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Assessing water resources adaptive capacity to climate change impacts in the Pacific Northwest Region of North America

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Abstract

Climate change impacts in Pacific Northwest Region of North America (PNW) are projected to include increasing temperatures and changes in the seasonality of precipitation (increasing precipitation in winter, decreasing precipitation in summer). Changes in precipitation are also spatially varying, with the northwestern parts of the region generally experiencing greater increases in cool season precipitation than the southeastern parts. These changes in climate are projected to cause loss of snowpack and associated streamflow timing shifts which will increase cool season (October–March) flows and decrease warm season (April–September) flows and water availability. Hydrologic extremes such as the 100 year flood and extreme low flows are also expected to change, although these impacts are not spatially homogeneous and vary with midwinter temperatures and other factors. These changes have important implications for natural ecosystems affected by water, and for human systems.

The PNW is endowed with extensive water resources infrastructure and well-established and well-funded management agencies responsible for ensuring that water resources objectives (such as water supply, water quality, flood control, hydropower production, environmental services, etc.) are met. Likewise, access to observed hydrological, meteorological, and climatic data and forecasts is in general exceptionally good in the United States and Canada, and access to these products and services is often supported by federally funded programs that ensure that these resources are available to water resources practitioners, policy makers, and the general public.

Access to these extensive resources support the argument that at a technical level the PNW has high capacity to deal with the potential impacts of natural climate variability on water resources. To the extent that climate change will manifest itself as moderate changes in variability or extremes, we argue that existing water resources infrastructure and institutional arrangements provide a solid foundation for coping with climate change impacts, and that the mandates of existing water resources policy and water resources management institutions are at least consistent with the fundamental

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objectives of climate change adaptation. A deeper inquiry into the underlying nature of PNW water resources systems, however, reveals significant and persistent obstacles to climate change adaptation, which will need to be overcome if effective use of the region's extensive water resources management capacity can be brought to bear on this problem. Primary obstacles include assumptions of stationarity as the fundamental basis of water resources system design, entrenched use of historic records as the sole basis for planning, problems related to the relatively short time scale of planning, lack of familiarity with climate science and models, downscaling procedures, and hydrologic models, limited access to climate change scenarios and hydrologic products for specific water systems, and rigid water allocation and water resources operating rules that effectively block adaptive response. Institutional barriers include systematic loss of technical capacity in many water resources agencies following the dam building era, jurisdictional fragmentation affecting response to drought, disconnections between water policy and practice, and entrenched bureaucratic resistance to change in many water management agencies. These factors, combined with a federal agenda to block climate change policy in the US during the Bush administration has (with some exceptions) led to institutional "gridlock" in the PNW over the last decade or so despite a growing awareness of climate change as a significant threat to water management. In the last several years, however, significant progress has been made in surmounting these obstacles, and the region's water resources agencies at all levels of governance are making progress in addressing the fundamental challenges inherent in adapting to climate change.

1 Introduction and background

The Pacific Northwest Region of North America (Fig. 1) is comprised of a diverse set of landscape characteristics which are strongly related to topography and proximity to the coast. The domain we consider in this paper encompasses the Columbia River basin (CRB), and coastal watersheds in the states of Washington and Oregon.

Much of the hydrologically significant precipitation in the region occurs in cool season (October–March), which in colder, snowmelt-dominant watersheds is mostly stored as snowpack, effectively transferring water availability from cool season to warm season (April–September) in snowmelt dominant watersheds (Hamlet, 2003). In portions of the region with relatively warm winter temperatures (mostly near the coast), water availability is either winter dominant (essentially following seasonal precipitation patterns in rain dominant systems) or has two peaks, one in the fall related to runoff production associated with rain, and a second peak in the spring related primarily to snowmelt.

1.1 Climate change scenarios for the Pacific Northwest

Climate change projections for the PNW, from global climate model (GCM) scenarios from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) are shown in Fig. 2 for two emissions scenarios: A1B (a medium-high emissions scenario), and B1 (a low emissions scenario) (Mote and Salathé, 2010).

The effects to regional temperature show a very high signal to noise ratio, meaning that the systematic changes in temperature are very large in comparison with the observed range of variability. For example, by the 2040s the new 5th percentile value is close to the 95th percentile shown for the second half of the 20th century. These projections show that we are very likely to enter uncharted territory for high temperatures in the future, and that cooler temperatures that were commonly encountered in the historic record are likely to become increasingly infrequent events.

The effect of different emissions scenarios on the results show strong differences at the end of the 21st century (almost twice as much warming for A1B as for B1), whereas by mid century the results for the two different emissions scenarios are remarkably similar. These findings show that reductions in greenhouse gas emissions will likely play a very important role in reducing impacts in the long term, while in the shorter-term (several decades) little reduction in warming impacts can be expected, and adaptation to impacts that are "already in the pipeline" may be the only viable approach to reducing undesirable outcomes associated with climate change.

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For annual precipitation, a very different picture emerges. The GCM simulations show a very low signal to noise ratio, meaning that the systematic changes are small relative to the range of observed variability. For the PNW as a whole, there are relatively small changes in annual precipitation, and the range of normal variations that occur from decade to decade (e.g. those associated historically with the Pacific Decadal Oscillation) will probably play a very important role in determining the actual outcomes related to precipitation in any future decade. The effects of different emissions scenarios on precipitation are likewise very modest (compare A1B to B1 at the end of the 21st century, for example). Although systematic changes in annual precipitation are small, many GCMs show systematic increases in winter precipitation and decreases in summer precipitation, which have some important implications for a number of impact pathways in the PNW (e.g. winter flooding, summer low flows, fire)

It should be noted that changes in precipitation simulated by GCMs are generally much more uncertain than changes in temperature, and greater caution must be exercised in interpreting precipitation results. Another way to say this is that we should expect more potential "surprises" in the effects of global climate change on PNW precipitation than we should for temperature.

1.2 Hydrologic impacts of climate change

Figure 3 shows a map of the ratio of peak snow water equivalent (SWE) to cool season precipitation (a measure of the importance of snow to the hydrologic cycle) for historical conditions and future scenarios. Overall the changes in hydrology can be characterized by a landscape-scale transformation from snowmelt dominant and mixed rain and snow basins to rain dominant behavior. Some areas, however, and most notably the portion of the CRB in Canada remain strongly snowmelt dominant.

In both mixed rain and snow and snowmelt-dominant basins, loss of snowpack due to warming and generally increasing winter precipitation in the scenarios increase winter flow, while summer flow declines (Fig. 4a, b) (Elsner et al., 2010). In rain dominant basins there is little shift in the seasonality of flow, and runoff volumes largely follow

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changes in precipitation in cool season (Fig. 4c). Increases in evaporation combined with relatively small positive changes in cool season precipitation tend to result in small changes (positive or negative) in annual flows (Elsner et al., 2010). These hydrologic impacts have many water resources implications in the PNW including impacts to water supply (Vano et al., 2010a, b), flood control (Lee et al., 2009, 2010), hydropower production (Hamlet et al., 2010), and environmental services (Mantua et al., 2010).

Increases in hydrologic extremes are a complex function of the seasonality of changing precipitation in the scenarios and effects to effective basin area and antecedent snow related to warming. Figure 5, for example, shows changes in flood risk over the PNW, for the 2040s A1B scenario. Relatively warm basins near the coast tend to show higher flood risk due to increasing cool season precipitation and the increasing effective basin area that accompanies rising snow lines, whereas colder basins in the interior often show decreasing flood risk in spring due to systematic loss of snowpack (Hamlet and Lettemaier, 2007). Low lying, rain dominant basins show modest increases in flood risk associated with increased winter precipitation (Mantua et al., 2010; Tohver and Hamlet, 2010). Water quality, and particularly water temperature and turbidity are also expected to be impacted by warming and precipitation changes (Mantua et al., 2010).

2 Overview of PNW water resources development

The Columbia River basin (CRB) is the dominant water resources system in the PNW, and is one of the most extensively developed hydropower systems in the world. The CRB encompasses most of Oregon (OR), Washington (WA), and Idaho (ID) in the US and about 30% of the basin area is in southern British Columbia (BC) in Canada. On average the CRB supplies about 70% of the PNW's electrical demand, and produces about 30% of the total hydropower in the US. Historical development and current water resources policy in the CRB has been strongly influenced by international agreements between the US and Canada, most notably the Columbia River Treaty (1964),

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which created the conjunctive hydropower and flood control policies that constitute the fundamental basis of the Columbia's reservoir operations (Hamlet, 2003). More recently, however, endangered species listings of a number of salmon species in the CRB and associated protection and restoration efforts in the basin have had a significant impact on water policy and dam operations in the CRB (BPA, 1994). Water supply for irrigation is also an important water resources objective in several sub-basins of the CRB, most notably the Snake River basin (primarily in Idaho), the Yakima River basin and Central Columbia basin in Washington State (WA), and the transboundary Okanagon/Okanagan basin in British Columbia and WA. The CRB is largely governed by federal water management agencies such as the Bonneville Power Administration (federal hydropower marketing), the US Army Corps of Engineers (flood control), the US Bureau of Reclamation (water supply for irrigation), National Marine Fisheries Service (NMFS) (salmon protection and restoration). Institutional arrangements in Canada are similar, with BC Hydro managing the province's hydropower resources and flood control operations, and various groups within Environment Canada and the Provincial government managing other aspects of water resources management.

In addition to the CRB, a number of sub-regional to local-scale water resources systems have developed in the PNW. Many of these are designed to provide water for irrigated agriculture or urban water supply (Fig. 1). In western WA and OR, for example, a number of small watersheds on the west slopes of the Cascades provide drinking water for urban populations (e.g. in the Vancouver, Seattle, and Portland metro areas), which are primarily located west of the Cascades. These systems are typically operated by local utilities. Irrigation plays an important role in many smaller watersheds east of the Cascades (Vano et al., 2010b). These smaller water supply systems are typically managed by local irrigation districts in collaboration with federal water management agencies such as the US Bureau of Reclamation.

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3 Supporting services for PNW water managers

Water resources management in the US and Canada is supported by extensive services for monitoring and predicting river flow. The US Geological Survey (USGS) (http://water.usgs.gov/) has primary responsibility for the US's stream gaging network, and provides free access on the internet to both real-time and historical records. Environment Canada supports a similar system in Canada (http://www.ec.gc.ca/rhc-wsc/default.asp?lang=En&n=4EED50F1-1). Similarly, historical meteorological and climatological data is available in the US from the National Climatic Data Center (NCDC) (http://www.ncdc.noaa.gov/oa/ncdc.html) and in Canada from Environment Canada (http://www.climate.weatheroffice.gc.ca/Welcome_e.html). Additional historical climate data and climate forecasts are available from NOAA's Climate Prediction Center (CPC) (http://www.cpc.noaa.gov/) and Environment Canada (http://www.weatheroffice.gc.ca/saisons/index_e.html). Seasonal forecasts of river flow are provided to water resources managers by groups like the National Resources Conservation Service (NRCS) (http://www.nrcs.usda.gov/feature/highlights/SnoServ.html), which also supports a large network of automated snowpack measurement sites (SNOTEL) (http://www.wcc.nrcs.usda.gov/snow/). Similar products are available in Canada from Environment Canada (http://www.env.gov.bc.ca/rfc/data/). The Pacific Northwest River Forecast Center (http://www.nwrfc.noaa.gov/) also provides a range of streamflow forecasting products, using both statistical approaches (regression equations) and ensemble streamflow prediction (ESP) methods using semi-distributed hydrologic models. Water managers also have access to quantitative flood forecasts based on weather forecasts provided by NOAA in the US (http://www.nwrfc.noaa.gov/) and Environment Canada (http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=7BF9B012-1), and these hydrologic forecasts feed flood warning systems that communicate these risks to emergency managers and the public. Individual water resources agencies also produce hydrologic forecasts or hire private-sector consultants to provide these products. Drought monitoring and prediction services are available in the US from the National

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Integrated Drought Information System (NIDIS) (http://www.drought.gov/portal/server.pt/community/drought_gov/202) and NOAA's North American Drought Monitor (http://www.ncdc.noaa.gov/oa/climate/monitoring/drought/nadm/). These kinds of services provide an extensive set of resources to water managers for coping with climate variability and hydrologic extremes. (It is worth noting that wide spread access to the world wide web in North America has completely transformed the level of access to these kinds of data and services in the last 15 years.)

Although primarily supported by academic research programs at present, a wide range of climate services including detailed hydrologic scenarios are also available to PNW water managers. Groups providing these services in the PNW include the Climate Impacts Group in the PNW (http://cses.washington.edu/cig/) and the Pacific Climate Impacts Consortium in B.C. (http://pacificclimate.org/). As an example of the kinds of climate change data resources that are now being generated, a recent two year project conducted by the Climate Impacts Group and a group of regional stakeholders has generated a comprehensive set of hydrologic scenarios to support water resources planning in the PNW (http://www.hydro.washington.edu/2860/). A number of more local scale groups, such as the Oregon Climate Change Research Initiate (OCCRI) (http://occri.net/), and a consortium of universities in OR, WA, and ID (http://www.webs.uidaho.edu/epscor/) have recently formed to provide additional climate services and stakeholder support at the sub-regional scale. Some of these groups also participate in west-wide climate change assessment activities in the US via collaborative projects with similar groups in California and the Southwestern US.

4 Overview of traditional water planning processes in the PNW

Until very recently, formal water resources planning in the US and Canada has been based almost exclusively on the use of observed streamflow records. These approaches implicitly assume a stationary climate system, and attempt to construct (and test, e.g. via simulation) water resources systems that are relatively robust to the

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observed climate variability represented by observed streamflow records. By extension, these well-tested systems are assumed to be relatively robust to future climate variability. Similar approaches are used to characterize the risk of extreme events. For example, estimates of the "100-year flood" (a flood event with an estimated 1% probability of occurrence in any one year) are typically based on the analysis of observed streamflow records (Stedinger et al., 2003). Projections of changing population, water or energy demand, or other factors related to water resources performance are commonly incorporated in planning studies, but systematic changes (or for that matter even decadal scale variations) in climate that affect these drivers are not typically considered in planning.

There are significant institutional and practical problems related to disconnections between the traditional timescale of water planning (∼20–30 years), and the timescale of analysis needed to inform sustainable resource management decisions in the context of climate change. In particular, planning horizons for water resources studies are too short to address the sustainability issues associated with population and hydrologic changes that are anticipated near the end of the 21st century. These problems are exacerbated by practical time scales associated with policy making, which are affected by political cycles which are of even shorter duration than those associated with traditional water planning. During the Bush administration in the US, for example, climate change assessment, greenhouse gas mitigation, and climate change adaptation efforts at the federal level were all but brought to a standstill. In the first year of the Obama administration, rapid progress has been made in addressing these deficiencies, and in bringing federal resources to bear on these important problems (see discussion in following sections). However, neither administration has created a viable framework for sustainable water planning, because the fundamental time scale of change in the political environments that affect these decisions has not been altered.

These issues related to the time scales of planning and political cycles that affect policy are extremely important because policy decisions related to water infrastructure and/or water allocation are generally very difficult, if not impossible, to reverse.

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Allocation of water to particular stakeholders for economic development, for example, typically results in private investment by these stakeholders. Regulatory actions that attempt to retract these water allocations in response to altered future conditions, therefore tend to create contentious struggles over property rights (Slaughter et al., 2010). The difficulties encountered in the PNW in attempting to remove existing dams (even those with acknowledged marginal economic benefits) in response to changing environmental values highlights the need for new ways to approach the sustainability of infrastructure and water allocation choices in light of a non-stationary climate.

The need for new technical approaches to water planning has also become apparent. Some academic studies have attempted to explore alternative methods for water resources planning using optimization rather than simulation (Labadie, 2004; Lund and Ferreira, 1996; Lee et al., 2009, 2010; Medellin-Azuara et al., 2008), but such techniques are rarely applied in formal long-term (meaning more than a year ahead) planning studies conducted by water resources management agencies. The reasons for the choice of simulation as the dominant planning approach are complex, but are partly related to the fact that optimization results are frequently difficult to interpret in the context of highly constrained systems governed by a large number of regulatory requirements. In addition, skillful long-term forecasts of future streamflows have not historically been available to planners, a situation which limits the practical utility of optimization. Optimization, when it is employed in water management at all, is commonly used only at very short lead times of a few days (e.g. in optimizing short-term hydropower operations in response to weather forecasts). As discussed in more detail below, attempts to identify effective adaptation strategies in response to climate change may ultimately provide a more important role for optimization in long-term water planning in the future.

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5 Institutional issues

Institutional constraints have been shown to play an important role in determining the ability of PNW water resources management systems to adapt to climate variability and climate change. Miles et al. (2000), for example, demonstrated that the ability to respond effectively to drought impacts in the CRB was impaired by institutional fragmentation, lack of centralized authority, and conflicted management objectives in times of water scarcity. By comparison, centralized management systems associated with flood control and hydropower production in the CRB were much more robust, due to well-established institutional roles, centralized management authority, and carefully coordinated conjunctive management objectives.

For water supply systems, rigid water law and inflexible institutional arrangements associated with water allocation (both within one type of water use and between different uses) can be important barriers to adaptation (Slaughter, 2007). Similarly, large, complex systems are arguably less flexible than their simpler, local-scale counterparts because of bureaucratic constraints that are obstacles to change. Gray (1999), for example, showed that the relatively small and autonomous Seattle Water Supply System was able to much more rapidly incorporate new information about climate variability into its operations than the larger, more institutionally complex, and more bureaucratically entrenched system in place in the Yakima River basin in Eastern WA. Likewise, the dramatic increase in complexity of the Columbia River basin's operating policies over the last 50 years or so has been identified as an important obstacle to climate change adaptation because of the difficulty and cost of evaluating the integrated effects of population, climate change, and other factors, and similar difficulties encountered in evaluating potential adaptation strategies (Cohen et al., 2003).

Historical perspectives and experience also play an important role in informing adaptive capacity to climate variability and climate change. Slaughter et al. (2007), for example, argued that management systems in the Snake River basin (located in the arid southeastern corner of the Columbia basin) were much more robust to drought impacts

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than the Klamath River basin in southern OR and northern CA largely because severe droughts were a common occurrence in the Snake basin whereas, until a severe water supply crisis occurred in 2001, water shortages had rarely (if ever) been experienced historically in the Klamath basin. Thus historical conditions in the Snake basin resulted in management systems that were informed by well-established and frequently exercised management plans designed to cope with drought, whereas in the Klamath basin an unprecedented drought in 2001 resulted in serious impacts to stakeholders because these institutional arrangements had not been established. A common assumption is that water scarcity is a good indicator of vulnerability to future increases in drought stress. This case study shows that the opposite may be true.

Loss of certain kinds of technical capacity in water management agencies, and/or emergence of new needs related to climate change adaptation outside the current technical capacity of most water management professionals has also been identified as a significant issue informing adaptive capacity. Following the dam building era (which effectively ended in about 1975 in the PNW), many large water management agencies shifted their focus from water resources engineering and the building of physical structures to the long-term management of existing systems and infrastructure. Staff who were capable of designing or revising reservoir operating policies were largely eliminated from many water resources management agencies over time because these services were not perceived to be needed in the new era. As a result, it is common to find reservoir operating policies dating from the time of dam construction with little meaningful change in the intervening time. Analyzing climate change impacts on water resources requires expertise in a number of different disciplines including atmospheric sciences (e.g. climate modeling, downscaling procedures) hydrology (specifically physically based hydrologic modeling), and systems engineering (e.g. reservoir simulation/optimization modeling). Of these, only reservoir simulation modeling expertise is typically present in most water management agencies. This situation supports the argument that many water management agencies are currently most effective as "caretakers" of the systems they currently manage, as opposed to "innovators" who

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can respond quickly to potentially changing needs associated with climate change. It is worth noting, however, that this situation has been changing rapidly over the last five years or so, and investments in technical capacity in these specific areas has been growing. BC Hydro, to cite one example, has invested $800k over the last four years in establishing a collaborative long-term relationship with the Pacific Climate Impacts Consortium to address climate change impacts. Similarly well-funded collaborative efforts between the Climate Impacts Group, Bonneville Power Administration, Northwest Power and Conservation Council, US Bureau of Reclamation, US Army Corps of Engineers are in progress in the US.

6 Prospects for water resources adaptation in the PNW

At face value, the availability of infrastructure and well-developed support services (discussed above) supports the argument that PNW water management systems have a relatively high capacity to deal with climate variability. To the extent that climate change results in modest changes in variability, one can legitimately argue that adaptive capacity to climate change and existing capacity to deal with climate variability are probably not very different. Some water resources practitioners, for example, have argued that adapting to climate change does not require special actions on the part of water management agencies because these agencies are already charged with ensuring that the performance of these systems in meeting water resources objectives is maintained over time, and already have effective tools in place to deal with these matters. Gene Stakhiv of the Institute of Water Research, commenting on climate change adaptation, wrote: "Notwithstanding the difficulties of anticipating and responding to the ill-defined impacts of global warming, particularly in its various hydrological manifestations, a case can be made that the water resources management community need not take any extraordinary precautions because they already practice or have at their disposal most of the measures and analytical tools that are being prescribed to anticipate or respond to the postulated adverse impacts of global warming." (Stakhiv, 1993).

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6.1 Evidence of autonomous adaptation capacity in the PNW

Although perhaps overly reductionist in tone, Stakhiv's argument is broadly supported by recent management experience in several PNW water supply systems. The response of Seattle Public Utilities (which manages Seattle's water supply system – see Cedar and Tolt reservoirs in Fig. 1) to increasing drought risk over time is a good example of autonomous adaptation to climate change. Although historical impacts to the hydrology of watersheds on the western slopes of the Washington Cascades (which supply Seattle's water) are only partly attributable to greenhouse forced climate change, none-the-less these watersheds have already experienced changes in climate and hydrologic variability that are comparable in magnitude to projections of climate change for the 21st century. Observed losses of 1 April snow water equivalent (SWE) in the Cascades from 1950 to the mid 1990s, for example, have been on the order of 15–35% (Mote et al., 2005, 2008), which are comparable in magnitude to mid-21st century projections of snowpack loss in the Cascades (Elsner et al., 2010). While it is true that Seattle Public Utilities did experience increased difficulty in managing the water supply during several years at the end of the 20th century (e.g. during severe droughts in the El Niño water years 1987–1988 and 1991–1992), it would be misleading to describe the utility as unable to respond effectively to these changes. In fact, there is considerable evidence that the utility learned from these adverse experiences (Gray, 1999), and has increased their capacity to respond to drought during El Niño years, effectively avoiding water supply impacts due to similar low snowpack conditions in 2004–2005 and 2006–2007. Similarly, Seattle Public Utilities has demonstrated exceptional ability to achieve conservation goals. Despite an increase in population, actual water demand in Seattle is currently at approximately 1970 levels. Although reductions in available water supply of about 15% are anticipated for the Seattle System by mid 21st century due to projected reductions in snowpack and summer streamflow (Wiley, 2004), these reductions in maximum safe yield seem well within the reach of ongoing demand management strategies, particularly since Seattle is not using all of its available capacity

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under current conditions.

As introduced above, a similar argument can be made for several other PNW water resources management systems with well-established institutional arrangements designed to cope with drought. In Idaho, for example, more than 99% of the consumptive water use is associated with irrigated agriculture, and a well-defined water allocation system establishing the priority of different water rights holders is combined with an extensive water management system designed to align demand with supply. When an unprecedented five-year drought emerged at the end of the 20th century causing documented impacts to the sustainability of groundwater and surface water resources, a $26 million state-funded buyout of water rights by the ID Dept of Water Resources occurred in 2008 in an attempt to realign long-term demand with available water supplies. As in the case of Seattle Public Utilities discussed above, there was no direct evidence that the drought that caused this management response was caused by global climate change, yet the system responded autonomously to the observed change in supply based on management objectives already in place. This response supports the argument that if climate change projections of reduced summer water supply in Idaho prove accurate, the current management framework may be sufficient to adapt to changing conditions as they emerge in real time.

Technological responses to water shortage are another kind of adaptive response that can happen largely autonomously via choices made by individual stakeholders. For example, in Idaho, there is evidence that farmers have responded autonomously to increasing water shortage over the last several decades by gradually installing more efficient irrigation technology, effectively avoiding serious impacts to crop production despite reduced overall water supply.

6.2 Prospects for adaptation in large, institutionally complex systems

While autonomous adaptation of the types discussed above seems very likely, a substantially different picture emerges when we begin to look closely at the prospects for climate change adaptation in larger and more institutionally complex water

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management systems. The Columbia River basin, the largest, most institutionally complex (and arguably the most important) water resources system in the PNW, provides an excellent case study for discussion of these issues.

The Columbia River water management system is inextricably linked to the PNW region's economy via hydropower production (on average supplying about 70% of the region's electrical energy), flood control, irrigated agriculture, navigation, and recreation. The Columbia also provides a huge range of ecosystem services to the region, many of which are linked (either directly or indirectly) to Native American culture and treaty rights (e.g. for hunting and fishing) in the basin. Attempts to mitigate ecosystem impacts associated with water resources development and other factors have focused primarily on the basin's endangered salmon populations, many of which are currently listed under the US Endangered Species Act (ESA). The basin is institutionally complex partly because of its size (covering most of WA, OR, and ID, and part of BC in Canada), but also because it is a transboundary watershed. The primary water management relationship between US and Canadian entities in the basin is governed by the Columbia River Treaty (CRT) of 1964. The CRT is fundamentally based on conjunctive management opportunities between winter hydropower production and flood control. The treaty facilitated the building of a number of large storage reservoirs in Canada (about 50% of the active reservoir storage is now in Canada), which, in concert with US projects, reduce flood risks and generate increased power in winter. The hydropower produced by the Columbia's dams is primarily marketed by the Bonneville Power Administration in the US and by BC Hydro in Canada, although several Public Utility Districts own and operate individual dams in the system as well. Although relatively narrow in scope in comparison with the full array of management issues affecting the Columbia today (see discussion below), the CRT is widely viewed as one of the most successful and long-lived international water treaties in the world.

Miles et al. (2000) examined the Columbia basin's vulnerabilities to climate variability in different sectors and (by extension) evaluated its adaptive capacity to climate change impacts. As noted above the study found substantial differences in adaptive capacity

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to high flow impacts and low flow impacts. The Columbia basin management system responsible for flood control is highly centralized with well-established authority associated a single management entity (the US Army Corps of Engineers). Operational decisions for flood control are one of the highest priority system objectives and are also well integrated with basin-wide hydropower operations. Under low flow conditions, by comparison, literally hundreds of individual management agencies must compete for a limited water supply. The complex interactions between these competing agencies that occur during droughts are in general poorly coordinated, and with the exception of large-scale hydropower production and well-coordinated irrigation systems in particular sub-basins of the Columbia (e.g. the Snake River basin in ID and the Yakima River basin in WA) lack a centralized decision maker with authority to act (Miles et al., 2000). These institutional characteristics are very important in the context of climate change adaptation, because the most severe climate change impacts in the Columbia are likely to be heavily weighted towards impacts to summer water supplies and to instream flow for fish rather than to high flow impacts (Hamlet and Lettenmaier 1999). Thus the Columbia's poorly integrated management systems associated with low flow conditions imply a high vulnerability to increasing low flow impacts associated with climate change in warm season.

The institutional vulnerabilities discussed above are exacerbated by the extreme difficulty in achieving meaningful change in the Columbia basin's management system. Inertia in the Columbia's management system is evident in nearly every sector, but nowhere is it more evident than in the struggle to mitigate ecosystem impacts resulting from water resources development. Despite three decades of legally mandated effort to mitigate impacts to endangered salmon in the basin, there is no compelling evidence that conditions for the Columbia's endangered salmon populations have dramatically improved, and the reservoir management system, despite many modest changes at the margins (e.g. related to instream flow targets and habitat restoration), remains remarkably similar at its core to the operational policies established in the mid 1960s and 1970s by the CRT emphasizing hydropower production and flood control as the

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dominant management objectives (Miles et al., 2000). The reasons for the apparent inertia in the Columbia basin's water management policies are complex, widely debated, and well beyond the scope of this paper. What seems clear, however, is that the current management system has been unable (or some might argue unwilling) to generate meaningful change in response to widespread ecosystem impacts in the basin. Whatever the root cause, this situation suggests very low adaptive capacity in this arena. This has important implications in the context of climate change, because serious ecosystem impacts related to loss of summer flow and increasing water temperature are projected to emerge in the Columbia basin in the 21st century (Mantua et al., 2010; Hamlet et al., 2010). Hamlet et al. (2010), for example, showed that without operational changes, impacts to regulated summer flow in the ecologically important Hanford Reach of the Columbia river would experience increasingly severe flow impacts in late summer. Attempts to mitigate these impacts to instream flow in the main stem of the Columbia would likely require significant reallocation of reservoir storage and commensurate tradeoffs with winter hydropower production (Payne et al., 2004). Based on the management choices made in the last 30 years there is little evidence to support the hypothesis that such adaptive actions are likely to occur under the current management framework. It remains unclear how such institutional vulnerabilies might be reduced.

Significant transboundary tensions are likely to emerge in the Columbia basin in response to differential impacts of climate change in Canada and the US (Hamlet 2003). Figure 3, for example, shows the transformation through time of the Columbia basin's snow resources due to regional warming. The spatial extent of snowmelt dominant and transient snow watersheds in the relatively warm US portions of the basin are dramatically reduced by mid-21st century, whereas in the colder Canadian portions of the basin, the hydrology is not as greatly affected, and remains snowmelt dominant even in the 2080s scenarios. Thus Canada is likely to have not only 50% of the active reservoir storage, but also the dominant portion of the natural storage as snowpack in the Columbia basin. In the US portion of the basin, loses of natural storage as snowpack

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are likely to create local impacts to summer flow that can only be mitigated by release of Canadian storage (Payne et al., 2004). Thus the creation of Canadian storage under the CRT that has broadly benefitted the US in many ways is also a source of vulnerability under of climate change scenarios, because water that might otherwise have flowed unimpeded across the border in summer is now impounded in Canadian reservoirs. Canadian storage reservoirs are managed as lake ecosystems, which presents a fundamental conflict with potential releases of water to mitigate losses of summer flow in the US portion of the basin. These issues are complicated by the fact that the CRT, which is likely to be the foundation for transboundary negotiations between Canada and US related to climate change impacts, does not directly address issues related to instream flow augmentation.

When taken together these diverse institutional constraints support the argument that adaptive capacity to climate change impacts in the Columbia basin is inherently low in comparison with smaller and less institutionally complex systems such as the Seattle Water Supply system or the well-coordinated water supply systems for irritation in Idaho discussed above.

An alternative viewpoint, however, is that given the formidable institutional obstacles at the highest level of integration in the Columbia basin, effective adaptation may be more likely to occur at the sub-basin to local scale. There is evidence that this approach is a workable alternative, and in fact a number of sub-basin planning efforts are beginning to include adaptation to climate change as an element of long-term planning. Some recent examples of planning efforts the sub-basin scale include studies in the Okanagan basin in BC (Cohen et al., 2006) and Yakima (Vano et al., 2010b) and Methow River basins in WA. Similarly, adaptation at the community scale is also taking place, a notable example in the PNW being the Communities Adapting to Climate Change program sponsored by the Columbia Basin Trust in BC (http://www.cbt.org/Initiatives/Climate_Change/?Adapting_to_Climate_Change). Although concerns remain about how all of these more local scale plans would be integrated to address basin-wide concerns discussed above (which can also influence the

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effectiveness of adaptation at the local scale), none-the-less this overall approach is attractive in that it avoids the issues related to institutional “gridlock” discussed above.

7 Issues related to technical capacity and operational support services

As discussed briefly above, technical capacity is an important element of climate change adaptation capacity. Many water management agencies currently have limited exposure to hydrologic modeling, which is an essential tool in assessing climate change impacts to streamflow and water system performance. Likewise the focus on simulation modeling as the basis for planning and a general lack of familiarity with optimization approaches poses some limitations on current adaptive capacity. Lee et al. (2009, 2010), for example, demonstrate that optimization techniques provide a potentially useful tool for rebalancing flood control operations in complex reservoir systems. Many water management agencies, however, do not currently have the technical capacity available to conduct these kinds of studies, nor are well-established procedures currently in place to guide water resources practitioners. As discussed below, these kinds of technical barriers to adaptation are gradually easing as water resources practitioners have embraced the technical challenges associated with climate change planning in collaborative efforts with academic researchers.

The robustness of operational services such as streamflow forecasts are also an important aspect of climate change adaptation. Some kinds of operational streamflow forecasts are already designed in such a way that they are “self tending”, meaning that they automatically update themselves in a non-stationary climate. Others are not self tending and would either require repetitive interventions in response to poor performance as the climate changes, or would require more comprehensive changes to make them self tending.

An example of a self tending forecasting system is a flood forecasting system that is composed of operational weather forecasts dynamically coupled to a physically based hydrologic model. At least from a conceptual standpoint, for this system to work well

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in a warmer climate the weather forecasts would only need to incorporate increasing greenhouse gas concentrations or other adjustments to account for a systematically warmer climate. With this change in place the weather forecast models would presumably simulate appropriate changes in temperature and precipitation, which would then drive the physically based hydrologic model to estimate the appropriate flood risk over some future time window. While one might imagine that model calibration issues or other unexpected problems might emerge as the climate changes, resolving these issues would not require a policy intervention or a fundamental change in the forecasting system, only improvements in the models used, which is already an established objective of these programs. Furthermore, making weather forecast models work well in the new climate conditions is clearly an important objective in a number of contexts, and does not add costs in and of itself.

An example of a non-self-tending system would be a regression equation used to calculate the 100-year flood based on annual precipitation statistics and basin area (such a system, developed by the USGS, is commonly used in the PNW for estimating flood risk in small, ungaged basins). Because such a system does not include temperature or seasonal changes in precipitation (which are the expected impacts in the PNW as discussed above) as explanatory variables in the regression equation, as the climate changes, estimates of flood risk in some areas are unlikely to reflect changing conditions (Hamlet and Lettenmaier, 2007). Without collecting new data to adjust the parameters in the regression equations these problems cannot be avoided under the current framework. Furthermore streamflow measurements may not be available in the most sensitive locations, which implies that the adjustments would not necessarily capture the most important changes. Replacing such a system with a more physically based hydrologic modeling approach that responds directly to temperature would tend to make the system more self tending, although validation remains a problem in ungaged locations.

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7.1 Design of operational water management systems in a non-stationary climate

Issues related to the design of water resources operating systems to cope with a non-stationary climate are similar in some ways to those associated with support services like streamflow forecasting systems discussed above. Operational decisions which are based on fixed reservoir rule curves (or other inflexible decision rules) are likely to require an expensive (and repetitive) policy intervention if climate change erodes the effectiveness of these management systems over time. Lee et al. (2010), for example, discuss these issues in the context of adapting flood control operations for climate change in the Columbia River basin. The Columbia basin currently uses a flood management system that adjusts the volume of flood evacuation in response to streamflow forecasts. This system is partly self tending in that forecasted changes in summer streamflow volumes in a warmer climate would automatically adjust the amount of flood control evacuation needed. However, Lee et al. (2009) demonstrate that evacuation schedules and the timing of refill would also need to change in response to streamflow timing shifts in order to maintain reservoir refill statistics. Because flood control materially affects many aspects of the Columbia's operations, a change in the current management system for flood control would require a full environmental impact assessment. Doing this multiple times would be extraordinarily expensive, and thus a barrier to effective adaptation. Furthermore, it is not clear exactly when (or how often) a new planning study or change in flood control operations should be implemented in a gradually changing climate. To avoid these problems, other kinds of flood control operating systems could be devised. One such scheme that has been put forward by Lee et al. (2010) is the concept of dynamic flood rule curves. In this system, the flood evacuation schedules for the entire system are optimized each month (using network optimization or other techniques) using ensemble streamflow forecasts from physically based hydrologic models. Such a system is "self tending" in that it responds dynamically to warmer temperatures or changes in precipitation which influence the streamflow forecasts and thereby the optimized flood evacuation requirements. These kinds of inherently flexible and self tending operational procedures present one way of coping with a non-stationary environment.

8 Evidence of increased technical capacity and familiarity with climate change impacts

The relatively recent development of a number of water management coalitions formed by groups of water management agencies to address the challenges of climate change planning is evidence that the issue is being taken seriously by these agencies, and that they are directly working with each other to increase adaptive capacity to deal with the issue. Examples of these kinds of coalitions include collaborative efforts between the American Water Works Association, Association of Metropolitan Water Agencies, Water Utility Climate Alliance, Western Urban Water Coalition (http://www.wuwc.org/html/about_news.html), and the coordinated efforts of the Bonneville Power Administration, NW Power and Conservation Council, and USBR in the Columbia River Basin under the direction of the River Management Joint Operating Committee for the Columbia basin. This rapidly expanding level of engagement on the issue of climate change represents a significant change in attitude over the last decade. In the late 1990s, many water managers felt that climate change was outside their sphere of influence and planning authority, and were often unwilling to engage with academics or other agencies on the issue. With the change in federal administration in the US and an increasing awareness of climate change as an important issue, it has become increasingly clear that water management agencies will now be called on to encompass climate change assessment in their planning. In response, there is evidence that these agencies increasingly feel the need to take ownership of the processes of climate change impacts assessment and strategic adaptation planning. Similarly, as water management agencies began to realize that policy decisions related to climate change would significantly affect the regulatory environment pertaining

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to water, they now feel an increasing need to control the messaging and interaction with decision makers and policy makers. In one pivotal case involving the US Fish and Wildlife Service (USFWS) and USBR, the transition from indifference to engagement was fostered by a lawsuit challenging an Environmental Impact Statement (EIS) prepared by USFWS and the USBR in CA (Natural Resources Defense Council (NRDC), v. Kempthorne et al., 2007). NRDC argued successfully in the case that the USFWS's "no jeopardy" finding in the Sect. 7 biological opinion was "arbitrary, capricious, and contrary to law" because, among other things, the opinion did not take into account the impacts of climate change. In the wake of this suit, the USFWS and USBR quickly realized that they did not (at the time) have the capacity to address climate change impacts in studies like these, and that developing this capacity was suddenly now an urgent practical need within the agencies. Prior to this, climate change planning had been seen more as an academic issue being imposed on the agencies from the outside. This case, in combination with a growing awareness of the climate change impacts, was arguably a significant factor relating to investment in capacity building in the USBR in the last three years. This lawsuit also represents a turning point for other major natural resources management agencies in the PNW, many of which were in essentially the same predicament with regard to existing capacity to address climate change impacts in planning studies.

The nature of these water management coalitions and their recent activities also suggests that the agencies involved now view the issues surrounding climate change differently. Climate change adaptation no longer means simply responding to needs related to impacts assessment and long-term planning, but now also has implications for institutional vulnerability related to changing political and regulatory risks. While a shift to more political viewpoint on the part of water management agencies may or may not have positive outcomes related to climate change adaptation (science and politics have been uneasy bedfellows in the past), it does speak to an increased awareness of the issue in the upper level leadership community of water management agencies, and is direct evidence of an attempt to increase adaptive capacity and to control outcomes

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related to climate change policy.

The development and use of specific information resources designed to support adaptation as a process is also evidence that climate change adaptation research and its user community is maturing. The widespread international use of the Climate Impacts Group's *Adaptation Guidebook* (Snover et al., 2007) (http://cses.washington.edu/cig/fpt/guidebook.shtml) is one example of this growing capacity in both academia and professional practice. Likewise, synthesis documents on impacts and adaptation from the IPCC (http://www.ipcc.ch/ipccreports/ar4-wg2.htm) and regional assessment groups like the CIG (Whitely Binder et al. 2010) provide evidence that adaptation is being taken seriously in the US and Canada and in the larger international water community.

9 Summary and conclusions

Climate change is projected to profoundly affect the hydrology of the PNW, with important impacts to PNW water management systems. While mitigation of increasing greenhouse gas concentrations will play a major role in the level of impacts experienced at the end of the 21st Century, impacts in the next several decades are not projected to respond to these factors. Thus adaptation will be a particularly important aspect of coping with climate change impacts in the near term.

The PNW has access to extensive water infrastructure, management capability, and support services. Thus in the short term, adaptive capacity to modest changes in climate is probably high in the PNW. This argument is supported by evidence of autonomous adaptation taking place in response to observed changes in natural variability, which although not necessarily caused by anthropogenic climate change per se, is consistent with projected future impacts in the region.

In large, complex water systems institutional barriers to adaptation abound, and it is unclear how these fundamental obstacles to change can be avoided. One approach

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may be to focus adaptation efforts primarily at the sub-basin scale, avoiding the institutional gridlock at the most fully integrated levels of governance.

There is considerable evidence that changes in water resources management paradigms will need to be reformulated to cope with a non-stationary climate. Techniques that are inherently flexible and self-tending are likely to be preferred over rigid operating system constraints that are commonly encountered in current practice. The use of optimization techniques to create dynamic operating systems that respond to forecasts is one such approach.

Although progress towards adaptation in the major water management agencies in the PWN has been limited in the past 15 years or so due to a number of factors, in the past three to five years there has been substantial investment in both increased technical capacity to achieve climate change adaptation objectives, and efforts to coordinate amongst various agencies to improve long-term planning and influence water policy at the national, state, and local level.

These efforts are being matched by steadily increasing resources being brought to bear on climate change research and the generation of products and services related to climate change adaptation in academia.

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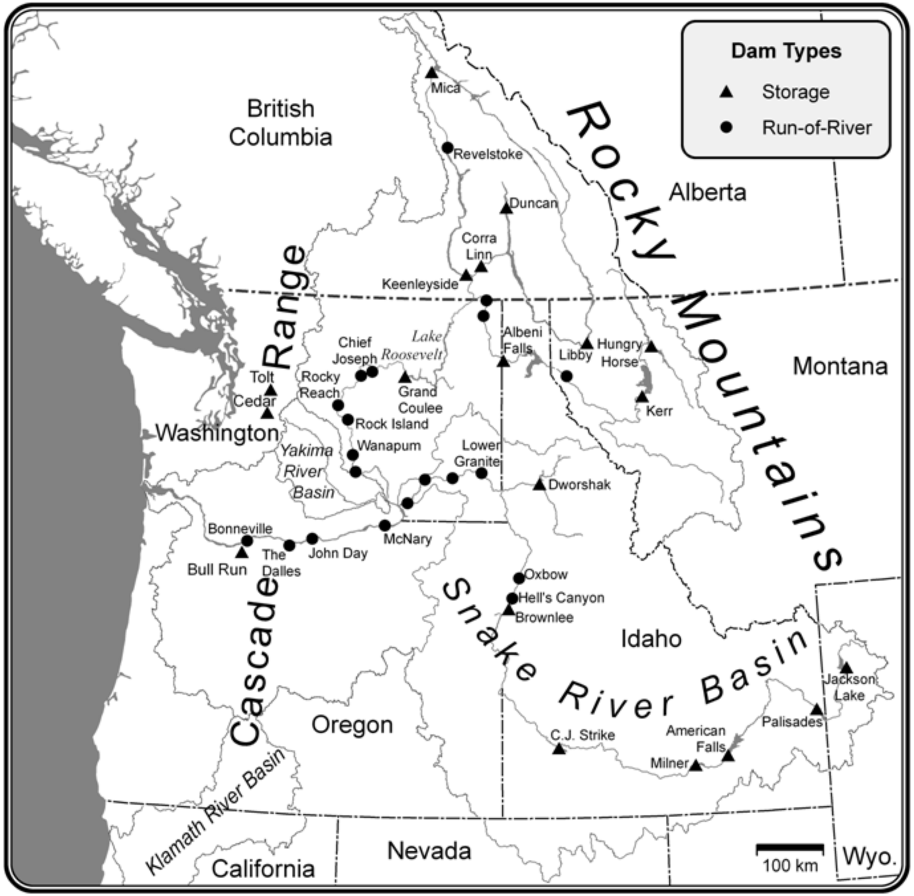

Fig. 1. Map of the Pacific Northwest including the Columbia River basin and Coastal Drainages in WA and OR. Major dams in the Columbia and selected projects and geographic features discussed in the text are shown.

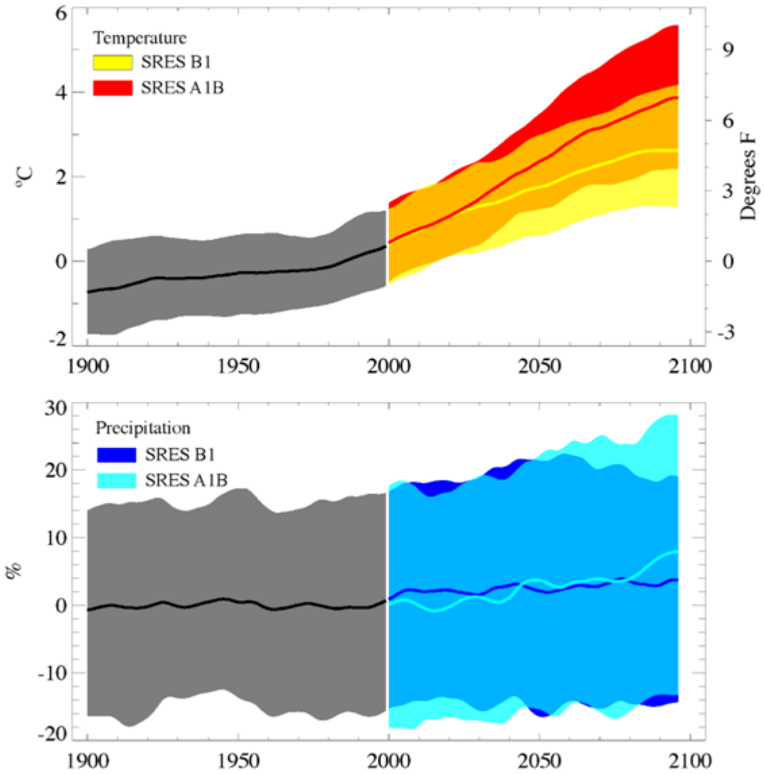

Fig. 2. Summary of 20th and 21st century annual temperature and precipitation simulations from 20 GCMs over the PNW for two greenhouse gas emissions scenarios. Solid lines show the mean. The grey bands show the range (5th to 95th percentile) for the historical simulations, the colored bands show the range of future projections for each emissions scenario. Source: Mote and Salathé (2010).

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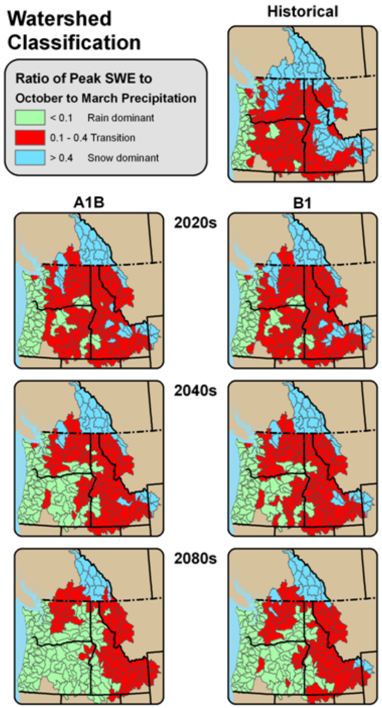

Fig. 3. Simulated changes in the fraction of cool season precipitation stored as peak snow water equivalent (a measure of basin hydrologic response). Basins at the 8-digit (4th level) HUC scale are characterized as rain dominant (<0.1), mixed rain and snow (0.1 to 0.4), or snowmelt dominant (>0.4) for historical conditions and six composite delta method climate change scenarios. Source: Tohver and Hamlet (2010).

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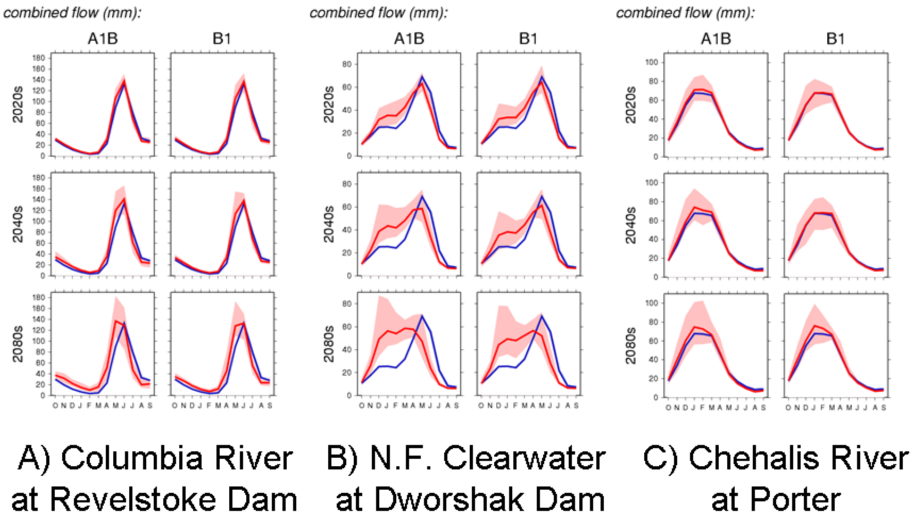

Fig. 4. Monthly average runoff simulations for three PNW watersheds for three future time periods and emissions scenarios, **(A)** the Columbia River at Revelstoke Dam, **(B)** the N.F. Clearwater at Dworshak Dam, **(C)** the Chehalis River at Porter. Blue lines show the 20th century climate (1916–2006), the pink bands show the range of the 10 hybrid delta climate change scenarios (based on the IPCC AR4), and the dark red line shows the average of the hybrid delta ensemble. Source: Columbia Basin Climate Change Scenarios Project: http://www.hydro.washington.edu/2860/.

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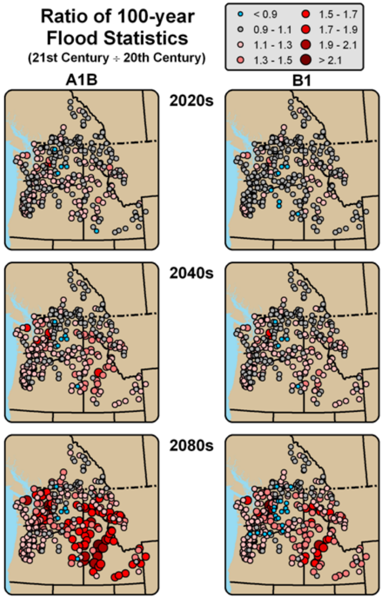

Fig. 5. Maps of the ratio of the 100-year flood magnitude (future/historical) for three future time intervals, under two scenarios for a 297 river locations in the PNW. (Higher ratios indicate more intense flooding events projected for the future). Source: Tohver and Hamlet (2010).

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