Effects of Climate Change on Water Resources in the Pacific Northwest: Impacts and Policy Implications

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Overview

The accompanying white paper (Mote, 2001) underscores the conclusions of recent scientific assessments (IPCC, 2001) that an increase in Earth's average temperature during the 21st century is very likely, with significant changes in regional climate. These changes will have important consequences for water resources in the Pacific Northwest[3] (PNW), because of changes in PNW water cycles that are likely to accompany global climate change (Hamlet and Lettenmaier, 1999).

In this paper we describe what we know now about the likely regional impacts of climate change on PNW water resources. The effects of global warming on regional climate are not as well understood as are the fundamental physical processes that affect global temperatures and other physical variables. However, some of the likely regional effects are clearly understood, and are relatively robust in the face of the uncertainties that exist. This discussion focuses primarily on these robust effects.

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[3] The Pacific Northwest (PNW) is defined here as the states of Washington, Oregon, and Idaho, and the portions of the Columbia River basin that lie in other states and in British Columbia (Figure 1).

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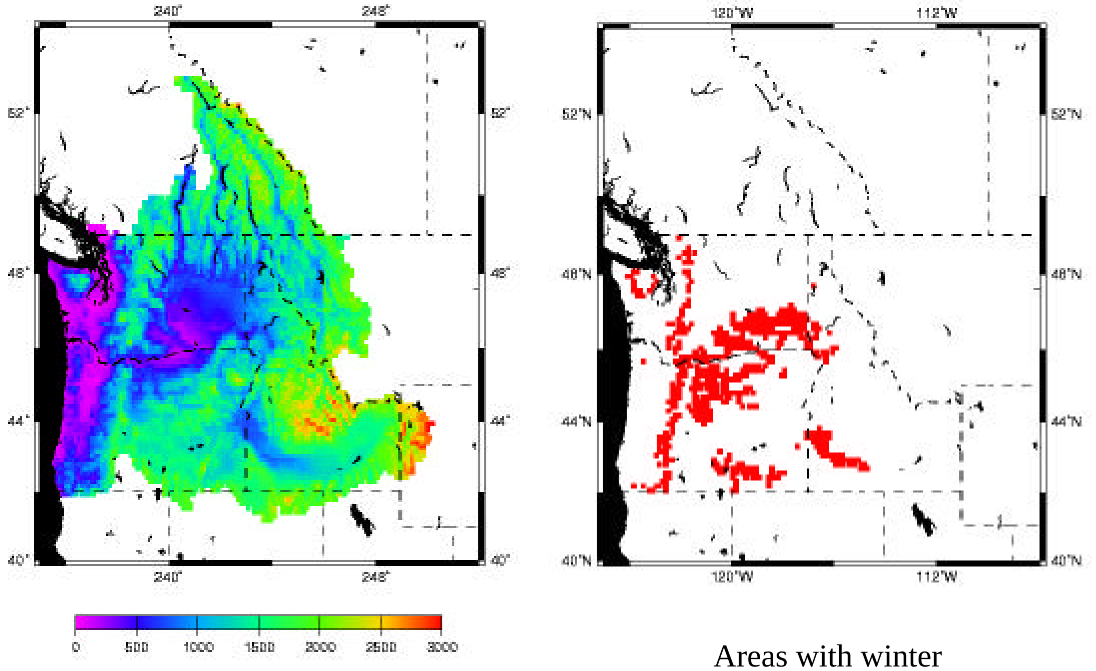
Background

PNW Geography and Climate

Proximity to the Pacific Ocean and the interactions between mountains and atmospheric flow are the dominant controls on the region’s climate. The major geographic features in the Pacific Northwest (PNW) are four mountain ranges: the Olympic Mountains in western Washington, the Cascade Mountains which run from British Columbia in the north into southern Oregon, the Coast Range in Oregon, and the Rocky Mountains which run north to south on the eastern edge of the region. Figure 1 shows a digital elevation map of the study region and areas with December temperatures close to freezing.



Elevation (m)

Areas with winter temperatures near freezing

Figure 1 - Digital elevation map of the PNW and areas of the region with transient snow in winter.

Figure 2 emphasizes the unevenness, in both space and time, with which precipitation is delivered to the PNW. Winter precipitation and annual runoff (which may originate as melting snow but is primarily determined by winter precipitation) are concentrated in the mountains, demonstrating that the **region’s water supplies are largely determined by what happens in the mountains in winter**. Winter storms moving inland from the Pacific first encounter the Olympic and Coast Ranges, and the western slopes of these mountains are extremely wet, typically receiving about 3000 mm (118 in) per year, with some areas at higher elevations receiving more than 4500 mm (177 in) per year. The western slopes of the

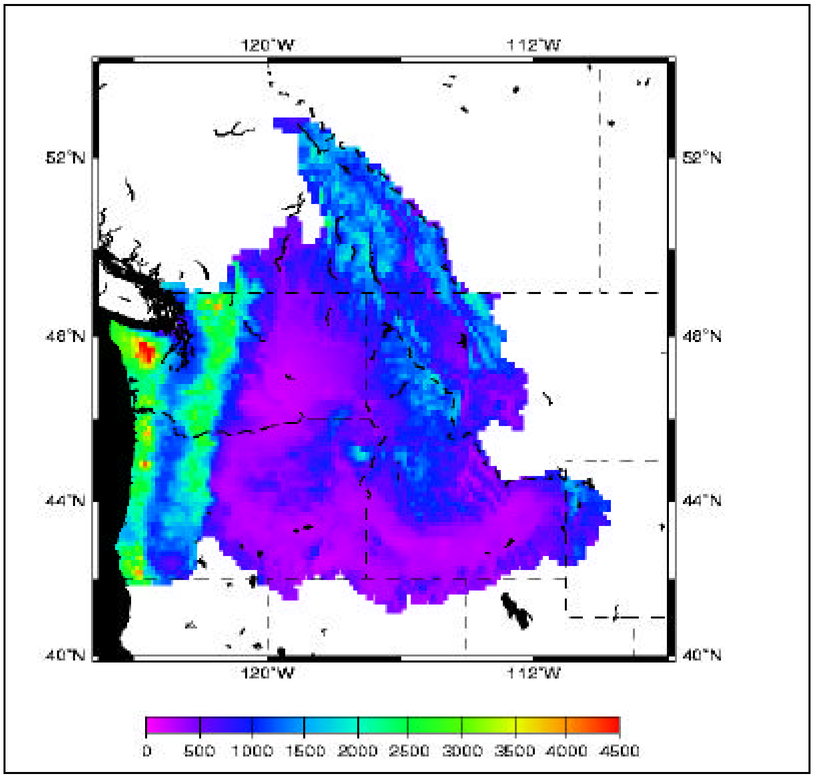
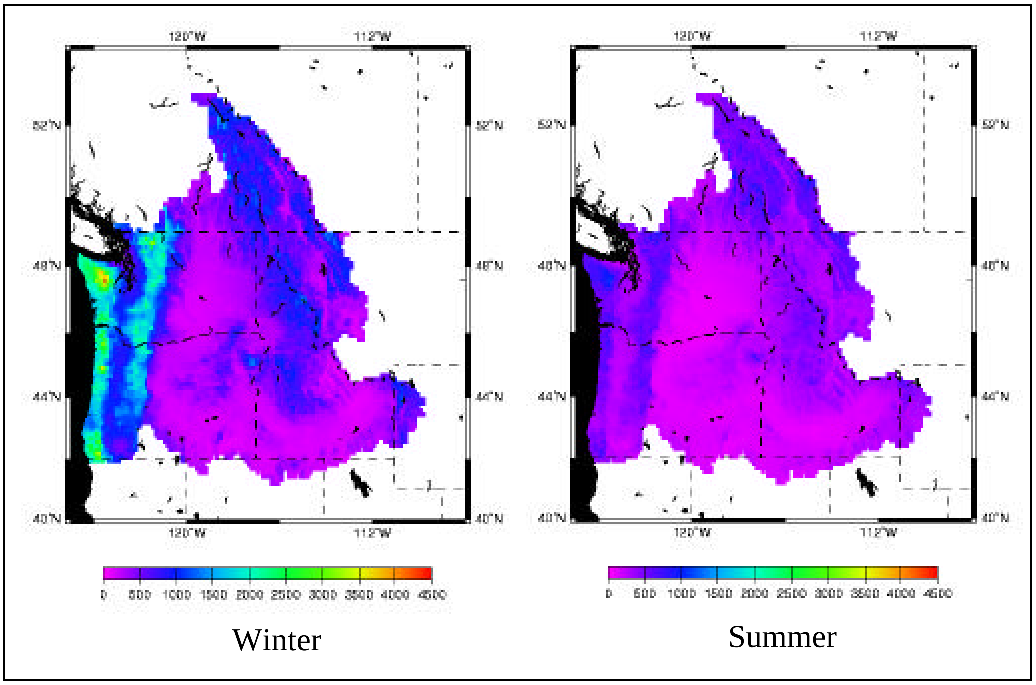


Figure 2(a) - Average annual precipitation for the PNW (mm).



Winter

Summer

Figure 2(b) - Average precipitation for winter (October-March) and summer (April-September) (mm).

Cascades are also very wet with many areas receiving on the order of 2500 mm (98 in) per year. East of the Cascade crest, however, the climate is arid, with precipitation on the order of 250 mm (10 in) per year in the interior Columbia basin. The areas at higher elevation in the Rocky Mountains typically receive 1500-2000 mm (59-79 in) of precipitation per year. About two thirds of the region’s precipitation occurs in just half the year (October-March[4]). The PNW is also somewhat unusual in that the variability (i.e., the difference from year to year) of winter precipitation is relatively small in comparison with other areas in the West, a characteristic that has informed the historic development of the region's water resources (discussed below).

Regional temperature variation depends on elevation, but also varies strongly from east to west. On the coast, the ocean moderates the climate year-round. Farther inland, and especially east of the Cascades, the climate becomes more continental, with warmer summers and colder winters.

Regional Hydrologic Types and Responses to Climate

To understand the potential effects of climate change on PNW water resources, it is useful to have a basic understanding of the hydrologic characteristics of its rivers. River flow is primarily determined by winter-dominant precipitation. What precipitation does fall at other times of the year is predominantly returned to the atmosphere through evaporation and transpiration from plants. Different river basin characteristics result in different responses to the strongly seasonal inflow of moisture to the region. Rivers at low elevation tend to respond quickly and directly to the precipitation that falls on the basin, since the basin temperatures are typically above freezing, and most of the precipitation falls as rain. Rivers of this type are called "rain-dominant" and show a characteristic winter peak flow in their annual hydrograph (Figure 3). Low-lying coastal rivers such as the Chehalis River in Washington are rain dominant.

Many rivers on the western slopes of the Cascades, like the Cedar and Tolt Rivers that supply Seattle's water, lie at moderate elevation and have winter temperatures close to freezing, which creates a “transient snow zone” (Figure 1). The transient snow zone is an area in the basin where precipitation frequently falls as snow but then melts a few days or weeks later, a cycle that is typically repeated many times each winter. The transient snow zone can contribute disproportionately to flooding if heavy rain and warm temperatures occur simultaneously when snow has accumulated (so called "rain on snow" events). Rivers of this type have a peak in their hydrographs both in the winter and in the late spring/early summer (Figure 3). The location of the transient snow zone is a factor in determining the climatic susceptibility of PNW water resources, because these areas are most hydrologically sensitive to changes in temperature.

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[4] For simplicity the terms “winter” and “summer” will generally refer to October-March and April-September respectively for the remainder of the paper.

“Snowmelt-dominant” river basins typically lie at higher elevations where temperatures are below freezing for most of the winter. In these basins, the winter precipitation falls predominantly as snow, where it is stored until the spring melt. Rivers of this type show a characteristic low flow period in the winter months, and a large peak flow in spring and early summer as the accumulated snow melts (Figure 3). Most of the tributaries that produce significant runoff in the Columbia and Snake River basins are snowmelt dominant rivers.

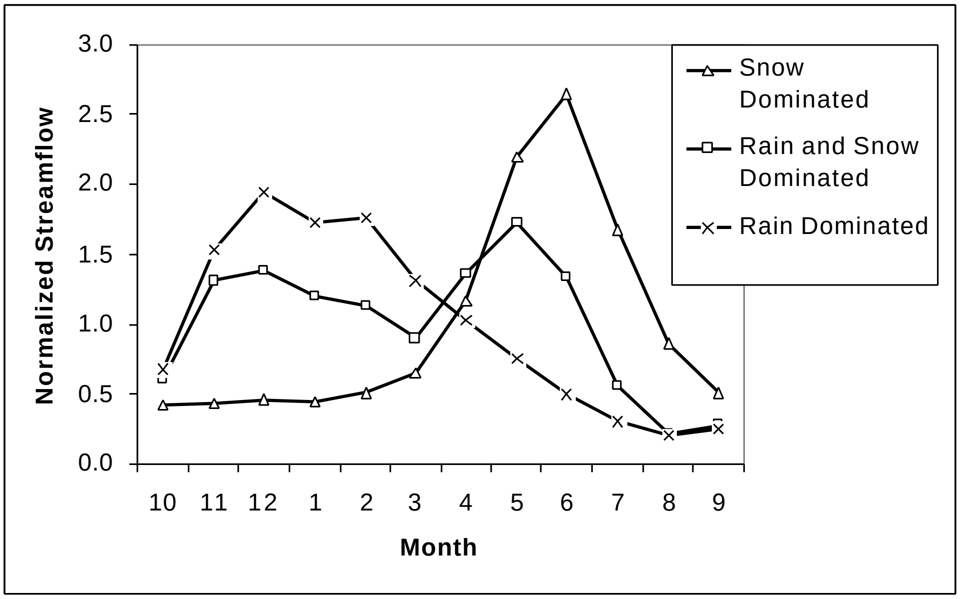

Figure 3 - Seasonal distribution of streamflow for snow melt dominant, transient snow, and rain dominant river basins in the PNW.

Patterns of Water Use

Patterns of water use in the PNW are diverse, and reflect differences in climate, population distribution, and socioeconomic development between the interior Columbia basin and the Cascade west slopes. West of the Cascades, urban and suburban populations are relatively large, and consumptive water use is dominated by municipal and industrial (M&I) uses. Rivers throughout the region are used extensively for hydropower, which supplies more than 70% of the region's electricity. East of the Cascades, consumptive water use is dominated by agricultural uses, while instream uses of water are dominated by hydropower production. PNW water resources systems are also operated for flood control, navigation, instream flow, and recreation.

Compared to the rest of the U.S., the PNW's extensive use of hydropower is unusual. Because of the PNW's abundant supply of hydropower, electricity prices in Idaho, Washington, and Oregon are ranked first, second, and sixth lowest in the nation (DOE, 1998). Significant portions of the PNW economy depend on this source of inexpensive energy. Both irrigated agriculture and the aluminum industry, for example, depend on inexpensive power for their economic viability within current markets. The capacity and reliability of hydroelectric systems is linked to climate, which places an unusual emphasis on climate in the context of energy planning in the PNW.

PNW Water Management Infrastructure

The historical development of PNW water resource systems and their associated infrastructure are linked to the PNW's abundant winter snowpack (which provides a great amount of natural storage) and relatively modest year to year variability in water supply. These characteristics permit PNW water resources systems to operate with very low ratios of reservoir storage to instream flow as compared with other parts of the western U.S.. West of the Cascades almost all of the major municipal water systems in Washington and Oregon have storage to instream flow ratios of less than 10%. The Columbia River system has a storage to streamflow ratio of about 30% (more than half of which is in Canada). In some specific areas the amount of storage is larger. The major Snake River irrigation projects upstream of Milner dam (near Twin Falls, Idaho), for example, can store about 60% of the average annual flow in the middle Snake. These numbers are small in comparison with other water resources systems in the west. The Colorado River system, for example, can store about 300% of annual flow (BPA, 1991).

The reliance of PNW surface water systems on natural storage – snow – rather than on man-made reservoirs leaves the region vulnerable to changes in the timing or variability of the riverine inflows to these systems, because there is a limited ability to reshape the river inflows to match seasonal patterns in the demand for water. As discussed below, this feature of PNW water resources is especially significant in the context of climate change, because of streamflow timing shifts associated with changes in temperature.

Existing Stresses on PNW Water Systems

PNW water resources systems are facing stresses associated with rapidly increasing human populations and the accompanying development of the region, and simultaneous attempts to mitigate impacts on ecosystems associated with this human development. These kinds of stresses are somewhat different in different parts of the region but share common features.

West of the Cascade crest, urban and suburban populations are rising rapidly and are expected to increase M&I water demand by 2010.[5] In

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[5] It should be noted that short-term decreases in per capita water use have resulted in net *decreases* in total municipal water demand in some urban service areas in recent years. These reductions in per capita demand are largely associated with reductions in landscape watering in summer due to greater percentage of the urban population occupying multi-family dwell-

addition, west side water systems must provide increased protection of instream flows for salmon and steelhead that have recently been listed under the U.S. Endangered Species Act. Furthermore, because infrastructure changes are difficult to approve and costly to implement, municipal water systems on the west side are now operated closer to their (imperfectly known) supply limits than they have been in the past, and demand management and conservation has been increasingly emphasized as an important aspect of year-to-year and long-term planning. These approaches tend to reduce infrastructure costs in the short term, but also may reduce the number of options and range of adaptation possible in the face of unexpected changes in demand or climate, because the water supply system is operated closer to its supply limits and further reductions in demand may be more difficult to achieve.

East of the Cascades the greatest conflicts over water are currently between flood control operations, hydropower production, irrigation withdrawals, and instream flow requirements for fish. The Columbia River system, for example, cannot satisfy all of these objectives simultaneously in conditions of moderately below average flow (for the current climate) and current level of development (see e.g., Miles et al., 2000). Rising PNW human populations will likely affect the Columbia River most significantly in the context of energy demand, but, as for west-side systems, efforts to balance the impacts on various competing objectives in the face of escalating conflicts over water may constitute the greatest stress on the existing water management system.

For both east and west side systems, significant changes in the timing or quantity of water supplies are likely to exacerbate existing stresses. The 2001 drought, for example, has brought into sharp relief some of the existing conflicts over water in the PNW, particularly between hydropower, irrigation, and salmon protection.

In large, complex systems like the Columbia River basin, and to a lesser extent in smaller municipal water systems typical on the west side, institutional concerns are also apparent. The interpretation of interviews reported by Callahan et al. (1999) and summarized by Miles et al. (2000) concluded that the Columbia's water resources were more vulnerable to low flows than to high flows, because of the nature of the institutions governing water management for different uses of water in the basin. The primary reason for this dichotomy is that flood control (the most important high flow impact pathway) is centrally coordinated on a basin-wide scale (including well-defined interactions between Canada and the U.S.) by the U.S. Army Corps of Engineers. During low flow conditions, on the other hand, hundreds of individual agencies must interact within a poorly-defined institutional framework to attempt to protect a much larger

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ings, changes in landscape watering practices in general, installation of high efficiency plumbing fixtures required by modern building codes, and other conservation measures.

number conflicting objectives. This disparity in the ability of the Columbia management system to adapt effectively to changing conditions associated with anomalously high and low flows is important in the context of climate change, the likely impacts of which are focused primarily on the low flow side. These institutional considerations are discussed in more detail in the companion paper on designing water policy to cope with climate change (Hamlet et al., 2001).

Expected Changes in Climate for the PNW in the 21st Century

In the analysis that follows, we use "middle-of-the-road" climate change scenarios for the 2020s and 2040s that are constructed from the monthly mean of individual scenarios from four of the eight global climate models[6] discussed by Mote (2001). Figure 4 shows the changes in temperature and precipitation for the scenarios and the individual scenarios from which they were constructed.

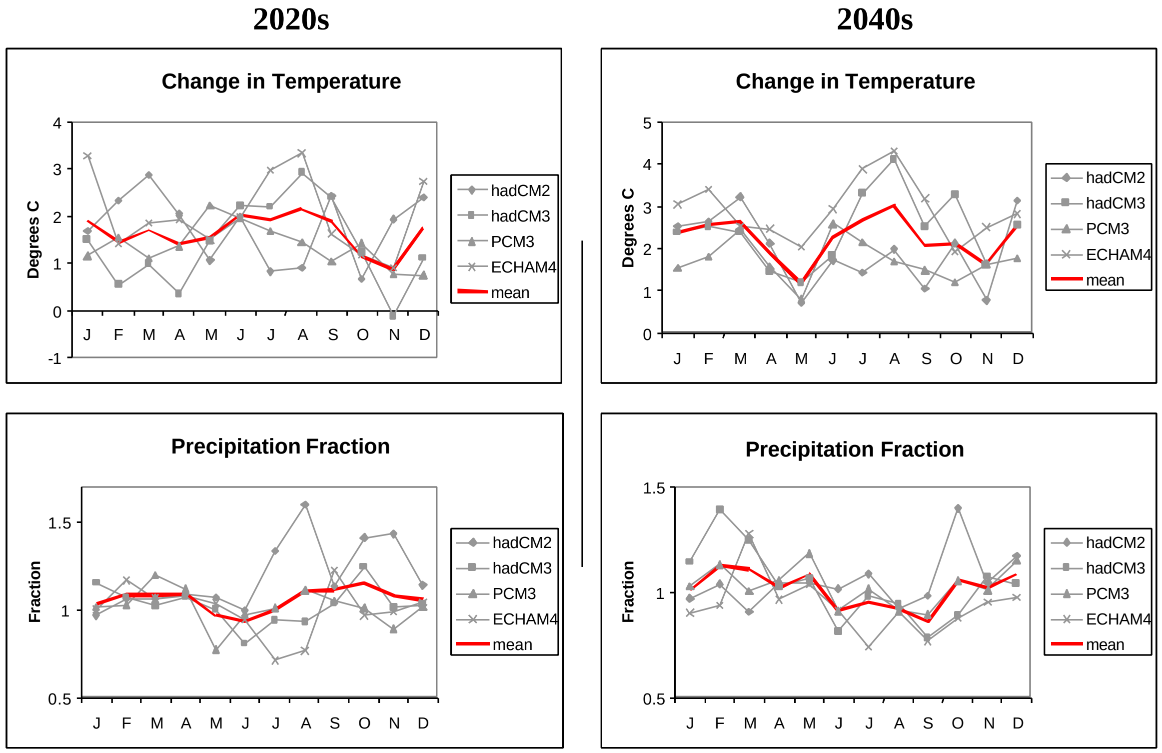

Figure 4 - Climate change scenarios for 2020s and 2040s for individual global climate models (gray curves) and for the composite (black).

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[6] The global climate models used to create the scenarios were HadCM2, HadCM3, ECHAM4, and PCM3

Hydrologic Implications

Increases in temperature, which are predicted with the greatest confidence in the climate scenarios, affect different types of river basins in different ways. In the case of snowmelt and transient snow basins, the impacts associated with increased regional temperatures stem primarily from reductions in spring snowpack. Figure 5 shows the changes in April 1 snow extent for the Columbia basin associated with the ECHAM4 climate scenario. Note that as the PNW climate warms the snowpack at moderate elevations and in the southern part of the basin is gone by April, whereas in the current climate these areas are typically snow covered in April.

In snowmelt dominated systems like the Columbia River and some rivers originating in the Cascade and Olympic ranges, higher winter temperatures would cause more precipitation to fall as rain in the winter, increasing winter streamflow as compared with the base case and leaving less water stored as snow to supply runoff contributing to summer streamflow (Figure 6). Higher spring and summer temperatures also melt the snow earlier, moving spring peak flows earlier in the year, and increasing the length of time between snowmelt and the onset of fall rains. These changes would result in less streamflow in summer, and are not very sensitive to changes in precipitation (Hamlet and Lettenmaier, 1999). Note that natural streamflows in northern parts of the basin at Corra Linn dam (in British Columbia) and at Chief Joseph dam (near Grand Coulee Dam) are less affected by timing shifts than are streamflows at Ice Harbor Dam on the Snake and at The Dalles in the lower basin (Hamlet and Lettenmaier, 1999).

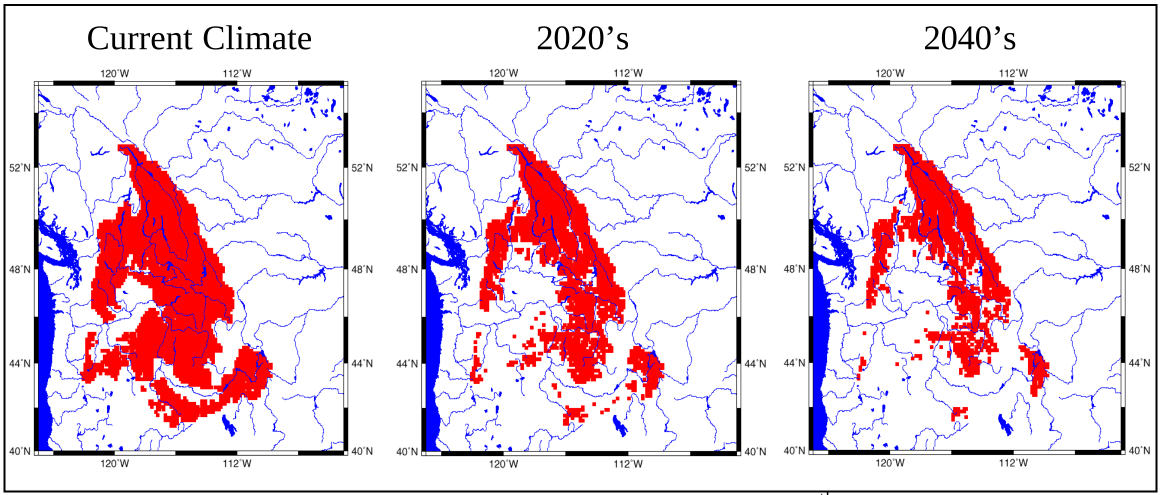

Figure 5 - Simulated snow extent in the Columbia basin on April 1 for 20th century climate (1961-1997) and future climate scenarios from the ECHAM4 global climate model

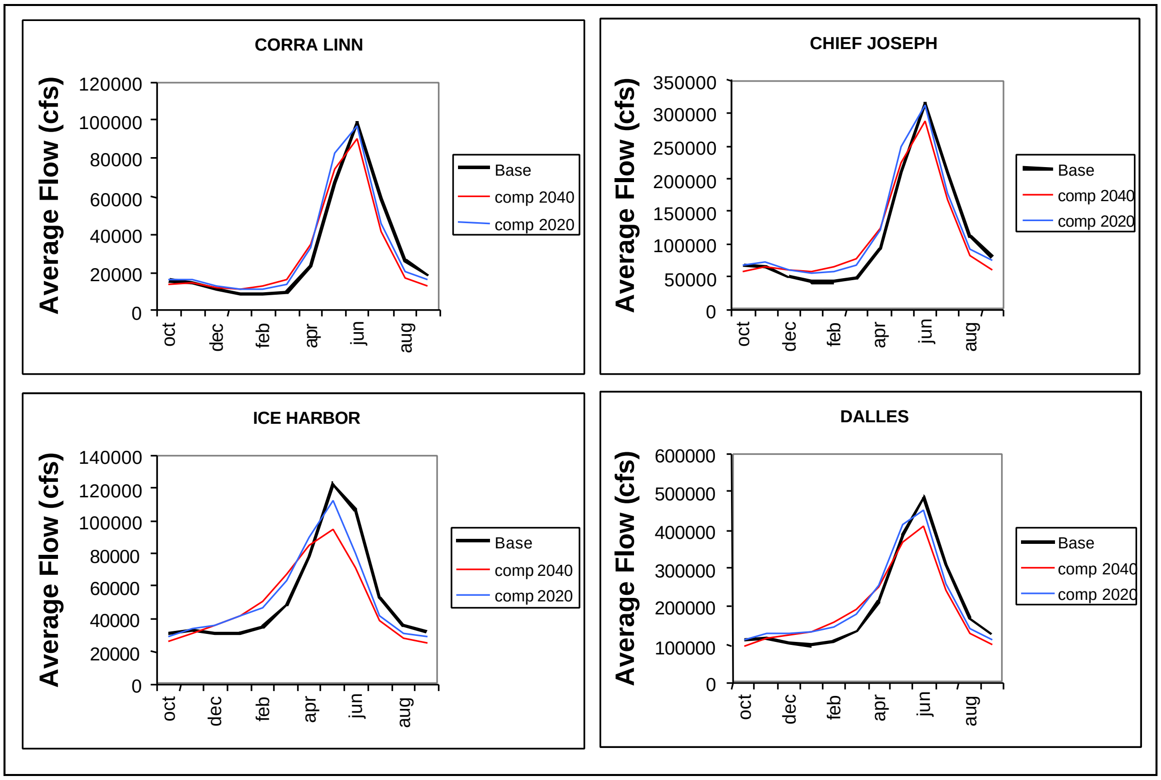

Figure 6 - Changes in simulated natural streamflow for the Columbia basin for the current climate and composite warming scenarios for the 2020s and 2040s

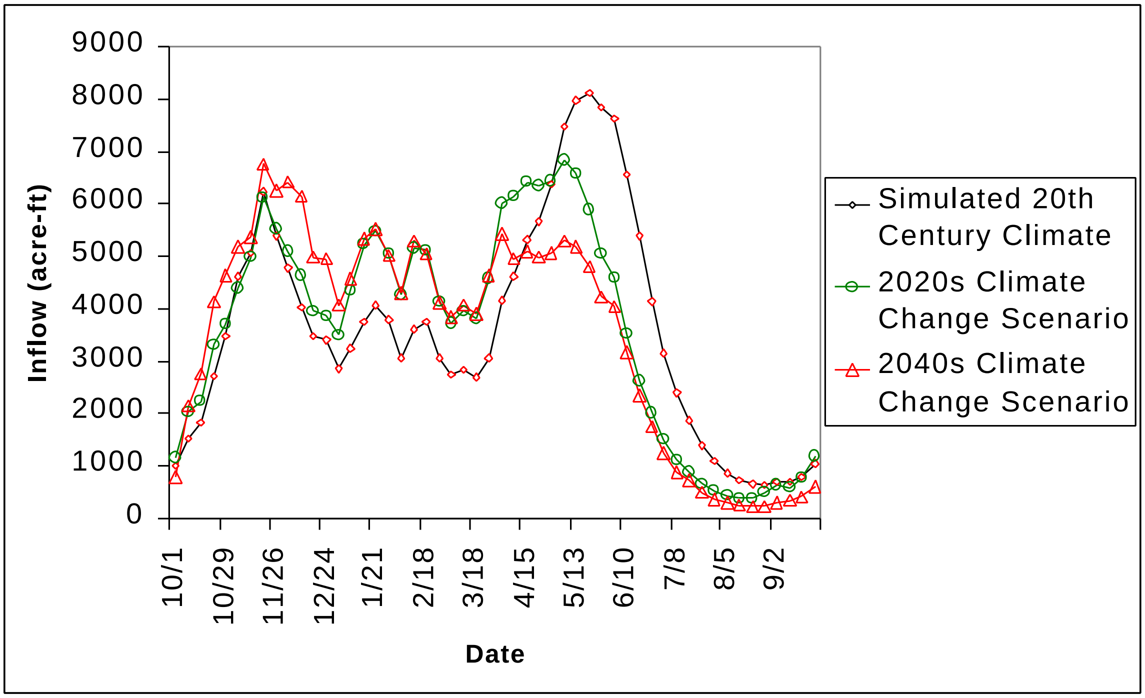

Figure 7 - Simulated average seasonal streamflow into Chester Morse reservoir from the Cedar River for 20th century climate and future climate scenarios (Source: Hahn et al., 2001)

In transient snow systems like the Cedar River basin, the transient snow zone would move to higher elevations as winter temperatures rise, shifting the system more towards a rain dominant character in winter, again increasing winter streamflows and reducing summer streamflows (Figure 7) (Hahn et al., 2001). Note that the timing shifts and reductions in summer streamflows in the Cedar River are more dramatic than for the Columbia River, and are more evident by the 2020s.

Key aspects of the projected changes in streamflow, namely changes in winter flow, summer flow, and the timing of peak spring flow, depend to varying degrees on the projected changes in temperature and precipitation. Projected changes in total annual precipitation (and especially summer precipitation) are less reliable (as discussed in IPCC 2001), but primarily affect annual streamflow volumes, and not the timing of flow. Most robust is the conclusion that winter snowpack and summer streamflow will decline as a consequence of warming (Hamlet and Lettenmaier, 1999).

Water Resources Impacts

We use the Columbia River and the Seattle Water Supply system as examples of water resources systems east and west of the Cascades that are likely to be affected by climate change. In each case we use hydrologic simulation models to examine the sensitivity of the existing infrastructure, current (or estimated future) water demand, and current operating policies to the changes in streamflow for the 2020s and 2040s described above. It should be noted that these are the impacts associated with middle-of-the-road climate change scenarios, and do not explore the plausible extremes that could occur (sensitivity to more extreme scenarios for the Columbia basin is explored in Hamlet and Lettenmaier, 1999).

Example 1: The Columbia River Basin

The snowmelt dominated Columbia River basin supplies hydropower, flood control, irrigation, lake recreation, and instream flow for fish. Figure 8 shows the reliability[7] with which these system objectives can be met for the current climate and middle-of-the-road climate change scenarios for the 2020s and 2040s. The largest changes in reliability are associated with those system uses that are strongly affected by reductions in summer streamflow (e.g., non-firm energy, summer fish flow targets, lake recreation, and irrigation). Reliability of system objectives that are strongly affected by changes in winter streamflow (e.g., “firm” energy, and flood control) are generally robust to the changes in streamflow. In general, the impacts are relatively small for the 2020s and become more significant by the 2040s.

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[7] Reliability is the simulated probability of meeting the system objective, in this case the percentage of months without failure in the simulation.

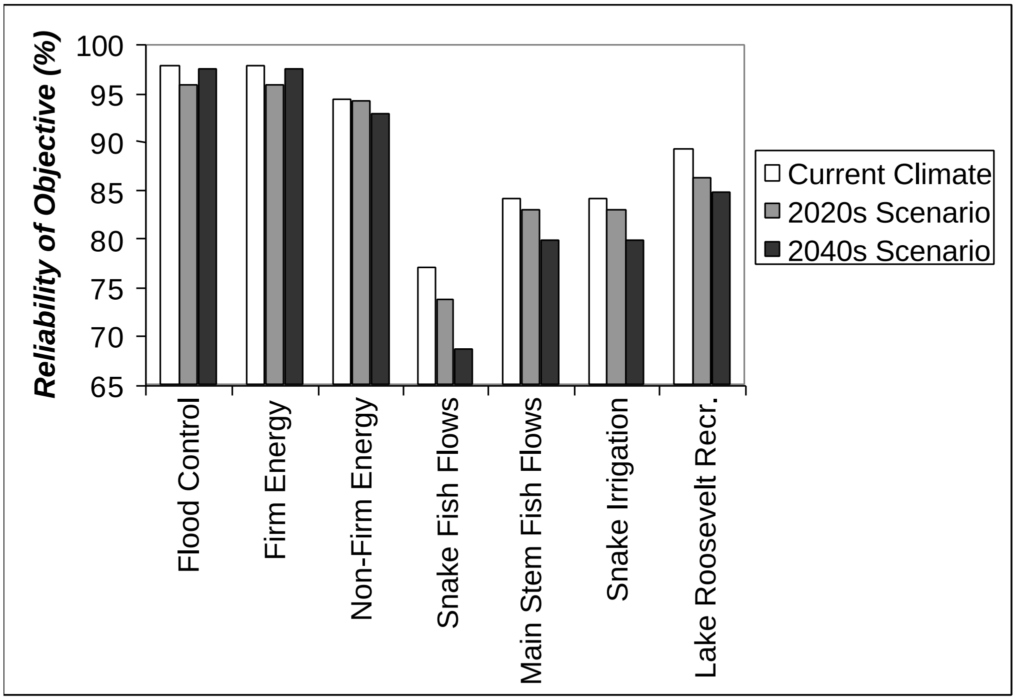

Figure 8 - Reliability of selected water resources objectives in the Columbia basin simulated by the ColSim reservoir model for the current climate (1961-1997), 2020s and 2040s.

Example 2: The Cedar River Basin

The Cedar River basin lies in the transient snow zone west of the Cascade crest, and provides about 2/3 of Seattle's water supply. Table 1 shows the reliability of meeting estimates of 2020's water demand for the current climate and for the 2020s climate change scenarios. The reductions in supply reliability simulated here are predominantly due to the changes in summer streamflow that result from earlier spring melt and reduced snowpacks.

	20th Century Climate (simulated hydrology)	**Composite 2020s (simulated hydrology)**
number of years of data	43 (1950-1993)	43 (perturbed 1950-1993)
total weeks of failure	11	22
maximum shortfall duration (weeks)	6	7
annual reliability	91%	88%
total shortfall (acre-ft)	23,839	45,990

Table 1 - Simulated reliability of water supply for the Cedar River portion of Seattle's water supply for estimated 2020 water demand for the current climate and the 2020's climate change scenario (source: Hahn et al., 2001).

Summary of PNW Vulnerabilities to Climate Change

The Achilles' heel of PNW water systems in the context of climate change is the region's very limited reservoir storage and reliance on snowpack to transfer water from the wet wintertime to the dry summertime. The results presented above demonstrate that as regional temperatures increase, the amount of water stored in winter as snow will decline, with a greater fraction of the annual runoff contributing to winter streamflow at the expense of summer streamflow. These effects will occur sooner (i.e., for smaller amounts of warming), and are most pronounced in water systems fed by river basins in the transient snow zone such as the Cedar River basin (See Figure 1 and 7). Areas with winter temperatures well below freezing may show only modest changes in streamflow timing for the same amount of regional warming, and hence will have delayed impacts. This is particularly true of the Canadian part of the Columbia basin which is at high elevation in the northern most part of the region (see e.g., Figure 6, Corra Linn).

Increases in winter flooding may also occur in basins in the transient snow zone, since higher temperatures will raise the snow line and increase the basin area directly contributing to streamflow during heavy winter precipitation events that are common in November and December. Changes in winter precipitation, which are uncertain, may either mitigate or exacerbate this effect.

The research reported here suggests that the greatest impacts on PNW water resources systems are likely to be associated with water resources objectives dependent on summer streamflow such as instream flow for fish, irrigation, urban water supply, lake recreation, and summer hydropower production. Water resources objectives dependent on winter streamflows, such as winter energy production in the Columbia basin, may have impacts associated with climate change, but are more likely to remain relatively unaffected by regional warming due to temperature related increases in winter streamflow that tend to compensate for the loss of reservoir storage in summer.

Many uncertainties remain regarding the exact nature of climate change in the PNW. There will undoubtedly be unexpected aspects of climate change. Interactions with natural climate variability, for example, may result in unexpectedly rapid changes in climate after a period of little change. While temperature increases have broad implications for water resources in the PNW that are largely independent of precipitation changes, the impacts may be exacerbated or ameliorated if significant changes in winter precipitation accompany regional warming. The most severe impacts would be expected for future conditions in which regional temperatures rise and winter precipitation decreases (see results for ECHAM4 scenarios in Hamlet and Lettenmaier, 1999).

Policy and Planning Arenas Affected by Climate Change Impacts

Climate, water, and water resources are linked to a large number of policy and planning arenas affecting the PNW, some of which are listed below. Ideally, climate change information should inform planning and policy decisions in these arenas:

1. Water use permitting (ground or surface water sources)
2. Federal or interstate water compacts
3. Long-term contracts between primary water suppliers and purveyors
4. Plumbing codes and water conservation plans (demand reduction)
5. Relicensing of dams by the Federal Energy Regulatory Commission (FERC)
6. Regional energy planning (conventional and hydropower)
7. Regional land use and development planning (surface and groundwater limitations)
8. Planning and implementation of water resources infrastructure
9. Storm water infrastructure planning
10. Water law (e.g., water markets, water banks)
11. International treaty agreements with Canada (e.g., Columbia River Treaty)
12. Salmon recovery planning and Endangered Species Act mitigation efforts
13. Reservoir operating policies and coordination (e.g., flood control)
14. Irrigated agriculture (e.g., water supply)
15. Forest resources (e.g., forest hydrology, roads)
16. Transportation (e.g., roadway flooding, bridge design, drainage)
17. Insurance and reinsurance industries (e.g., flooding, landslides)

Some specific adaptation pathways and institutional considerations for water resources are discussed in more detail by Hamlet et al. (2001).

Policy Implications

Following the listing of numerous runs of anadromous fish under the U.S. Endangered Species Act, the region has responded by increasing joint planning efforts and cooperation between management agencies. A similar effort to increase cooperation will be needed to address the likely challenges of lower summer streamflows brought by a warming climate. There is much that can be done, and in our view should be done soon, to minimize the risks associated with warming. For example, existing efforts to monitor important climatic and hydrological variables could be enhanced, and coordinated long-term water resources planning should begin on a river basin scale (Hamlet et al., 2001). Contingency planning designed to cope with unexpected developments, and monitoring programs designed to trigger emergency adaptation measures and evaluate adaptive measures would also provide valuable and costeffective “insurance”" for the region. These steps could be taken in the absence of more detailed knowledge of the future changes in water resources, and modified as further knowledge becomes available.

In river basins in the Cascades and in southern areas of the region like the Snake River basin, significant changes in spring snowpack and streamflow timing are likely to appear within 20 years, resulting in reductions in summer water availability. Increases in winter flooding will probably also occur in these areas, since warmer temperatures will raise the snow line and increase the area of the basin that directly contributes to streamflow during heavy winter precipitation events. Given the long lead time required to plan and implement changes to water resources infrastructure and policy, long term planning should begin to address the potential risks associated with climate change as soon as possible, and to formulate specific response strategies and contingency plans that can inform regional water policy and legislation.

In large snow melt dominated systems like the Columbia River basin, and particularly in the northern sub-basins, impacts on summer streamflows associated with temperature changes may be delayed for some time. Because of the inherent complexity of the institutions governing the Columbia, the economic dependence of the region on the Columbia basin's water resources, complicated international agreements with Canada that are central to the basin's operation, and the entrenchment of stakeholders in existing conflicts over water, timely long-term planning for climate change may be even more pressing in the Columbia system than it is in the rest of the region. Furthermore, planning for localized changes in the southern part of the basin (e.g., for irrigation in the Snake River basin) may need to proceed more rapidly than planning for the basin as a whole.

The need for regional coordination and oversight, particularly in large, complex water systems like the Columbia, is apparent. In the Columbia, and for the region as a whole, fragmentation of water management systems designed to deal with low flows severely limits the ability of the region to cope effectively with climate variability resulting in low streamflow (Miles et al., 2000). This weakness in the region's management systems implies a similar inability to cope with climate change, because climate change will likely increase the risk of low flow conditions and exacerbate the existing conflicts over water in the basin. Without better coordination, a planned response to the potential risks associated with climate change may be extremely challenging or impossible to implement. These issues and specific strategies for dealing with them are discussed in more detail in the companion paper discussing regional adaptation strategies (Hamlet et al., 2001).

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