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Perspectives on Climate Change, Mountain Hydrology, and Water Resources in the Oregon Cascades, USA

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From both social and environmental perspectives, water is the main connection between highland and lowland processes in mountain watersheds: Water flows downhill while human impacts flow uphill. For example, in the Oregon Cascades mountain range, geology, vegetation, and climate influence the hydrologic connections within watersheds. Geology determines which watersheds are surface runoff-dominated and which are groundwater-dominated. In this Mediterranean climate with dry summers, surface runoff watersheds will consistently experience near-zero late summer discharge, so declining snowpacks will have little effect on low flows. This contrasts with groundwater-dominated watersheds, where a shift from snow to rain or a decline in precipitation will reduce recharge, thereby reducing late summer groundwater contributions to streamflow. Earlier snowmelt causes forests to transpire earlier, resulting in decreased springtime streamflow. Reduced snowpacks lead to soil moisture stress, making forests more vulnerable to extensive wildfires and affecting the lifespan and composition of forests. Monitoring and quantifying these complex linkages and feedbacks require appropriate measurement networks. Sampling strategies often use watershed typology to identify where measurements should be focused. Such an approach should include not only established

watershed classification parameters such as topology and geology but also interannual climate variability and land cover. As concerns of water scarcity and vulnerability move to the forefront, our watershed classifications should be extended to include ecosystem and social–ecological parameters. An integrated and agent-based modeling scheme called Envision has been developed to simulate alternative future landscapes at the watershed scale. Using fully coupled models of hydrology, ecosystems, and socioeconomics, decision-makers can simulate the effects of policy decisions in conjunction with other climate forcing, land use change, and economic disturbances. To understand the combined impacts of climate change and humans on water in mountain watersheds, researchers must develop integrated monitoring and modeling systems that explicitly include connections across eco-hydrologic and social–ecological systems.

Keywords: Mountain hydrology; water scarcity; vulnerability; snow; climate change; watershed classification; eco-hydrology; social–ecological system; agent-based modeling; USA.

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Introduction

Mountains are a source of high-quality water and critical water storage (Viviroli et al 2007; Viviroli et al 2011), rich biodiversity, hydropower, food, and building materials (Ives et al 1997; Blyth et al 2002; Beniston 2003). Water, as the fundamental linkage across the biosphere and as the essential resource for human society, is the ubiquitous connection for virtually all aspects of the mountain social–environmental system.

Mountain systems worldwide have been the subject of recent attention with regard to vulnerability to climate change impacts. Within this context of climate change, vulnerability has been described as “the degree to which [geophysical, biological, and socioeconomic] systems are susceptible to, and unable to cope with, adverse impacts” (Schneider et al 2007). More broadly, Adger (2006) defines vulnerability as “the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt.”

However, vulnerability to climate change is relative and should be viewed in terms of the specific nature of the entity (eg a mountain watershed, a community) and the particular climate change stressor(s) (eg increased winter temperature, declining snowpacks) and have specific means for evaluating the resulting complex interactions between the entity and the climate change stressor(s) (Ionescu et al 2009). The concept of dynamic vulnerability, in which linkages and feedbacks between biophysical and socioeconomic stressors produce nonlinear vulnerability responses (Westerhoff and Smit 2009), is particularly relevant to mountain watersheds with their strong gradients of climate, hydrology, and ecosystems and human interactions.

This paper presents examples of climate-induced vulnerability to water scarcity in the Oregon Cascades mountain range. It is perhaps surprising to investigate water scarcity in what is typically considered a water-rich region. However, complex interactions of climate, geology, vegetation, and humans create circumstances of

water scarcity that can severely impact mountain ecosystems and downstream communities. What is needed is a means of identifying the factors contributing to water scarcity, their linkages and feedbacks, and how those translate into spatio-temporally varying expressions of vulnerability to climate-induced water scarcity. Vulnerability is closely tied to the concepts of resilience and adaptive capacity (Smit and Wandel 2006; Adger 2006). By understanding the dynamic, complex interactions within the mountain watershed that lead to vulnerability, one can start to understand the resilience of the system and aim to develop some adaptive capacity.

Using selected watersheds in the Oregon Cascades mountain range, USA, as a case study region, this paper will address such questions as:

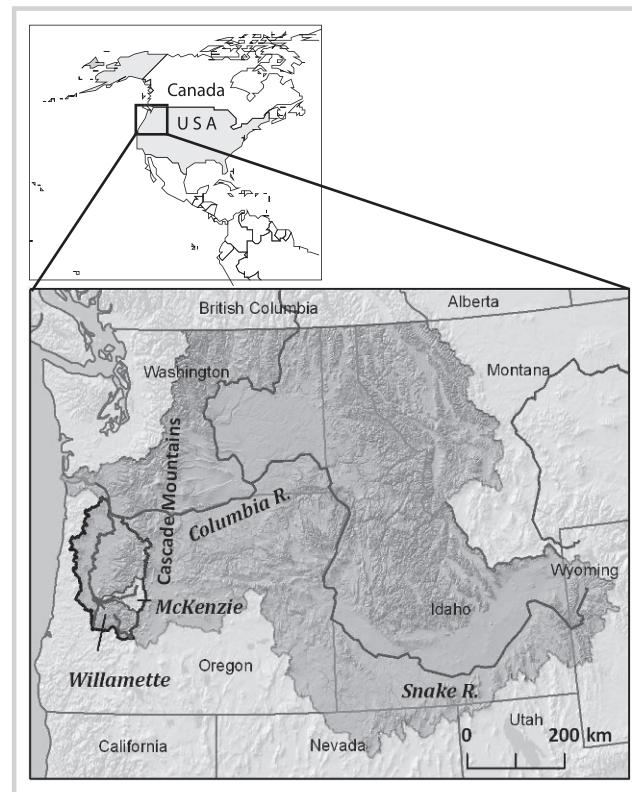
- How do the combined spatial patterns of declining snowpacks and watershed geology affect streamflow?
- How do the temporal patterns of declining snowpacks affect forest phenology and streamflow?
- Do our current snow and climate monitoring systems represent watershed-scale snowpack dynamics, and will they be adequate in the future?
- What modeling strategy can integrate watershed-scale hydrologic, ecosystem, and socioeconomic system processes as they are perturbed by climate change, land use change, and policy and demographic pressures?

The next section provides examples of connections between climate, snow, geology, and land cover. The following section presents ideas for characterizing watershed variability as a key step in developing optimal observation networks for changing climate, snow, and land cover. Concluding, I present a modeling framework that represents a new paradigm for integrating eco-hydrology and social-environmental components for simulating potential water scarcity.

Water connections and climate change in watersheds of the Oregon Cascades Mountain Range, USA

The Pacific Northwest, USA, is a region of high annual average precipitation but a wide range in its spatial and temporal distribution. Across the Oregon Cascades mountain range, there is an extraordinary variation in annual average precipitation with values ranging from a maximum of more than 3800 mm on the windward, upland slopes to a minimum of 500 mm in the leeward rain shadow of the mountains (Taylor and Hannan 1999). Even the wettest parts of this mountain system experience seasonal drought since over 70% of annual precipitation falls from November to March, and only a small fraction falls during the July–September period. In the upland portions of these mountain watersheds, at least half of the annual mountain precipitation falls as snow (Serreze et al

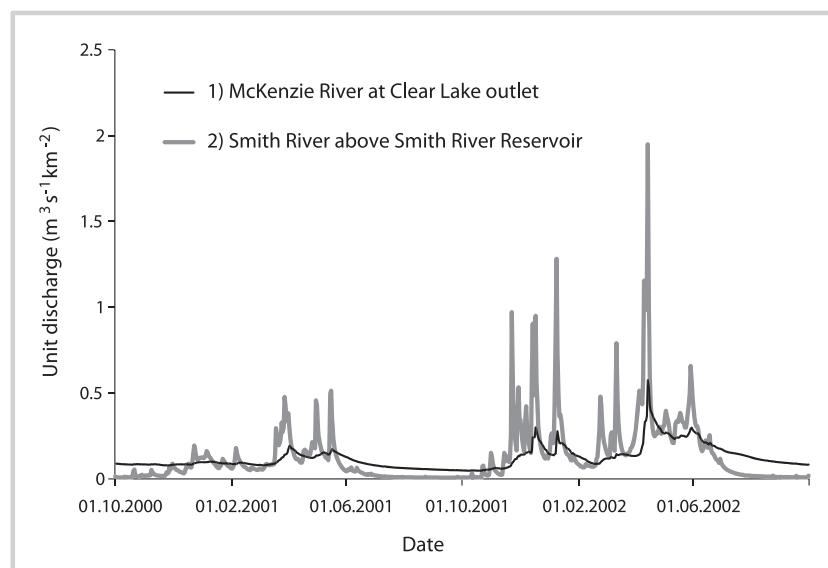
FIGURE 1 Location of the study area showing the Columbia, Willamette and McKenzie River Basins. (Map by Eric Spores)



1999), although much of this snow is close to the melting point and is at risk of converting to rainfall with only a 2°C winter temperature increase (Nolin and Daly 2006). Rising temperatures are shifting precipitation from snowfall to rainfall (Knowles et al 2006), causing decreased snow cover (Mote et al 2005; Mote 2006), and earlier snowmelt is leading to earlier spring runoff (Stewart et al 2005; Regonda et al 2005). A well-documented shift in vegetation phenology also shows an earlier onset of spring temperatures and budburst across the western United States (Cayan et al 2001).

However, the effect of climate change on streamflow is not uniform across all watersheds. Connections between water, geology, vegetation, and streamflow must also be considered. The fate of precipitation is affected by geology and land cover, and therefore each watershed can have a distinctly different response to climate change. Jefferson et al (2008) examined discharge data for the Clear Lake watershed in the headwaters of the McKenzie River Basin, Oregon (Figure 1). Clear Lake basin is a groundwater-dominated system located on young, highly permeable, and porous basalt bedrock. Much of the groundwater recharge is derived from snowmelt, and with mean residence times on the order of 5–10 years (Jefferson et al 2006), the groundwater system is responsive to changes in precipitation. With warming temperatures, there has been a transition from snowfall to

FIGURE 2 (1) Shift to earlier runoff in the McKenzie River at Clear Lake and modeled projected changes in discharge under a warmer climate. (2) Hydrographs for the surface runoff (Smith River) versus groundwater dominated (McKenzie River at Clear Lake) showing the differences in response to precipitation events and summer low flow. (Based on Jefferson et al 2008)

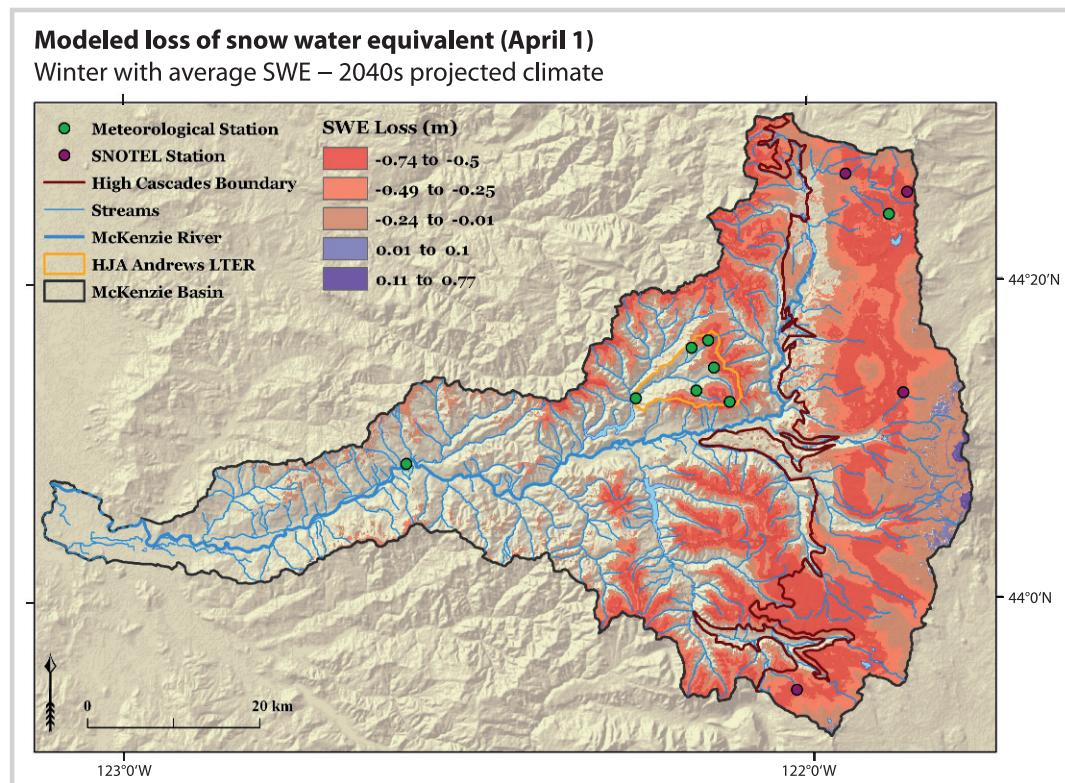


rainfall, and since the mid-20th century this watershed has exhibited a 17-day shift toward earlier runoff (Figure 2). The dry, summer season flows that are supported by groundwater have and are projected to decline further as temperatures increase with significant negative impacts on salmonids and hydropower generation in the McKenzie River. In contrast, a neighboring watershed (the Smith River) of similar elevation and size, which is formed on older basalt rocks and is a surface-runoff-dominated system, shows almost no sensitivity in its summer low-flow response to climate warming. This is because this watershed has a negligible groundwater component, and its summer flow is always extremely low (Figure 2). A shift from snow to rain will not affect the near-zero summer discharge of this surface-runoff system. Thus, the degree to which the bedrock controls groundwater recharge or surface runoff characteristics of the watershed determines its sensitivity to climate change (Tague and Grant 2009). In this region as in others where bedrock can change across a watershed, geology controls the watershed response to climate change. Looking to the future, Figure 3 shows the projected losses in snow water equivalent in the McKenzie River Basin where higher temperatures are projected to shift winter precipitation from snow to rain. The greatest declines in snowpack are projected to occur in the McKenzie headwaters, the primary groundwater recharge zone (Jefferson et al 2006). The future climate model results of Jefferson et al (2008) and Tague and Grant (2009) suggest that this groundwater-dominated watershed will experience a dramatic shift in peak flow to mid-winter because of the shift from snowfall to rainfall and a major decrease in summertime flows as groundwater contributions decline. Thus, this system will likely experience an increased probability of flood and drought over a single water year.

In addition to the subsurface controls on streamflow, vegetation is another watershed scale connection between climate and water. In the Pacific Northwest, forest canopy can intercept up to 60% of snowfall (Storck et al 2002). Vegetation modifies the wind redistribution of snowfall through canopy interception, sublimation (Hedstrom and Pomeroy 1998; Essery and Pomeroy 2004), and the surface energy balance of the snowpack (Hardy et al 2000, 2004; Melloh et al 2001; Link et al 2004). Vegetation affects more than just the accumulation and ablation of snow; its seasonal growth patterns are affected by snowcover and by snow-derived soil moisture. Because they are evergreen, subalpine coniferous forests can photosynthesize throughout the year, though low soil temperatures ($<5^{\circ}\text{C}$) significantly reduce photosynthesis and use of soil moisture (Billings 1969; Day et al 1989). While snow remains on the ground, soils remain cold since available energy must first contribute to warming and melting the snowpack. Once the snowpack melts and soil temperatures increase, conifer photosynthesis increases and water use increases.

As an example, such a phenological shift appears to account for a decline in spring season streamflow at a long-term ecological research site in Oregon (Moore 2010). This study showed a decline in the runoff ratio (streamflow normalized by precipitation) ranging from 19–41% over a period of 5 decades (Table 1) during which time the winter temperature also increased and snow water equivalent also declined by 8 mm yr^{-1} from 1941–2010 (Figure 4). Precipitation, measured starting in 1980, slightly increased, though this was not statistically significant. Declining spring snow cover is pervasive across the mountain watersheds of the western United States (Mote et al 2005). In their work documenting an increase in forest mortality, especially for younger trees, van Mantgem et al (2009) suggested that soil moisture stress

FIGURE 3 Modeled loss of snow water equivalent (1 April) for projected climate in the 2040s. The volume of snowpack storage loss is 0.6 km³, most of which is in the groundwater recharge zone in the High Cascades basalt. (Courtesy Eric Sproles)



due to warmer temperatures and longer, drier summers may be responsible. Westerling et al (2006) noted that warmer spring and summer temperatures and declining western U.S. snowpacks were likely responsible for major increases in the frequency of large, intense wildfires since the early 1980s. Thus, we see that climate–water–vegetation connections work in multiple ways: Earlier snowmelt causes forests to “wake up” earlier, which can result in decreased springtime streamflow; reduced snowpacks lead to soil moisture stress, making forests more vulnerable to extensive wildfires, thereby changing land cover of entire watersheds; and climate-induced soil moisture stress also appears to decrease the lifespan of forests, changing their composition and ability to serve as a carbon sink. These changes are primarily concentrated in the mountain

regions yet affect water yield and other ecosystem services (such as carbon sequestration) that are important to lowland populations downstream.

Connecting hydrologic, ecologic, and human components: perspectives on integrated strategies for monitoring and modeling in mountain watersheds

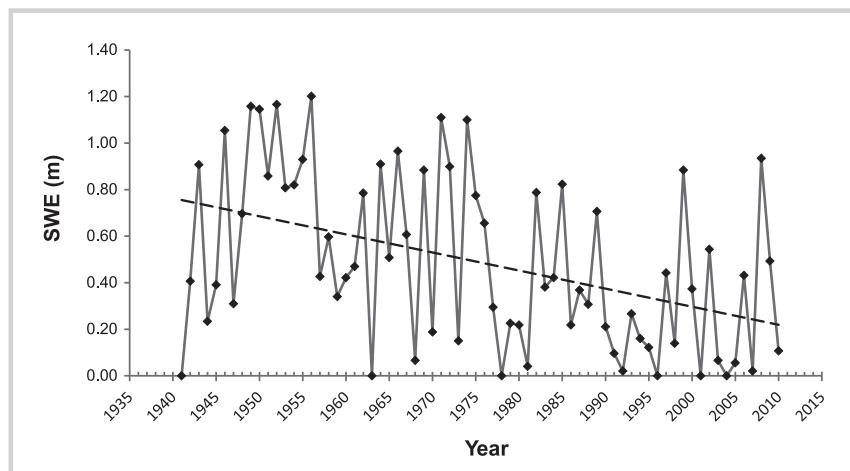
Integrated watershed classification to improve our monitoring schemes

Much of what we know about climate change impacts on water in mountain systems is drawn from empirical analyses obtained from station data or from models that

TABLE 1 Runoff ratio and changes in runoff ratio for 3 undisturbed watersheds in the H. J. Andrews Experimental Forest, Oregon. All values for the change in runoff ratio are statistically significant at $p = 0.05$. (From Moore 2010)

| | Runoff ratio (streamflow/ precipitation) | Change in runoff ratio | | |
|---------------------------|--|------------------------|-------------|-------------|
| | | Watershed 2 | Watershed 8 | Watershed 9 |
| | | 1958–2005 | 1963–2005 | 1968–2005 |
| Annual | 0.6–0.8 | | −0.13 | −0.11 |
| March–May | 0.7–1.2 | −0.19 | −0.40 | −0.21 |
| September–November | 0.2–0.4 | | | −0.04 |

FIGURE 4 Measured 1 April snow water equivalent at Santiam Junction (elevation 1140 m). The dashed line is a linear trend of -8 mm per year . (Data courtesy of the USDA Natural Resources Conservation Service)



have been calibrated and validated using such station data. However, most meteorological stations are situated in the lowlands (Diaz 2005). In the western United States, most snowpack monitoring sites are located in areas where snowpack is dependable and plentiful because they were designed to serve as an index for predicting streamflow yet are now being used for climate change monitoring. Although Snowpack Telemetry (SNOWTELE) sites operated by the US Natural Resources Conservation Service provide critical snowpack data, they do not necessarily provide an accurate representation of watershed-scale snow cover. For example, the four SNOWTELE sites in the McKenzie River Basin are situated at elevations ranging from 1140–1510 m, while the seasonal snow typically occupies an elevation range from 750–3400 m, and 50% of the snow-covered area is above the highest-elevation SNOWTELE site (Brown 2009). Figure 5A shows the present-day distribution of 1 April snow cover and those areas of the watershed that are within 1 standard deviation of the average value of snow water equivalent (SWE). Three of the four SNOWTELE sites are located within this “average” SWE zone. Figure 5B shows the projected future distribution of snow water equivalent in the basin for the late 2040s, and none of the SNOWTELE sites are within this average zone; the lowest-elevation site, Santiam Junction, is no longer in the snow zone at all. As such, these critical snowpack monitoring stations will no longer be capable of providing representative measurements of snow water equivalent in the near future. This is just one example of the potential limitations of the current SNOWTELE network, which consists of about 1000 stations across the western United States.

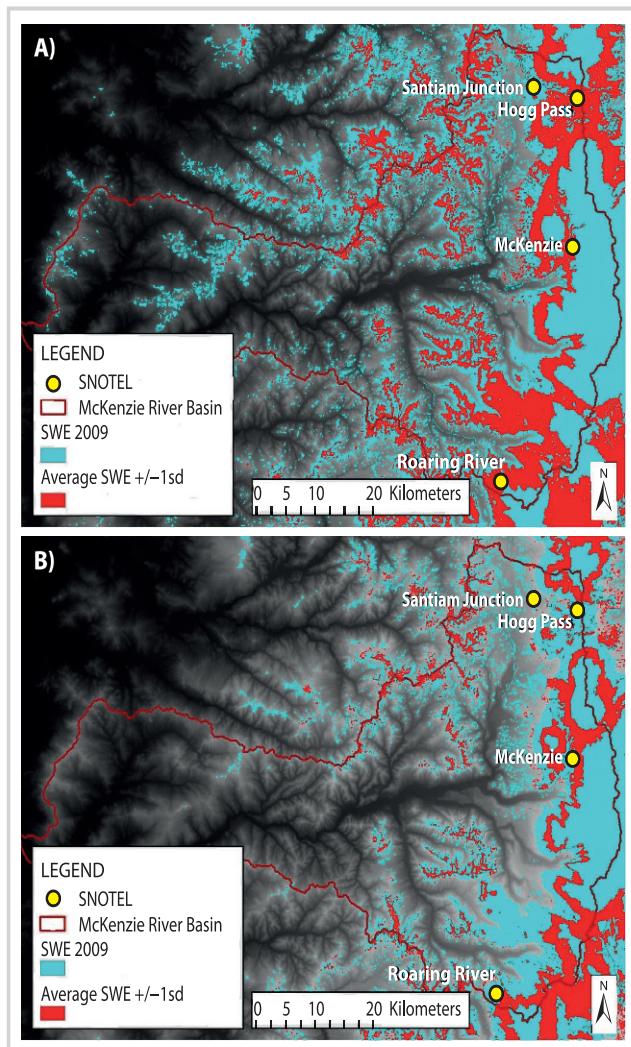
Ground-based monitoring networks are spatially limited and often have short or incomplete periods of record. With finite resources, sampling strategies must be carefully considered such that they provide data that represent the full range of important variability of

mountain eco-hydrology, not just where it is expeditious or cost effective to measure. We simply cannot sample everywhere all the time. Moreover, intensive measurements are expensive not only in terms of infrastructure but also data management.

With its regular repeat coverage, satellite remote sensing can provide valuable spatially extensive information on vegetation, snow, and glaciers, yet cloud cover often inhibits observations, and spatial resolution may not be optimal for watershed analyses. While high-spatial-resolution satellite imagery is more available than in the past (eg QuickBird, IKONOS), such imagery is expensive and has limited spatial extent, and the sensors are “tasked,” meaning that they do not have regular orbital repeat data acquisition. Thus, we rely on remote sensing imagery from sensors such as Landsat Thematic Mapper with 30-m spatial resolution but only 16-day temporal resolution, or the Moderate Resolution Imaging SpectroRadiometer (MODIS) with daily coverage but 500-m spatial resolution.

This leads us to computer modeling, which has become an important tool for examining the spatial-temporal role of snow and ice in mountain watersheds. Physically based models can represent spatially distributed flow and transport processes in watersheds. However, such models can be complicated and may also have input data requirements that are difficult to supply, especially in mountain watersheds. Modeling typically requires watershed-specific calibration, but for predictive purposes such calibrated results may not necessarily be extrapolated elsewhere in time or space. Still, carefully calibrated results may be accurately extrapolated to other watersheds if their hydrologic behaviors are similar. Watersheds will differ in terms of topology, geology, land cover/land use, climate, etc, but hydrologically relevant similarities can be identified and used to classify watersheds. Watershed similarity indices and classification schemes are very useful for ungauged basins

FIGURE 5 (A) Present-day distribution of 1 April snow cover (blue), the region of average snow water equivalent (red) and the location of SNOTEL snow monitoring stations; (B) distribution of 1 April snow cover and average snow water equivalent in the late 2040s. (Courtesy Kelly Gleason)



and regions of sparse measurements since they can be used to identify (a) watersheds that are similar to those where more intensive monitoring and model calibration work has been performed and (b) watersheds that are hydrologically sensitive but not yet included in a monitoring or modeling scheme. Sivapalan et al (1987, 1990) developed nondimensional hydrologic and geomorphologic similarity measures to aid in characterizing storm runoff and flood frequency. Wolock et al (2004) developed the concept of a hydrologic landscape region (HLR) using a combination land surface form, geologic texture, and climate variables to define 20 classes for the United States. Land surface form refers to an upland and lowland connected by a valley side, and the percent of each of these components describes the land surface form (Winter 2001). Geologic texture is the soil and bedrock permeability class, and the climate variable is computed as annual precipitation minus potential

evapotranspiration. Poor et al (2008), however, found that this national-scale HLR was too coarse for use in regional or finer-scale watershed studies.

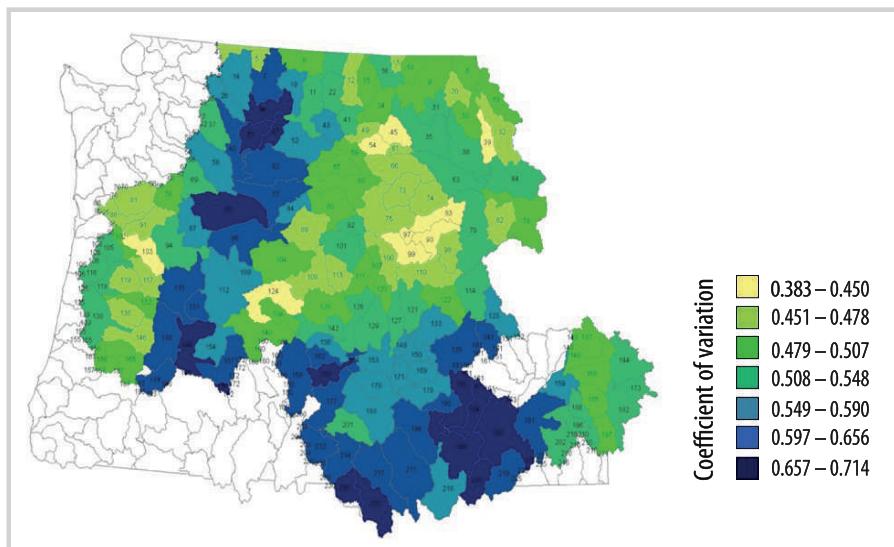
While apparently effective on the large scale and for rain-dominated watersheds, the studies cited above fail to include the seasonality of precipitation and snowpack storage and therefore would not work well in snow-dominated mountain watersheds, particularly in the Oregon Cascades where winters are wet but summers are dry. Wigington (personal communication) has developed a “Hydrologic Landscapes” classification system for the state of Oregon that identifies spatially tractable variables that control hydrologic processes including annual and seasonal climate (including snow), aquifer permeability, terrain position, and soil permeability. In their preliminary tests, these factors clearly distinguish watershed behavior and provide a basemap that can be used for a wide range of modeling and monitoring purposes. This watershed classification is designed specifically for hydrologic characterization. However, if we want to identify watersheds where social–ecological systems may be at risk of water scarcity in times of changing climate and changing land use, one should also include additional attributes such as climate variability, ecosystem characteristics, and social–ecological variables in an integrated classification.

For instance, I suggest that the interannual variability, in addition to climatological seasonality of precipitation, be incorporated. Consider two snow-dominated watersheds: Both have climatologically high winter precipitation and low summer precipitation. However, one of the watersheds has high interannual variability in winter precipitation, while the other has low variability in winter precipitation. Their respective ecosystems and water management systems have developed based on both the seasonality and interannual variability of winter precipitation. In a nonstationary climate, each of the two watersheds will have a stable mean and variance of winter precipitation.

In a nonstationary climate, such as with global warming, the mean will increase, and the variance may also increase. The effect of such nonstationary changes would lead to the case where a formerly small (eg 1 standard deviation) difference from the mean may be equivalent to a 3 standard deviation shift from the original distribution. Thus, for a watershed with low natural interannual variability, it may push it well beyond its range of resilience. For a watershed with high natural interannual variability, it may be resilient to a point, but it may exceed a critical threshold.

Computing the coefficient of variation (standard deviation normalized by the mean) of November–March precipitation for the period 1971–2000 for subwatersheds in the Columbia River Basin, we see that the wet, western side of the Cascades is a low variability region, whereas the drier side historically experiences high variability in winter precipitation (Figure 6). The Willamette River Basin, on the western side of the Oregon Cascades, is an example of a

FIGURE 6 Coefficient of variation for the US portion of the Columbia River Basin as computed for each sub-watershed in the basin. (Courtesy Aimee Brown)



watershed with historically low variability in winter precipitation. In contrast, the Deschutes River Basin, on the western side of the Oregon Cascades, has relatively high interannual variability in winter precipitation.

Both basins have $>3.70 \times 10^8 \text{ m}^3$ of reservoir storage capacity and multiple hydropower generation facilities, but operation strategies are very different because of their differing interannual variation in precipitation. Projected future climate from downscaled IPCC model results indicate that, for the A1B scenario (a more integrated world with rapid economic growth, quick spread of new technologies, and a balanced use of energy sources; IPCC 2007), the region would likely experience increases in winter temperature and precipitation, increases in summer temperatures, and decreases in summer precipitation (Christensen et al 2007).

Such changes will manifest differently in different watersheds; ecosystem resilience and water management adaptive capacity will determine eco-hydrologic outcomes and social-ecological sustainability. For instance, with an increase in interannual variability, management strategies for reservoirs and hydropower generation in the Willamette River Basin may begin to resemble those of the Deschutes River Basin, while managers in the Deschutes River Basin may be forced into a completely novel situation.

Ecologic regionalization is another means of characterizing and classifying landscapes. The US Environmental Protection Agency developed an “ecoregions” concept that has been widely used for stream chemistry and water resources management (Omernik 1987, 1995). McMahon et al (2004) stress the need for a theory-based approach to developing an ecoregions classification that is based on the structure and function of the ecosystem and that can be systematically evaluated

using hypothesis testing. An eco-hydrologic approach to watershed classification could be developed by developing or combining similarity indices that combine watershed typology with ecoregion classification concepts.

Some watersheds may be hydrologically and ecologically similar but have very different degrees of human community stability and resilience. If we want to explicitly consider resilience and the impacts of water scarcity on ecosystem services, our watershed typology should also consider the human dimension. For this, we might incorporate the framework of complex social-environmental systems developed by Ostrom (2009). In this work, she identifies 10 variables that promote self-organizing sustainable resource use including (1) size of resource system; (2) productivity of system; (3) predictability of system dynamics; (4) resource unit mobility; (5) number of users; (6) leadership; (7) norms/social capital; (8) knowledge of the social-ecological system; (9) importance of the resource to users; and (10) collective choice rules. Although not specifically adapted for mountain watersheds, this nascent approach could certainly be developed for that purpose and integrated with other watershed classification schemes.

An integrated modeling framework to understand watershed connections in a changing world

The final topic in this perspectives paper touches on integrated and interactive modeling of climate change and land use impacts on the hydrologic, ecologic, and human components in mountain watersheds. Documenting and assessing vulnerability is a key first step, but modeling allows us to diagnose sensitivities and explore alternative strategies. Füssel and Klein (2006)

describe the evolving conceptual framework of climate change vulnerability assessment, ranging from impact assessment (in which climate change is imposed on a static community and the main focus is on mitigation policy) to adaptation policy assessment (in which communities exhibit dynamic behavior in the face of multiple stressors and the focus is on adaptation policy). Using a “bottom up” approach, Young et al (2010) demonstrate how examining the sensitivity of the community to climate change and its adaptive strategies within the context of climate-induced natural hazards, water shortages by economic sector, and social-political-economic systems. This documentary approach is useful for understanding vulnerability and adaptive responses in the past and present, but it may not be robust for helping communities develop adaptive capacity for novel stressors or novel combinations of stressors in the future.

In the modeling realm, the traditional approach to assessing watershed-scale impacts of climate change on water resources has been to rely on water resources planning models (eg Leavesley et al 1996; Yates et al 2008), but these typically neglect the effects and feedbacks of the human and/or ecosystem components. In the area of decision support modeling of landscape change, approaches have been based on the paradigm of “predict-then-act” (Hulse et al 2008), which combines information about changing land use and water resources with optimal economic and ecosystem services outcomes so that managers may identify a “best” scenario and follow a course of action by which to attain it. However, such models do not incorporate feedbacks between land use, water, management, and decision-making, and the result is that optimal outcomes may be unstable when there is large uncertainty in one or more of the landscape components. Moreover, they do not shed light on policies that may lead to more sustainable futures. A new decision support approach referred to by Hulse et al (2008) as “explore-then-test” seeks to identify those strategies that produce good, though perhaps not optimal, outcomes for a wide range of possible future scenarios. It is the connectivity of landscape elements (vegetation, geology, water, etc) as well as the multiple forcings (climate change, land cover disturbance, land use change) and feedbacks that create nonlinear and threshold effects across watersheds.

Here the focus is on water scarcity across watersheds at the scale of the Willamette River Basin ($30,000 \text{ km}^2$). The Willamette is a UNESCO HELP (Hydrology for the Environment, Life, and Policy) watershed, and the HELP program promotes sustainable water use through better communication between hydrologists and stakeholders (HELP Task Force 2001). Water scarcity is determined by the abundance of water and demands on the resource, as well as the timing of supply and demand. Within a watershed, we also are concerned with location of water scarcity since, as described earlier, geologic differences

between sub-watersheds strongly influence water availability during the low-flow season. Thus, water scarcity is affected by climate change, geology, land cover disturbance (eg fire, timber harvest), land use change (eg transition from forest-to-agriculture or agriculture-to-municipal), water use patterns (eg consumption per unit of municipal or agricultural land use), dam operations, and population growth. Multiple socioeconomic factors affect land use and water use at the watershed scale including the skills and traditions of landowners in the watershed, government regulations (eg the Endangered Species Act), land values and water prices, and water management infrastructure (eg dams, irrigation, aquifer storage and recovery), and these need to be considered when attempting to assess the effects of climate change and land/water management on water resources.

In recent work, Bolte et al (2006) have developed a modeling framework called “Envision” that connects process-based hydrologic and ecosystem models with socioeconomic models and agent-based decision-making. The simulation outputs are a series of alternative future landscapes that can be visualized for interpretive ease. Envision represents the landscape using Integrated Decision Units (IDUs), which are polygons possessing attributes relevant to landscape change and water availability. These attributes are derived from geospatial data sets such as land ownership, land use/land cover, census information, zoning, transportation networks, watersheds and stream networks, hydropower production, and flood control structures. Landscape change and water availability occur as the result of interacting natural and human-induced processes.

Because Envision is a “pluggable” architecture, hydrologic, ecosystem, and socioeconomic submodels can be used as input to explore the effects of natural (eg climate change, wildfire, invasive species) and human-induced (eg land use change, water control structures) forcings in the landscape. Each submodel will have its standard set of spatial-temporal inputs. For instance, the hydrologic submodel requires temperature, precipitation, land cover type, and topography. The ecosystem submodel requires those parameters and variables as well as additional vegetation type and ecosystem response characteristics. A socioeconomic submodel is used to assign profitability to different land and water uses based on statistical models driven by historical data. These submodels interact at daily to monthly timescales to represent hydrologic, ecosystem, and socioeconomic processes over a conforming set of IDUs.

In this multiagent model framework, Envision agents (individuals or private sector groups) adopt plans or adhere to existing rules, “policies,” that govern landscape management. Combinations of policies, in conformance with community goals and values, are termed scenarios (such as unbridled growth, planned growth, environmentally sound land management, etc). Envision

model runs for different future scenarios also include stochastic sampling of parameters to provide estimates of variability. Feedbacks between humans, policies, and the landscape are explicitly modeled. The Envision model has been used to characterize floodplain trajectories (Hulse et al 2008) and impacts of urban expansion (Guzy et al 2008) and is currently being used for wildfire–land management, long-term ecological management, and a variety of coupled human–natural systems applications (Bolte 2011).

This integrative modeling approach represents a new paradigm because it allows scientists and managers to “envision” the rich complexity of landscape patterns that result when decision-making entities and their policies are included as part of evolving landscapes. New work in this arena is proceeding with Envision applied to the problem of water scarcity in the Willamette Valley in western Oregon in which the snow-dominated headwaters in the Cascades Range are responsible for roughly half of the water supplied to the lowland valley, the latter of which is home to 70% of Oregon’s population. Figure 7 diagrams the components in the Envision modeling framework as applied to this project. A visualization component allows users to examine in great visual detail the simulated alternative landscapes for each forcing or set of combined forcings (Hulse et al 2002, 2008; Bolte et al 2006).

Running numerous permutations of hydrologic, ecologic, and socioeconomic models will provide the necessary information to determine when, where, and what combination of human and climate-induced forcings leads to water scarcity in the Willamette River Basin. For instance, the hydrologic model will explore how higher temperatures affect snowpacks, soil moisture, dam operations, and streamflow. This will be coupled with the ecosystem model that will simulate changes in forest and riparian cover (with feedbacks to streamflow and soil moisture). The socioeconomic model will investigate linkages between factors driving water use and land use change and water supplies (with feedbacks to the hydrologic and ecologic models). Finally, with its agent-based approach in which intervention can be included, Envision will also allow us to evaluate various adaptation and mitigation strategies on water scarcity.

Tying this back to Ostrom’s 10 variables promoting self-organization for sustainable resource use, we see that the Envision framework can quantify these variables in the submodels (eg size of resource system, productivity of system, predictability of system dynamics, resource unit mobility) and employ them in the agent-based interactions based on policies and scenarios (eg number of users, norms/social capital, knowledge of the social-ecological system, importance of the resource to users, collective choice rules). As with any model, the quality and availability of data affects model output and with multiple models with multiple feedbacks, this poses a greater burden. Researchers and managers running these

integrated simulations must strive to provide accurate, representative data at spatial and temporal scales that are appropriate to the task.

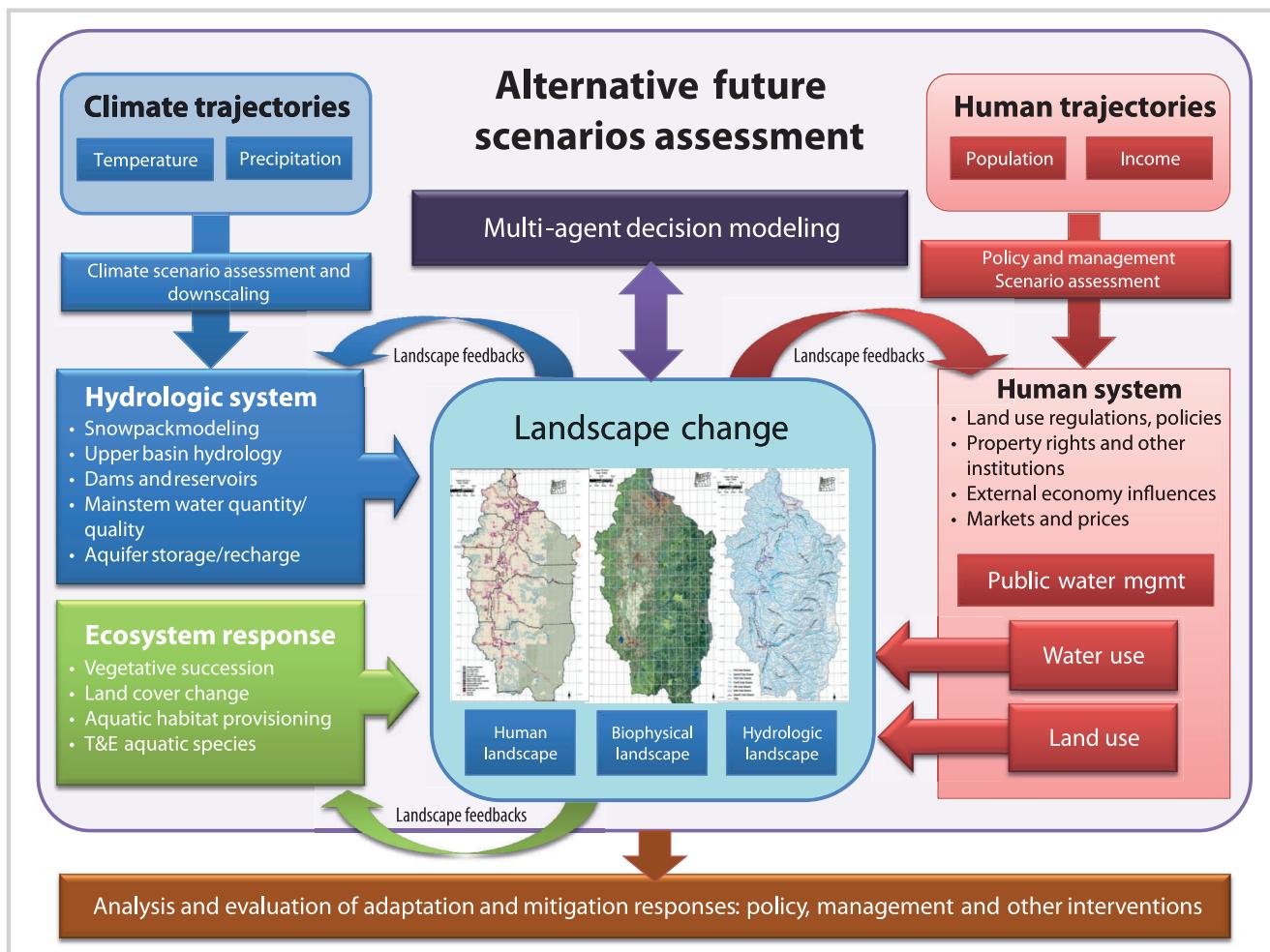
Concluding thoughts

These Oregon Cascades watershed examples demonstrate that connections throughout mountain watersheds are typically as complex as the topography and even more so when one considers not only the hydrologic connections by linkages to ecosystems and human–natural coupled systems. Geology, vegetation, land use, and many other factors influence the states, stocks, flows, and transit times of water in a watershed. Importantly, these physiographic factors also affect the sensitivity of hydrologic systems to changing climate. Numerous studies are undertaken each year that attempt to address the water resource impacts of climate change; however, few of them consider the representativeness of the monitoring systems from which they derive their data. Moreover, when we consider future climate impacts on watersheds, our monitoring systems may be even more lacking.

What is needed is an objective and comprehensive means of characterizing watersheds in terms of their physiographic and climatological parameters so that we can optimize our sampling strategies for present-day and future climate conditions. The demands for integrated understanding of hydrologic, ecologic, and social-environmental impacts of climate change in mountain watersheds means that we need to consider not only physical parameters but also biotic and human elements in our sampling strategies. A new paradigm in modeling is also required. For this, the Envision modeling framework offers an excellent example of agent-based modeling that links process-based models of hydrology, ecology, and socioeconomics to simulate and visualize alternative future landscapes-based natural and human-induced forcings. Our use of the Envision modeling framework in the Willamette River Basin is viewed as a tested for other watershed-scale investigations and is currently being prepared for simulations in other UNESCO HELP basins including the Blue Nile in Ethiopia and the Olifants River in South Africa.

In summary, a robust and representative monitoring scheme is needed to characterize the complex interactions that can lead to water scarcity within a mountain watershed, with consideration not only for the present-day conditions but for projected future climate as well. But documenting and explaining interactions of climate change, water, geology, vegetation, and humans in the mountain system is only the first step. Modeling can provide a means to explore strategies for increased resilience and adaptive capacity. The Envision model is the first of its kind that incorporates hydrologic,

FIGURE 7 Diagram of the Envision model. (Courtesy John Bolte and Donn Foote)



ecosystem, and socioeconomic processes within an agent-based framework. Such a modeling approach allows decision makers the means to visualize how policies and potential scenarios interact with various

stressors to create alternative future landscapes, thus giving them key insights for planning that can enable this region to prevent, mitigate, or adapt to water scarcities.

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REFERENCES

- Adger WN.** 2006. Vulnerability. *Global Environmental Change* 16:268–281.
- Beniston M.** 2003. Climatic change in mountain regions: A review of possible impacts. *Climatic Change* 59:5–31.
- Billings WD.** 1969. Vegetational pattern near alpine timberline as affected by fire-snowdrift interactions. *Vegetatio* 19:192–207.
- Blyth S, Groombridge B, Lysenko I, Miles L, Newton A.** 2002. *Mountain Watch: Environmental Change and Sustainable Development in Mountains*. Cambridge, United Kingdom: UNEP World Conservation Monitoring Centre.
- Bolte J.** 2011. *Envision Case Studies*. <http://envision.bioe.orst.edu/caseStudies.htm>; accessed on 26 July 2011
- Bolte J, Hulse D, Gregory S, Smith C.** 2006. Modeling biocomplexity: Agents, landscapes and alternative futures. *Environmental Modeling Software* 22:570–579.
- Brown A.** 2009. *Understanding the Impact of Climate Change on Snowpack Extent and Measurement in the Columbia River Basin and Nested Sub-basins* [MS thesis]. Corvallis, OR: Oregon State University.
- Cayan DR, Kammerdiener SA, Dettinger MD, Caprio JM, Peterson DH.** 2001. Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society* 82:399–416.

- Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kollm R, Kwon WT, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, et al.** 2007. Regional climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University Press, pp 847–940.
- Day TA, Delucia EH, Smith WK.** 1989. Influence of cold soil and snowcover on photosynthesis and leaf conductance in two Rocky Mountain conifers. *Oecologia* 80:546–552.
- Diaz HF.** 2005. Monitoring climate variability and change in the western United States. In: Huber UM, Bugmann HKM, Reasoner MA, editors. *Global Change and Mountain Regions: An Overview of Current Knowledge*. Advances in Global Change Research. Dordrecht, The Netherlands: Springer, pp 267–274.
- Essery R, Pomeroy J.** 2004. Vegetation and topographic control of windblown snow distributions in distributed and aggregated simulations for an arctic tundra basin. *Journal of Hydrometeorology* 5:735–744.
- Füssel HM, Klein R.** 2006. Climate change vulnerability assessments: an evolution of conceptual thinking. *Climatic Change* 75:301–329.
- Guzy MR, Smith CL, Bolte JP, Hulse DW, Gregory SV.** 2008. Policy research using agent based modeling to assess future impacts of urban expansion into farmlands and forests. *Ecology and Society* 13(1):37.
- Hardy JP, Melloh R, Koenig G, Marks D, Winstral A, Pomeroy J, Link T.** 2004. Solar radiation transmission through conifer canopies. *Agriculture and Forest Meteorology* 126:257–270.
- Hardy JP, Melloh R, Robinson P, Jordan R.** 2000. Incorporating effects of forest litter in a snow process model. *Hydrological Processes* 14:3227–3237.
- Hedstrom NR, Pomeroy JW.** 1998. Measurements and modeling of snow interception in the boreal forest. *Hydrological Processes* 12:1611–1625.
- HELP [Hydrology for the Environment, Life and Policy] Task Force.** 2001. *The Design and Implementation Strategy of the HELP Initiative*. Doc. No. H00/1, IHP-V, Technical Documents in Hydrology No 44. Paris, France: United Nations Educational, Scientific and Cultural Organization (UNESCO).
- Hulse DW, Branscomb A, Enright C, Bolte J.** 2008. Anticipating floodplain trajectories: A comparison of two alternative futures approaches. *Landscape Ecology* 24(8):1067–1090. <http://dx.doi.org/10.1007/s10980-008-9255-2>.
- Hulse DW, Gregory SV, Baker JP, editors.** 2002. *Willamette River Basin: Trajectories of Environmental and Ecological Change*. Corvallis, OR: Oregon State University Press.
- Ionescu C, Klein RJT, Hinkel J, Kumar KSK, Klein R.** 2009. Towards a formal framework of vulnerability to climate change. *Environmental Modeling and Assessment* 14:1–16.
- IPCC.** 2007. Summary for policymakers. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University Press, pp 1–18.
- Ives JD, Messerli B, Spiess E.** 1997. Mountains of the world: A global priority. In: Messerli B, Ives JD, editors. *Mountains of the World: A Global Priority*. New York: Parthenon, pp 1–15.
- Jefferson A, Grant G, Rose T.** 2006. Influence of volcanic history on groundwater patterns on the west slope of the Oregon High Cascades. *Water Resources Research* 42:W12411. <http://dx.doi.org/10.1029/2005WR004812>.
- Jefferson A, Nolin AW, Lewis SL, Tague C.** 2008. Hydrogeologic controls on streamflow sensitivity to climate variability. *Hydrological Processes* 22(2): 4371–4385. <http://dx.doi.org/10.1002/hyp.7041>.
- Knowles N, Dettinger MD, Cayan DR.** 2006. Trends in snowfall versus rainfall in the western United States. *Journal of Climate* 19: 4545–4559.
- Leavesley GH, Markstrom SL, Brewer MS, Viger RJ.** 1996. The modular modeling system (MMS): The physical process modeling component of a database-centered decision support system for water and power management. *Water, Air, and Soil Pollution* 90:303–311.
- Link T, Marks D, Hardy J.** 2004. A deterministic method to characterize sub-canopy radiation environments. *Hydrological Processes* 18:3583–3594.
- McMahon G, Wilken EB, Gauthier DA.** 2004. Toward a scientifically rigorous basis for developing mapped ecological regions. *Environmental Management* 34(Suppl 1):S111–S124.
- Melloh R, Hardy JP, Davis RE, Robinson P.** 2001. Spectral albedo/reflectance of littered forest snow during the melt season. *Hydrological Processes* 15: 3409–3422.
- Moore K.** 2010. *Trends in Streamflow From Old Growth Forested Watersheds in the Western Cascades*. [MS research paper]. Corvallis, OR: Oregon State University.
- Mote PW.** 2006. Climate driven variability and trends in mountain snowpack in western North America. *Journal of Climate* 19:6209–6220.
- Mote PW, Hamlet AF, Clark MP, Lettenmaier DP.** 2005. Declining mountain snowpack in western North America. *Bulletin of the American Meteorological Society* 86:39–49.
- Nolin AW, Daly C.** 2006. Mapping “at-risk” snow in the Pacific Northwest, U.S.A. *Journal of Hydrometeorology* 7:1164–1171.
- Omernik JM.** 1987. Ecoregions of the conterminous United States. *Annals of the Association of American Geographers* 77:118–125.
- Omernik JM.** 1995. Ecoregions: A spatial framework for environmental management. In: Davis WS, Simon TP, editors. *Biological Assessment and Criteria: Tools for Water Resource Planning and Decision-Making*. Boca Raton, FL: Lewis Publishers, pp 49–62.
- Ostrom E.** 2009. A general framework for analyzing sustainability of social-ecological systems. *Science* 325:419–422.
- Poor CJ, McDonnell JJ, Bolte J.** 2008. Testing the hydrological landscape unit classification system and other terrain analysis measures for predicting low-flow nitrate and chloride in watersheds. *Environmental Management* 42:877–893.
- Regonda SK, Rajagopalan B, Clark M, Pitlick J.** 2005. Seasonal cycle shifts in hydroclimatology over the western United States. *Journal of Climate* 18:372–384.
- Schneider SH, Semenov S, Patwardhan A, Burton I, Magadza CHD, Oppenheimer M, Pittock AB, Rahman A, Smith JB, Suarez A, Yamin F.** 2007. Assessing key vulnerabilities and the risk from climate change. In: ML Parry, Canziani, OF, Palutikof JP, van der Linden PJ, Hanson CE, editors. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University Press, pp 779–810.
- Serreze MC, Clark MP, Armstrong RL, McGinnis DA, Pulwarty RS.** 1999. Characteristics of the western United States snowpack from snowpack telemetry (SNOWTELE) data. *Water Resources Research* 35: 2145–2160.
- Sivapalan M, Beven K, Wood EF.** 1987. On hydrologic similarity 2. A scaled model of storm runoff production. *Water Resources Research* 23:2266–2278.
- Sivapalan M, Wood EF, Beven K.** 1990. On hydrologic similarity: 3. A dimensionless flood frequency model using a generalized geomorphologic unit-hydrograph and partial area runoff generation. *Water Resources Research* 26:43–58.
- Smit B, Wandel J.** 2006. Adaptation, adaptive capacity and vulnerability. *Global Environmental Change* 16: 282–292.
- Stewart IT, Cayan DR, Dettinger MD.** 2005. Changes toward earlier streamflow timing across western North America. *Journal of Climate* 18:1136–1155.
- Storck P, Lettenmaier D, Bolton SM.** 2002. Measurement of snow interception and canopy effects on snow accumulation and melt in a mountainous maritime climate, Oregon, United States. *Water Resources Research* 38(11):1223. <http://dx.doi.org/10.1029/2002WR001281>.
- Tague C, Grant GE.** 2009. Groundwater dynamics mediate low-flow response to global warming in snow dominated alpine regions. *Water Resources Research* 45(7):W07421. <http://dx.doi.org/10.1029/2008WR007179>.
- Taylor GH, Hannan C.** 1999. *The Climate of Oregon: From Rain Forest to Desert*. Corvallis, OR: Oregon State University Press.
- van Mantgem PJ, Stephenson NL, Byrne JC, Daniels LD, Franklin JF, Fulé PZ, Harmon ME, Larson AJ, X Smith JM, Taylor AH, Veblen TT.** 2009. Widespread increase of tree mortality rates in the western United States. *Science* 323: 521–524.
- Viviroli D, Archer DR, Buytaert W, Fowler HJ, Greenwood GB, Famlet AF, Huang Y, Koboltschnig, Litaor MI, López-Moreno JL, Lorentz S, Schädler B, Schwager K, Vulle M, Woods R.** 2011. Climate change and mountain water resources: Overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences* 15:471–504. <http://dx.doi.org/10.5194/hess-15-471-2011>.
- Viviroli D, Dürr H, Messerli B, Meybeck M, Weingartner R.** 2007. Mountains of the world, water towers for humanity: Typology, mapping, and global significance. *Water Resource Research* 43:W07447. <http://dx.doi.org/10.1029/2006WR005653>.
- Westerhof L, Smit B.** 2009. The rains are disappointing us: Dynamic vulnerability and adaptation to multiple stressors in the Afram Plains, Ghana. *Mitigation and Adaptation Strategies to Global Change* 14: 317–337.
- Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW.** 2006. Warming and earlier spring increase western U.S. Forest wildfire activity. *Science* 313(5789): 940–943. <http://dx.doi.org/10.1126/science.1128834>.

Winter TC. 2001. The concept of hydrologic landscapes. *Journal of the American Water Resources Association* 37:335–349.
Wolock DM, Winter TC, McMahon G. 2004. Delineation and evaluation of hydrologic landscape regions in the United States using geographic information system tools and multivariate statistical analyses. *Environmental Management* 34(Suppl 1):S71–S88.

Yates D, Galbraith H, Purkey D, Huber-Lee A, Sieber J, West J, Herrod-Julius S, Joyce B. 2008. Climate warming, water storage, and Chinook salmon in California's Sacramento Valley. *Climatic Change* 91:335–350.
Young G, Zavala H, Wandel J, Smit B, Salas S, Jimenez E, Fiebig M, Espinoza R, Diaz H, Cepeda J. 2010. Vulnerability and adaptation in a dryland community of the Elqui Valley, Chile. *Climatic Change* 98:277–305.