacts on several of the primary water sectors in the system, including both in-stream and out-of-stream uses (Callahan et al., 1999; Miles et al., 2000). With respect to the response capacity of each sector, we gathered information on the institutions – defined here as the "structures of rules used to govern people and resources" (http://www.indiana.edu/~workshop/) – that are currently in place to respond to climate change within each sector, and the degree to which each sector has access to relevant climate change information associated with

Feature of water use	Range of characteristics	
Spatial scale and flexibility of use/activity	Full watershed to reach-specific and Highly flexible to minimal flexibility	Sensitivity and adaptability to climate change effects on streamflow
Temporal flexibility of use/activity	Highly flexible to minimal flexibility	
Institutions that enable response	Existing frameworks able to adjust practices to non-existing frameworks and/or unable to adjust practices	Response capacity in the human system
Access to information on streamflow and climate change	Readily accessible to minimal access	

Fig. 4. Assessing sensitivity and adaptability, including factors related to response capacity, of water users with respect to climate change effects on streamflow in the McKenzie River watershed.

impacts on water resources (Fig. 4). We expected institutional characteristics to influence the perception of risk among water users and managers, as well as the ability of organizations and individuals to respond to climate change (Miles et al., 2000; Berkhout et al., 2006; Dow et al., 2007). At the same time, the degree to which information on climate change and its potential effects reaches stakeholders is likely to affect their ability to respond and adapt (Ziervogel and Downing, 2004). In particular, early understanding of potential local-level impacts of climate change can give communities "time to develop the capacity to adapt to climate impacts" (Whitely Binder, 2006, 915).

4.1. Interviews and presentation of climate change scenario

We conducted in-depth, semi-structured interviews with water users and other stakeholders representing specific water uses in the McKenzie River watershed. Because the interviewees are all considered experts in their fields and were speaking in a professional capacity, these interviews were considered exempt from human subjects review by the Institutional Review Board at San Diego State University. A total of 18 people were interviewed, focused on four key water sectors: habitat for endangered fish species, municipal water, guided fishing (as example from the recreation sector), and flood control. Interviewees were chosen based on their in-depth knowledge of one or more water sectors in the McKenzie River basin. The number of interviews reflects the fact that there were no more than two to five key informants identified for each sector. All of the interviewees who have been cited by name in the text had the opportunity to review this article and have given permission for their names to be used.

The interviews began with the presentation of a climate change scenario and a discussion of the types of changes in streamflow that they illustrate (Fig. 3). Based on these projected changes, the interviews focused on understanding: (1) the spatial scale and distribution of water use by each sector and the flexibility of those uses in space (i.e. could they be relocated to other parts of the watershed or other watersheds if needed?), (2) the timing and the degree of temporal flexibility of each use, (3) the kinds of institutions in place for each use that could potentially assist the sector's response to climate change, and (4) availability and access to scientific information related to the spatial and temporal aspects of climate change effects on water resources used by each sector (Fig. 4).

5. Vulnerability of McKenzie water sectors

We summarize our findings by looking at vulnerability to climate change across sectors. We evaluate characteristics that affect sensitivity (the degree to which the system responds to change, which is influenced by spatial distribution, timing, and frequency of climate change impacts) and adaptability (the degree to which adjustments in practices, processes, or structures are possible, including characteristics that enable them to resist adverse consequences and capitalize on new opportunities) (IPCC, 1996; Ford et al., 2008). For each sector, we then highlight one key aspect of adaptability by evaluating the institutions that influence the response capacity of the human system.

5.1. Fish habitat for endangered species

Projected changes in streamflow, along with associated changes in stream temperature, in the McKenzie River are likely to have substantial impacts on fish habitat. Habitat managers must interpret these changes within the context of existing spatial patterns of fish habitat, key species of interest, and a wide range of other threats to fish populations. One of the key species of concern for fish managers in the McKenzie and larger Willamette River watershed is spring Chinook salmon (*Oncorhynchus tshawytscha*), a species listed as threatened and considered likely to become endangered (Good et al., 2005). Historically, spring Chinook are believed to have consisted of seven spring-run populations in the upper Willamette system; however, the 1998 status review noted that the McKenzie population was the only remaining naturally reproducing population, and the only one that was potentially self-sustaining (Good et al., 2005). Because the McKenzie population constitutes much of what remains, it is considered by managers to be the anchor for recovery of the species in the Willamette basin (Bickford, 2007; Ziller, 2007). While the spatial distribution of spring Chinook is limited outside of the McKenzie River watershed, it is more widely distributed within it and can be found in both the Western and High Cascades portions of the watershed (Bickford, 2007). However, managers note that levels of production are low in the Western Cascades portion and juvenile production – the focus of recovery efforts – is reliant on the High Cascades portion, where stream temperatures currently remain low throughout the summer (Bickford, 2007; Ziller, 2007).

Changes in streamflow associated with climate change have the potential to affect the spatial distribution of spring Chinook in the McKenzie River. Managers in the Oregon Department of Fish and Wildlife (ODFW) note that the reduction in late summer flow may be particularly critical, as salmon move into spawning areas in September (Ziller, 2007). Most of the Western Cascades have streamflow below the minimum needed by salmon at that time of year – a situation that would be unchanged under climate change scenarios; however, managers suggest that reduced flows in the High Cascades portion of the watershed (Fig. 3) could affect how far upstream salmon would go (Ziller, 2007), increasing the sensitivity of the species. Others cited this potential for reduced spatial distribution within the watershed, combined with somewhat limited spatial flexibility associated with spring Chinook's strong attachment to their natal location (Bickford, 2007), as having the potential to limit the species' adaptability under climate change.

Fish habitat managers clearly incorporate spatial thinking regarding this species, and also note that spring Chinook salmon are part of a larger system and they are susceptible to many limiting factors across their range, creating a population that is "always in flux and always dependent on something else" (Bickford, 2007; Ziller, 2007). Those other factors include fish passage at the Willamette and Columbia Rivers, upwelling conditions in the ocean and level of ocean survival, level of ocean harvest, and disease, among others (Good et al., 2005; Ziller, 2007). These conditions can either intensify or ameliorate sensitivity to climate change by improving or diminishing (for example, in the case of increased ocean survival or disease, respectively) their ability to resist adverse changes.

While the spatial distribution and flexibility of spring Chinook populations appear to create substantial vulnerability to climate change, the constraints are even more severe for bull trout (*Salvelinus confluentus*), a species with patchy and scattered distribution in the Pacific Northwest that is also listed as threatened (USFWS, 2005). Bull trout previously existed in a number of watersheds in the Oregon Cascades, but the spatial distribution outside the McKenzie River watershed is now limited, with only about a half dozen streams in the Oregon Cascades producing them (Allen, 2008; Ziller, 2007). Therefore, like spring Chinook, the McKenzie is considered a key population of bull trout (Kretzing, 2007). Its spatial distribution within the McKenzie River is small, however. The species uses the Western Oregon Cascades portion at later life stages for migration and overwintering, but spawning and juvenile rearing are limited to a small area of the upper McKenzie that is the sole refugia for the species in the watershed, creating a clear focus on spatial aspects of this species and its habitat on the part of managers (Allen, 2008; Bickford, 2007; Kretzing, 2007). Bull trout is a highly temperature-sensitive species, requiring temperatures below 12–16 °C to persist and 8 °C to spawn, making them very reliant on High Cascades geology (Allen, 2008). Because of this, the most viable populations are in the few tributaries in the High Cascades that are "very cold, stable, and spring-fed" (Allen, 2008). In addition, biologists focus on other spatial aspects of habitat, noting that the High Cascades has a greater amount of spawning habitat with appropriate gradients (Bickford, 2007). Further, they point out that bull trout are thought to have very high fidelity to their natal location, which also may limit their spatial flexibility (Bickford, 2007), and therefore their adaptability.

Managers consider the narrow spatial distribution of bull trout problematic even in the absence of climate change, primarily because it leaves the population exposed to any kind of disturbance in the primary spawning area (Bickford, 2007). Experts note that if production were spread over a greater area it would leave the population less vulnerable to potential disturbances in any of those locations (Bickford, 2007). However, some managers perceive streamflow from the High Cascades as stable and less sensitive to climate change, leading to the perception that bull trout habitat also will have lower sensitivity (Allen, 2008). In this case, although this view does incorporate spatial and temporal aspects of streamflow, this could actually lead to an underaccounting for potential impacts of climate change. However, the McKenzie River is the focus of recovery efforts for bull trout in part because many other basins that previously supported it are already on the edge of appropriate temperatures for the species, with climate change expected to worsen the problem (Allen, 2008). Therefore, the degree to which changes in High Cascades streamflow impact bull trout habitat in the McKenzie River will have a substantial impact on how likely the species is to persist at a broader spatial scale.

In contrast to spring Chinook and bull trout, Oregon chub (*Oregonichthys crameri*) is restricted to the Western Cascades portion of the watershed. The species was historically found throughout the Willamette River valley, but was listed as endangered in 1993 when only eight of the 29 historic populations were found to exist (USFWS, 1998). The recovery plan calls for increasing both the number of populations and their spatial distribution, and there are now 20 populations that are considered viable (having more than 500 adults with a stable or increasing 5-year abundance trend) spread across four major watersheds (Scheerer, 2007). Oregon chub is a floodplain fish that used to move around during floods, but is now fairly resident and includes six known populations in the lower McKenzie, one of which is an introduced population established by managers (Scheerer, 2007). The species became endangered due to loss and alteration of habitat, in many cases associated with changes in seasonal flow resulting from dam construction, as well as to the presence of non-native, warm-water fish, such as largemouth bass, smallmouth bass, crappie, bluegill, and western mosquitofish (Scheerer, 1999). Although it is contrary to its life history, experts note that the species appears to being doing better in locations where it is more isolated; this is thought to be due to the absence of the non-native fish species, which appear to limit the abundance of Oregon chub where they co-exist (Scheerer, 2007, 1999; USFWS, 1998).

Experts suggest that the current spatial distribution of Oregon chub – including a mix of locations with and without non-native species present – may be key to the sensitivity of the species to climate change. Oregon chub are strongly influenced by temperature and spawn when temperatures warm to 15–16 °C in the spring (Scheerer, 2007). In the case of the McKenzie River, water temperatures in some locations are low enough that the non-native warm-water species tend not to be present, leaving a relatively narrow temperature window that is warm enough for Oregon chub to spawn and cool enough to be unsuitable for the non-native warm-water species. Researchers suggest that the decrease in spring flow predicted to occur with climate change could benefit the non-native species by increasing temperatures, thereby creating more suitable warm-water habitat (Scheerer, 2007).

In addition to a broader spatial distribution than the other listed species, Oregon chub appears to have a greater degree of spatial flexibility. Because it is a fairly resident species, it is possible to establish individual populations around a specific area and build up the genetic base to the point of creating a recovered population (Ziller, 2007). This ability to establish new populations, which is a focus of recovery efforts for the species, gives much greater flexibility, and thereby greater adaptability, because these populations can also be moved if the habitat the fish were translocated to ultimately does not provide for the establishment of a new population (Ziller, 2007).

5.1.1. Response capacity: fish habitat for endangered species

> "Recovery plans are supposed to be living documents" (Scheerer, 2007)

Because spring Chinook, bull trout, and Oregon chub are all listed under the Endangered Species Act (ESA), there are already institutions for their management in place that could provide a potential framework for responding to the effects of climate change. Once species are listed, primary responsibility lies with the U.S. Fish and Wildlife Service (USFWS) in the cases of bull trout and Oregon chub, and with the National Marine Fisheries Service (NMFS) in the case of spring Chinook. Recovery plans are developed for each species listed under the ESA, and these recovery plans "are supposed to be living documents" (Scheerer, 2007), providing a "fair amount of latitude to shift priorities each year" (Bickford, 2007). In the case of spring Chinook, development of the recovery plan is still in progress, while a draft recovery plan for bull trout was created in 2002 and an update of the Willamette Recovery Chapter of the Draft Plan was completed in 2008 (Ziller, 2007; Allen, 2008). The Oregon chub recovery plan is finalized and focuses on both increasing the number of populations as well as increasing their distribution (Scheerer, 2007).

The process of initially completing and finalizing recovery plans can be "a daunting task," that occurs over long time periods. Therefore, although these recovery plans provide a framework for management that could be beneficial in the context of climate change, incorporating new data and modifying the plans can be challenging (Allen, 2008). At the same time, however, there is recognition that the plans tend to quickly become outdated, and there is flexibility associated with the fact that recovery plans are guiding documents rather than regulatory documents, so priorities can be re-assessed and changes can be made based on new data (Allen, 2008). In many cases, when species are listed, working groups are formed that are generally headed and facilitated by a USFWS (or NMFS) biologist, with members who are invited to participate on the team and provide guidance in developing the plan. These working groups also have the ability to evaluate new information, compare it with the recovery plan, and incorporate it for future planning (Allen, 2008). These characteristics enhance adaptability by allowing for adjustments in practices to be made (Table 2).

Other institutions are also involved in management of endangered species, and would likely play a key role in the context of climate change. Because the U.S. Forest Service (USFS) is a primary land manager in the habitat of these species, they

Table 2
Examples of opportunities and constraints associated with projected changes in streamflow for water use sectors in the McKenzie River watershed.

Opportunities	Constraints
Oregon chub recovery plan explicitly requires better spatial distribution as part of delisting	Spring Chinook and bull trout are very reliant on High Cascades portion of the watershed
Listing under ESA means that committees regularly review the status of endangered fish	Lack of information on potential effects of climate change specific to each endangered species
USACE dams are part of a larger system, which could provide spatial flexibility	USACE's primary mandate is flood control, so ability to maintain summer flows for other uses may be restricted by flood requirements
USACE already has a temperature control tower at Cougar dam and a climate change team in place	USACE's decisions about winter releases are dependent on rule curves
Superior water use right by EWEB (although may be altered by Endangered Species Act)	USACE rule curves are mandated by Congress and very difficult to change
EWEB has well-funded water conservation program in place	Wastewater treatment already challenging at winter–summer transition, which will likely have the greatest change with warming
EWEB able to commission climate change research specific to their use	Wastewater treatment infrastructure and regulation are based on historical flow data and are already difficult to meet operationally; exacerbated with climate change scenarios
Guided fishing can employ some spatial flexibility (spending part of the year in the upper watershed or on other rivers) that provides a response option to temporal constraints	EWEB lacks forecasting tool customized to the McKenzie River
Guided fishing could benefit from lower flows in the spring	Recreational uses are primarily in summer and would be impacted by lower summer and fall flow
McKenzie River Guides Association already politically engaged, has a lobbyist to work on state-level political issues	Lack of state-wide institutional support for sectors such as recreation

USACE = U.S. Army Corps of Engineers; EWEB = Eugene Water and Electric Board; ESA = Endangered Species Act.

consult with USFWS on management activities in order to make sure they do not result in harm to the endangered species (Kretzing, 2007). They also provide information on where the populations are and where restoration should focus, as well as providing risk assessments for some proposed management activities (Bickford, 2007). Although, in general, specific information on likely impacts of climate change on these species is extremely limited, this provides a potential for producing some of the information that would be needed to inform adjustments in practices.

At the state level, the Oregon Department of Fish and Wildlife is responsible for all the species in the state; however, once they become listed, the responsibility for management and control shifts to the federal level (Ziller, 2007). This shifts ODFW from the primary manager, with the ability to independently manage a species, to "a cooperator in the process" (Ziller, 2007). In this sense, some of the flexibility in management could potentially be diminished, as management activities are then evaluated at the federal level (Ziller, 2007). However, according to one of its staff members, USFWS provides input on the state's plans for management activities but "gives broad discretion to the state" in terms of implementing those actions (Allen, 2008). These multiple levels of management could promote adaptation by providing additional sources of information and review, but also have the potential to impede flexibility, and thereby adaptability, due to additional layers of decision-making.

Despite the relative flexibility of these institutions, data are limited on potential impacts of climate change on these species, which limits the degree to which it has been incorporated into planning and constitutes one constraint to adaptation for this sector (Table 2). However, at the state, regional, and national levels, USFWS is now incorporating climate change into determining whether species should be listed or delisted, and into recovery planning and other programs (Allen, 2008).

5.2. Flood control

Flood control is the primary mandate of the U.S. Army Corps of Engineers (USACE), which operates two dams, Cougar and Blue River, on tributaries of the McKenzie River. These are part of the larger Willamette system, which includes 13 dams and reservoirs managed by USACE that work as a system (Rea, 2007). Between Cougar Dam, which is the fifth largest, and Blue River Dam, they provide 14% of the conservation storage (water that can be used to meet authorized purposes) for the system (Taylor, 2007). After fulfilling its primary authorized purpose of flood control, according to a senior staff member, "the rest is not our water" and they "have a balancing act to meet downstream needs" (Rea, 2007). Decisions regarding releases of water from the reservoirs to meet their primary mandate of flood control determine the amount of water available for other activities, including recreation and fish and wildlife. In general, the reservoirs are drawn down into the fall and reach their minimum by November, leaving space available for flood control between November and February. As the flood risk abates in the spring, reservoirs are filled until the flood risk is near zero in May and the stored water is used to meet all the other authorized purposes (Taylor, 2007). The decisions about filling and releasing water are guided by "rule curves," which mandate that reservoir water levels be maintained at or below the time-varying height specified by the curves, except during a flood. Thus, the rule curves determine the legal maximum allowable reservoir height, to enable flood control, and are based on flood control diagrams that were put together 50–60 years ago based on conditions over the previous 30 years (Taylor, 2007; Rea, 2007).

Changes in winter precipitation, including both increased winter flow and an increase of rain rather than snow (Fig. 3), will increase the flood risk that USACE is mandated to manage (Taylor, 2007). In response to this increased risk, USACE likely would have to be more conservative when re-filling their reservoirs in order to leave available space for flooding. When combined with spring runoff that is predicted to be lower than in the past due to the earlier and lower snowmelt peak (Fig. 3), the activities that rely on conservation storage are put at greater risk (Taylor, 2007). This could be exacerbated by decreased summer flows from the High Cascades portion of the watershed (Fig. 3, Table 1), which would likely impact the drawdown of reservoirs as this may occur more quickly than if baseflows remained higher (Taylor, 2007). These changes in the quantity and timing of streamflow could complicate the already-difficult task of meeting the water demand for all the activities that rely on conservation storage, creating greater sensitivity to climate change in the system. But, because USACE is operating with rule curves that are based on historic hydrologic conditions, accommodating changing hydrology presents challenges (Taylor, 2007).

The question of flexibility of water use by USACE depends greatly on the scale at which it is evaluated. At the scale of the McKenzie River watershed, spatial flexibility is limited, with dams being in fixed locations on two of the river's tributaries. At the same time, being part of a larger system of reservoirs can provide both flexibility and constraints (Table 2). For example, water quality requirements on the Willamette River could not be met in late summer without releases from reservoirs in this system (Taylor, 2007). At certain points along the Willamette River where water can potentially be drawn from a number of different reservoirs there is wide latitude in terms of how to meet regulatory requirements for minimum flow needed for water quality, and this ability to adjust practices increases adaptability. However, the released water may come from a reservoir, such as Cougar, that has not yet filled and potentially will not fill because of releases for these other uses (Taylor, 2007). In this sense, flexibility at the scale of the Willamette system would translate to a constraint at the scale of the McKenzie River if it was the source of additional water. In addition, certain reservoirs within the system are given high priority for recreational uses, which means that USACE must "pull from other reservoirs and sacrifice other reservoirs" to meet downstream requirements (Rea, 2007), influencing all of the other watersheds within the system (Taylor, 2007). According to one USACE senior staff member, releasing that constraint would provide much greater flexibility, but would constitute a trade-off with recreation in those locations (Rea, 2007).

The ways in which operations will be adjusted in response to altered streamflow will depend on the response within the McKenzie River watershed as well as in each of the other watersheds that make up the system. Therefore, adaptability will depend in part on the response of those watersheds. If streamflow in other watersheds is more affected by climate change than in the McKenzie River, that may mean that reservoirs such as Cougar would have to be drawn down even more quickly to meet downstream needs (Taylor, 2007). However, if other watersheds are less affected, there is potential for fewer releases from McKenzie reservoirs.

5.2.1. Response capacity: flood control

"Changing the rule requires going back to Congress" (Rea, 2007)

In terms of response capacity, the U.S. Army Corps of Engineers faces both opportunities and constraints (Table 2). They have a national team established to evaluate the impacts of global climate change. Although it is currently not well-funded and is oriented more towards sea-level change and the effects on navigation, it provides an institutional structure that could begin to address some of the impacts on dam operations (Vaddey, 2007). However, USACE functions within an institutional and regulatory framework unlike any of the other water sectors in that they are required to abide by rule curves that are Congressionally authorized. In addition, minimum streamflow requirements were put into place when the dams were authorized, which also must be met (Rea, 2007). Any change in these rules requires going through a detailed evaluation of the hydrology, as well as the economic and environmental trade-offs of the proposed change, and the project would have to be reauthorized through Congress (Rea, 2007; Taylor, 2007). This process requires justifying why the proposed change would be a better way to operate the project, a task that is complicated by the fact that the system is operated as a whole rather than as individual dams and reservoirs, as well as the fact that any change would impact some users positively and others negatively, creating potential resistance to such changes. There has been some discussion of adjusting the rule curves in recent years, both in the McKenzie and in other parts of the Pacific Northwest where climate change effects on water resources have been evaluated (Miles et al., 2000; Lee et al., 2009). However, it would be a costly and extremely time-consuming process (Taylor, 2007), with the feasibility study taking a minimum of 3–5 years followed by the time needed for Congress to act on it (Rea, 2007).

In addition to these complications, according to a senior USACE staff member, an important complication associated with changing the rule curves is whether all the unintended consequences of the change can be adequately assessed (Rea, 2007). Some of these consequences may be associated with downstream uses, such as endangered species habitat and state-level water quality mandates, which are the two principal regulatory issues that confront USACE managers (Rea, 2007). Because the water quality regulations focus on temperature, and require that there be no anthropogenic heating, they are particularly relevant in the context of climate change and the potential for lower streamflow (Rea, 2007). However, the McKenzie River is unique within the Willamette system in that the Cougar Dam has a temperature control tower that began functioning in 2005 which draws a mix of deep cold water and warmer surface water from the reservoir, allowing the temperature of the released water to be optimized for endangered species (Rea, 2007; Duffe, 2007). The fact that the infrastructure for temperature control already exists at Cougar Reservoir, the fifth largest in the Willamette system, provides some existing capacity to ameliorate stream temperatures and presents an opportunity to respond that does not exist in other locations (Table 2).

The fact that USACE operates with Congressional authorization, in addition to endangered species and water quality regulations, clearly present constraints in terms of their ability to respond to changing conditions. However, at the same time, they do have flexibility annually in terms of making decisions about where water is needed and where it will be drawn from. Although the rule curves are based on data that are many decades old, the annual decisions rely on real-time tools that are updated with information for the current water year (Rea, 2007). Further, there is an interagency team that involves representatives from multiple agencies and user groups and provides input on managing flows from the reservoirs on a year-to-year basis (Taylor, 2007). This framework is already in place and has the ability to adapt over time, potentially providing a space in which climate change impacts might be integrated into the planning process and decisions about flow allocation.

5.3. Municipal water

The Eugene Water and Electric Board (EWEB) manages water from the McKenzie River to provide drinking water for more than 200,000 people in the city of Eugene and surrounding areas in Lane County, OR.[1] Although EWEB's water use is derived from the entire watershed, the spatial aspects of changing streamflow will influence them to some degree due to the fact that the infrastructure for water intake and treatment is in a fixed location and constitutes a large financial investment (Newcomb, 2007). At the same time, there is a strong temporal aspect to EWEB's provision of water, both under current conditions and under scenarios of climate change. Water demand follows a bell curve, peaking between June and August, with summer use reaching as much as three times the yearly average (Taylor, 2008) and the most

[1] Although EWEB also generates hydroelectric power on the McKenzie, constituting $\leq$15% of their total power portfolio, this paper focuses on water provision.

difficulty matching supply and demand occurring in August and September (Newcomb, 2007).

Depending on the magnitude of change, a decrease in summer flow and lengthening of the dry period which are expected to occur with climate change (Fig. 2, Table 1) could affect the ability of EWEB to deliver water particularly at the end of the dry period, suggesting heightened sensitivity to climate change that might necessitate changes in how and when EWEB uses water (Morgenstern, 2008). These changes in streamflow could create competition with other uses (Taylor, 2008), particularly given that the Oregon Department of Water Resources is still allocating water rights on the McKenzie River, based on historical resources, which would be diminished under climate change scenarios (Newcomb, 2007). EWEB holds a number of water rights on the McKenzie River, some of which are superior to in-stream water rights. However, the Endangered Species Act can provide mechanisms for elevating rights of endangered species, leaving doubts as to whether holding those rights would continue to guarantee first access to water from the McKenzie River under conditions of decreased summer flow (Taylor, 2008).

Lower summer flow is also likely to be important for major water users, such as Weyerhaeuser, which has a pulp mill adjacent to the McKenzie River that operates a pump station to pull water directly from the river. The mill has rights to as much as 81 cubic feet per second (cfs) from the river and uses an average of 16 million gallons per day, with cooling being one of their major water uses (Weyerhaeuser Co., 2007). This water does not go directly back into the McKenzie River, but does reach the Willamette, where new Total Maximum Daily Load (TMDL) requirements on temperature were established in 2006. According to one of the engineers at the mill, September represents the point of highest vulnerability in terms of meeting these temperature regulations (Weyerhaeuser Co., 2007). A decrease in late summer flow associated with climate change would likely exacerbate the difficulty in meeting these requirements.

While changes in summer flow will influence water quality for some users, changes in the quantity and timing of winter and spring streamflow may have a stronger impact for others. Earlier spring snowmelt and increased winter flow, both of which are expected with climate change (Fig. 3), have potential impacts on water quality, which affect the ability of EWEB to process water and influence the sensitivity of this use to climate change. Increased winter flow has a direct effect on turbidity, which impacts the ability to treat the water (Morgenstern, 2008). Currently, the surface water treatment facility allows for settling time followed by filtration of the water to remove particulates; any increase in turbidity means that a larger capacity is needed to treat those flows, resulting in a reduction in overall capacity and an increase in the cost of treatment (Morgenstern, 2008).

The possibility of increased winter flow would also impact wastewater treatment, creating the need for increased treatment of stormwater. However, an even greater impact would likely result from the reduction in snowmelt and shift to earlier summer drought (Fig. 3) (Ruffier, 2007). Currently, wastewater treatment is regulated by two different seasonal flow rates: one for winter, where the discharge limits are higher and a greater mass of solids is permitted, and one for summer, which begins on May 1 and runs through September. The transition period from winter to summer already presents difficulties for meeting water quality standards, due in part to the use of a transition date that is not based on actual streamflow conditions so it can be difficult to meet operationally. Therefore, any shift in streamflow patterns that causes the summer dry period to begin earlier would only exacerbate the challenges of the transition period (Ruffier, 2007).

5.3.1. Response capacity: municipal water

> "The buzzword has been sustainability – but it's not about sustaining what was, it's about being adaptable...." (Newcomb, 2007)

In terms of municipal water, the response to changing streamflow lies primarily with the Eugene Water and Electric Board. Institutional characteristics that strengthen EWEB's response capacity include its relatively well-funded existing water conservation program, which currently receives approximately 10% of the EWEB water budget. In particular with respect to a potential decrease in summer flow, this program would provide a mechanism for creating programs that focus on reducing water use at specific times of the year (Morgenstern, 2008). In terms of constraints, EWEB lacks a specific forecasting tool that is customized to the McKenzie River watershed, though they do have funds targeted toward this and have efforts underway to coordinate with other institutions to find additional funding towards this goal (Morgenstern, 2008). Internal funding has also allowed them not only to access information on the impacts of climate change, but also to fund research that responds to questions specific to their water use needs. However, the availability of funds also requires awareness on the part of EWEB's Board of Directors and the public regarding potential impacts of climate change and the need for such tools (Morgenstern, 2008).

The scale of analysis is also important in terms of EWEB's response capacity. Internally, they have substantial flexibility to adjust practices, and therefore adaptability, in terms of addressing restrictions through conservation and in terms of the ability of the planning staff to gather current information and make a case to the Board of Directors to implement change. As part of EWEB's planning process, they are looking at diversifying their water resources – including groundwater, other sources in the Willamette, and federal storage projects – in order to plan for the potential of having less water from the McKenzie River, reflecting adaptability in terms of adjusting practices and structures in anticipation of change (Morgenstern, 2008).

However, municipal decisions take place within a state-level regulatory framework. Any change in regulation under changing climate would come from the Oregon Water Resources Department, and EWEB's decisions would be constrained within those regulations (Morgenstern, 2008). This is particularly relevant in the case of state-level water quality standards, which strongly influence water use decisions at the local-level (Ruffier, 2007). In addition, there are some "institutional barriers to good planning" that originate at the state level, such as the fact that water rights are based on how much water is used, providing a disincentive for conservation (Newcomb, 2007).

Finally, from the infrastructural side, there are substantial constraints on adaptation. One expert on wastewater management pointed out that infrastructure is designed based on historical events and if the frequency of events changes there will be "a mismatch." This problem is exacerbated by the fact that the lead time for changes in infrastructure can be as long as 75–100 years (Ruffier, 2007). This suggests that while there is institutional flexibility in terms of managing municipal water in the face of climate change, there are limits on that flexibility and the types of adjustments in practice that can be made imposed by the existing infrastructure.

In addition to EWEB, a wide variety of stakeholders are actively involved in watershed management, many of whom are represented on the McKenzie Watershed Council (Morgenstern, 2008; Six, 2007). EWEB is one of the major partners on the Council, while USACE, endangered species representatives, recreation groups, and some of the main industries who influence or are influenced by water quantity and quality, such as Weyerhauser, are also represented. The Oregon Department of Environmental Quality, which sets regulations on water quality, is not a member, but also works closely with the Council (Six, 2007). The Council's main focus areas are fish and wildlife habitat, water quantity and quality, recreation, and human habitat, but because it includes a broad range of users, it has the potential to provide an institutional structure that could be used as a forum to negotiate changes to the management of water resources under changing conditions (Six, 2007). These types of existing stakeholder networks have been found to be important for dissemination of climate information, and this type of locally based watershed planning may be valuable for building adaptive capacity in managing climate change impacts (Ziervogel and Downing, 2004; Whitely Binder, 2006). Although the capacity to adapt to changing conditions is considered a benefit of this type of collaborative resource management, the level of conflict among competing water uses would likely play an important role in determining whether the Council would serve to strengthen the response capacity of these user groups, with adaptability considered to be lower where there is a high level of conflict (Miles et al., 2000; Heikkila and Gerlak, 2005).

5.4. Recreation, the example of guided fishing

The recreation sector, in general, and guided fishing, in particular, is likely to be impacted by temporal aspects of changing streamflow due to the seasonal nature of these activities. The fishing season opens at the end of April every year (although certain parts of the river are open to catch-and-release fishing all year) and, for some fishing guides, the main season on the McKenzie is spring while others guide on the river year-round (Helfrich, 2007). The spring is the time period when the greatest absolute decrease in streamflow is expected to occur in both the High Cascades and Western Cascades portions of the watershed (Fig. 3, Table 1). This shift could be a benefit for guides since high flows, such as those that occurred in 2008 when the snowpack was well above average and spring runoff was high, can make fishing difficult at that time of year (Steele, 2009).

Lower streamflow in the spring, in combination with a shift toward snowmelt occurring earlier in the year, also could impact the timing of the start of the season, and could extend the season for a number of users. However, while changes in streamflow may allow for an earlier start to the season, some guides expressed concern that the biology of the system may not coincide with that shift; for example, the fishing season relies on insects that hatch in response to the number of hours of light and this would not be expected to move forward with higher temperatures (Helfrich, 2007). In addition, the impact of this change on guided fishing may be mediated by the impact on flood and water quality management. Currently, some guides suggest that large releases of water from the reservoirs in the spring mean that they are trying to "start fishing when the water is way too high" (Helfrich, 2007); while natural streamflow in the spring is expected to be lower with climate change, whether spring releases from reservoirs are lower will depend in part on the response of USACE to changes in winter precipitation and streamflow.

While lower spring streamflow has potential benefits for guides, lower flows in summer and early fall would have a negative impact (Helfrich, 2007; Steele, 2009). The lower summer flows could affect the ability of the boats to navigate rapids and shoals, which influences the experience of those paying for recreation on the McKenzie River (Helfrich, 2007). One guide pointed out that they "compete globally for recreation dollars" and that "what sells is the experience" (Helfrich, 2007). For fishing, this requires having enough water for the boats to float and for the fish to survive (Helfrich, 2007). Changes in streamflow associated with climate change would potentially constitute one factor affecting this experience; however, it would be in addition to factors that are already having an effect such as housing development that can bring with it lawns, fertilizers, loss of shoreline vegetation, and bank erosion that impact the quality of fishing, particularly in the lower watershed (Helfrich, 2007). Ultimately, according to one guide, "if that experience isn't there, you can't convince them to come back and word starts to travel" that the experience and the fishing on the McKenzie are diminished (Helfrich, 2007).

To some degree, these temporal constraints can be mitigated by spatial flexibility that can provide a greater degree of adaptability within this water sector (Table 2). Although some guides stay on the McKenzie River all year, others spend part of the year on other rivers outside the state; these "McKenzie-Idaho guides," who have permits on rivers outside the region for part of the year, have the ability to strategize to guide the best rivers for different times of the year (Steele, 2009; Helfrich, 2007), improving their adaptability by enabling them to adjust practices in order to lessen or "resist adverse consequences" (IPCC, 1996) of new conditions. This flexibility also exists within the state, where guides may move to the Rogue River or another location that is having a particularly good year (Steele, 2009). However, to the degree that these rivers are similarly impacted by climate change, these strategies would be less effective in improving the adaptability of this water sector. Finally, this kind of spatial flexibility in response to a temporal constraint may also exist within the McKenzie River watershed. Although many guides do not work on the upper part of the river because it is more difficult, those that do can capture "more of a private wilderness experience" in the part of the watershed that is less impacted by development (Helfrich, 2007). Whether the decrease in summer flow in the High Cascades portion of the watershed would be of a large enough magnitude to impact this experience is unclear.

5.4.1. Response capacity: recreation, the example of guided fishing

> "[We] stay politically engaged because we have to" (Steele, 2009)

As with other sectors, recreational activities such as guided fishing are heavily affected by decisions made at state and regional levels. According to one guide, much of the attention is focused on the off-shore impacts of declining fisheries and tends to overlook the impact on the inland businesses and industries that also rely on healthy fisheries and are impacted by closures and other state-level decisions (Steele, 2009). As a result, groups such as the McKenzie River Guides Association, which is the predominant guide industry organization for Oregon, have become more politically engaged than in the past (Steele, 2009). Their representatives spend a significant amount of time at the state capitol advocating for legislation, and they have a lobbyist who also advocates on their behalf (Steele, 2009). However, this political engagement occurs in spite of the fact that there is little in terms of state-wide organization for this sector. In comparison to the other water sectors, this sector consists of a wider variety of users who have relatively little access to information on climate change specific to their uses. In addition, according to one board member of a guiding organization, the level of institutional support for the guide industry is "almost none" (Steele, 2009).

6. Conclusion

The characteristics that contribute to vulnerability are often not known a priori (Smit and Wandel, 2006). However, in the case of the McKenzie River, our knowledge of the importance of spatial and temporal aspects of change in the natural system (Table 1) informed our analysis and allowed us to explore their impact on and interaction with the human system, including the degree to which water managers account for them. This research illustrates that the implications of changing streamflow vary substantially among different water users, with vulnerabilities being determined in part by the spatial scale and timing of water use and the flexibility of those uses in time and space.

The main focus of fisheries management within the McKenzie River is the support of three key populations (Oregon chub, spring Chinook salmon, and bull trout). Recovery efforts for each of these three species are typically focused on specific locations that are selected based on the perceived likelihood of improving population viability. Thus, fisheries management is inherently spatial. Managers utilize experience and science-based information on the spatial pattern of current and historic habitat quality within the McKenzie watershed in designing and deciding on recovery strategies. With a warming climate, however, this spatial pattern changes. There is likely to be a reduction in the spatial extent of current habitats. For both spring Chinook salmon and bull trout, this change is coupled with a somewhat limited spatial flexibility and is likely to increase their sensitivity to warming and limit their adaptability to climate change impacts on streamflow. In contrast, the adaptability of Oregon chub is enhanced by the potential for a spatially flexible management response because, for this species, new populations can be more readily developed in new locations rather than simply extending the range of existing populations (Table 2).

Users that rely specifically on late summer flows, such as municipal water, also have heightened sensitivity to the projected streamflow changes associated with climate change. The fact that the timing of the projected decrease in streamflow coincides with the timing of peak municipal water use as well as the most difficult time period for meeting TMDL requirements leads to increased sensitivity in this sector. Thus it is the combination of temporal constraints on the user combined with climate-driven changes in the timing of water availability that contribute to the heightened sensitivity. While fishing guides will also face constraints associated with their sensitivity to a decrease in summer flow, changes in spring flow may present some opportunities, and their overall vulnerability may be lowered due to the existence of some spatial and temporal flexibility in their activities, at least on the part of some guides (Table 2). This case illustrates that spatial and temporal aspects of changing streamflow and water use can interact, where spatial flexibility on the part of water users may improve adaptability to temporal constraints resulting from the response of the natural system to climate change.

Flexibility and adaptability, however, are also influenced by the responses of other users. For example, more than one sector exhibits sensitivity to changes in winter flows, with implications for other water use sectors as well as other water use seasons. Municipal water activities related to water quality and wastewater treatment face constraints with increased winter flows, while the flood control sector will likely be particularly sensitive to these changes in the quantity and timing of streamflow. At the same time, users such as USACE and municipal water have the capacity to alter the spatial-temporal characteristics of the system via reservoir management and withdrawals, respectively, with implications for other users. In the case of the McKenzie, flood control requirements may limit the ability to ameliorate, and may even exacerbate, climate-driven summer flow reductions. The fact that these sectors manage flows that impact a variety of other users, among whom there are competing multiple uses that are dependent on flows at different times of the year, makes the degree of sensitivity to the spatiotemporal aspects of changing streamflow and the response of this sector particularly relevant to others within this human–natural system.

Adaptation can be considered as a portfolio of responses rather than a single response (Pielke, 1998), and adaptive capacity can be strengthened by awareness of the potential impacts of climate change, as well as by institutional characteristics that influence the portfolio of possible responses. In the case of the McKenzie River, our findings suggest that these also vary from one water use sector to another and that impacts on one sector may have important implications for other sectors.

In several sectors we found opportunities for adaptation through existing institutions, such as the well-established conservation program within EWEB that could lead efforts to alter water use in ways that take into account temporal aspects of changing streamflow (Table 2). In addition, in the case of all three endangered fish species, the recovery plans developed following their listing as threatened or endangered, and the associated working groups that have been formed for their management, provide a framework that could be beneficial in responding to climate change. In particular, the fact that the recovery plans are considered guiding documents rather than regulatory documents suggests that they have potential to facilitate adjustments in practice under new conditions. This reflects a type of "managerial flexibility and the ability to incorporate new information" that has been identified as a key element in effectively responding to climate change (Miles et al., 2000, 419). However, at the same time, a lack of location-specific scientific information on climate change effects can make it difficult to integrate the spatiotemporal aspects of changing streamflow into planning for climate change impacts. There is a need, for example, to better quantify potential increased sensitivity of summer flow in High Cascade streams as a limitation on fish recovery efforts that rely on these locations.

In some sectors, adaptation is limited by the long time period required to develop adaptation mechanisms, such as the multi-year process required for developing fish recovery plans or the time required to develop infrastructure. Our study also identified institutional mechanisms that may impede adaptation. For example, although USACE may benefit from centralized management of water resources, another characteristic that has been identified as beneficial in responding to climate change (Miles et al., 2000), the need for Congressional authorization and dependence on historical rule curves and water quality requirements may hinder an effective response. On the other hand, in the recreation sector, a lack of regional organization for fishing guides may limit the diffusion of science-based information on climate change impacts throughout the community. Given the importance of early understanding of climate change impacts at the local-level in giving communities time to develop the capacity to adapt (Whitely Binder, 2006), this may lessen their capacity to respond and adjust, for example, through planning to shift some of their activities to different locations or times of year or guiding their efforts to influence proposed legislation regarding permitting and zoning of guided fishing in the state.

Although it has been suggested that existing institutions will have difficulty responding to climate change "outside their range of experience," (Tompkins and Adger, 2005), and much adaptation is reactive (Adger et al., 2005), our analysis of four water sectors in the McKenzie River watershed suggests that some institutions have substantial barriers to the flexibility needed to manage for new conditions, which will likely make even reactive adaptation delayed, while others are better positioned to effectively respond to changes in water resources associated with climate change, even where it is outside their current range of experience.

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