3. Climate Change and Freshwater Resources in Oregon

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Summary and Knowledge Gaps

Climate change will affect various sectors of water resources in Oregon in the 21st century. The observed trends in streamflow show significant declines in September flow and, although not significant, increases in March flow in many transient rain-snow basins. These streamflow trends are associated with rising temperature and coincident declines in snowpack in spring in the latter half of the 20th century. While there are no distinct trends in high precipitation events, such events are associated with climate variability such as ENSO and PDO. Effects of ENSO and PDO are more pronounced at the beginning and end of the wet season in the Willamette River basin.

The amount and seasonality of water supply is projected to shift as the distribution of precipitation changes and temperatures rise. Higher summer air temperatures accompanied by reduced precipitation are projected to increase evapotranspiration and decrease stream flow in summer. Although there are no distinct spatial patterns of changes in precipitation and temperature across the State in the 21st century (uniform increase in temperature across the region), significant regional variations do exist. The magnitude of change depends on the importance of snow in the current water budget, so projected changes are greater for mountainous regions than for low-elevation areas. Transient rain-snow basins, such as those in the Western Cascade basins, are projected to be more sensitive to these changes in precipitation and temperature. The high Cascade basins that are primarily fed by deep groundwater systems could sustain low flow during summer months. Basins in the east of the Cascades are projected to have low summer flow in a distant future as groundwater recharge declines over time. April 1 snow water equivalent (SWE) will decline and the center timing of runoff will become earlier in transient rain-snow basins as snowpack is projected to decline consistently in the 21st century.

These model projections should be viewed with caution for several reasons when considering climate change impacts on water supply in Oregon. First, this chapter shows that few consistent trends in runoff are apparent in streamflow records from Oregon; instead, the direction and magnitude of change in streamflow varies by season, by basin size, and among ecoregions in Oregon. Second, observed streamflow trends (e.g., declining flows in summer, or

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in September) may be explained by factors that may not be directly related to global climate change. For example, recent low-flow years are attributable to low precipitation years (especially 2001 and 2005) and perhaps to interannual variations in snowpack associated with cyclical variation in ocean temperatures, while long-term decreases in summer flows are attributable to the combination of summer precipitation decline and increasing water withdrawals for consumptive use. Third, model projections do not account for possible resilience and adaptations in natural ecosystems that may alter water use and lead to smaller than expected changes in streamflow. More work is needed on vegetation responses to climate variability, the interactions between soil water and vegetation, and the relationship between streamflow and precipitation (runoff ratios) in large basins.

Water quality is also projected to change with rising air temperature and seasonal shifts in flow availability. Water temperature is projected to rise as air temperature increases in the 21st century, particularly in urban streams where natural riparian vegetation is typically lacking. A decline in summer stream flow will exacerbate water temperature increases, because the low volume of water will be heated up more quickly than during times with larger instream flows. Changes in water temperature can have significant implications for stream ecology and salmon habitat in many Oregon streams. Lower order streams in transient rain-snow basins and in semi-arid eastern Oregon will be the most vulnerable to rising summer air temperature and diminished low flow. Sediment and phosphorus loads are expected to increase in winter as winter flow is projected to rise. Conservation-oriented urban development could potentially reduce storm runoff amount and subsequent sediment and pollutant loads, providing potential opportunity for local adaptation to climate change. At the basin scale, new dam or reservoir operation rules might be required to maintain environmental flows in summer. The complex interactions among changing hydrology, watershed biogeochemistry, and land management need further investigation.

As shown in the Portland water consumption case study (Section 3.6), when other demand factors are held constant, increases in temperature alone result in higher demands for peak season water. While demand during winter months is expected to remain constant, research on urban water demand suggests temperature-induced water consumption, particularly among single family residential (SFR) households. These impacts are also evident at multiple scales, including the household, neighborhood, and region. At the regional scale, urban land uses have different water demands, and will have varying impacts on water demand. Overall, single-family residential land use is the largest consumer of water. At the neighborhood scale, the density of urban development helps predict future water use, where higher density residential developments have lower per capita water demand. Finally, at the household scale, a coupling of structural attributes (e.g.,e.g., building and lot area) and temperatures affect water demand. High-density housing developments with smaller homes could limit the growth of residential water demand relative to other water uses in the region.

Uncertainty is still high in projecting future changes in runoff, water quality, and urban water demand in Oregon. While the main source of uncertainty stems from the choice of global circulation models, additional sources of uncertainty include GHG emission scenarios, downscaling methods, hydrologic model structure and parameterization, and impact assessment methods. Multi-ensemble models that take into account all sources of uncertainty with different weights might provide a means of quantifying different sources of uncertainties. Communicating uncertainty to water resource decision makers is another challenge for adaptive water resource management in a changing climate. While a more sophisticated hydrologic impact assessment model is yet to be developed, climate adaptation strategies can be implemented at multiple spatial scales.

Land use planning may be helpful in meeting the future water needs of the State. Currently, land use and water resource management agencies have limited coordination in their responsibilities. Zoning and public involvement can be instrumental to improving the coordination between land and water management agencies. Zoning can be used to link types of future development that include a combination of infill, expansion, connecting existing developments, with explicit identification of water demands on different land uses in the region. To date, few plans have explicitly included dimensions of integrated land and water management. Outreach and education campaigns can help inform the public about the relationship between water demand and supply, but can also assist in adapting to a future with increasingly limited resources. The details of those plans and the precise nature of the outreach and education campaigns will require further investigation, and will likely be part of the second assessment of Oregon's water resources.

3.1 Introduction

The hydrology and water resources of Oregon are sensitive to changes in precipitation and temperature, but the rate of change varies across basins with different topographical, geological, and ecological characteristics. According to the Fourth Assessment Report (AR4), many Oregon streams will experience higher winter flow and reduced summer flows as temperature rises and the variability of precipitation increases. In addition, various human activities, especially land cover modification and dam or reservoir operations, have modified the hydrologic regime of many Oregon streams since the late 1800s. Understanding the complex interactions among climate systems, terrestrial systems, and human systems is essential to predicting future changes in water resources and implementing sustainable water resource management in Oregon.

For this first statewide climate impact assessment, we have both initiated some new research studies using downscaled climate change simulations, and compiled existing relevant studies, putting them into the context of climate change impact assessment. While most studies rely on empirical statistical data analysis using observed data, some case studies use downscaled global circulation model results combined with hydrologic simulation models for climate change impact assessment (e.g., Graves and Chang, 2007; Franczyk and Chang, 2009; Chang et al., 2010a; Praskievicz and Chang, 2011; Chang and Jung, 2010; Jung et al., in review). Others use synthetic climate change scenarios (e.g., Tague et al., 2008 and Tague and Gran,t 2009). Based on these case studies and the best available information, we attempt to assess the current status of Oregon water resources and identify emerging water issues under the stress of climate change.

This chapter is composed of six main sections. Section 3.2 assesses observed variability and trends in various components of hydrology (e.g., snow water equivalent, glacier mass balance, extreme hydrologic events) in selected Oregon river basins. Section 3.2 assesses future changes in surface water hydrology including spatial and temporal variations of runoff, snow water equivalent and uncertainty in projecting future runoff. Section 3.3 describes future projections of surface water, methods of downscaling for hydrologic impact assessment, trends in future precipitation and temperature in the 21^{st} century, and uncertainty associated with climate impact assessments. Section 3.4 examines potential changes in groundwater systems and their contribution to streamflow under future climate change scenarios. Section 3.5 investigates possible changes in water quality with a focus on water temperature and nutrients. Section 3.6 describes case studies of Portland and Hillsboro municipal water demand associated with climate variability. Section 3.7 discusses water infrastructure management, including urban water demand management and dam operation. The concluding section offers a concise summary of the main findings of this water resources impact assessment and discusses possible future research directions.

3.2. Observed Variability and Trends (Historic Perspective)

Streamflow in Oregon is highly variable in space, and over multiple time scales. It varies in space according to elevation, topography, geology, and basin area, and varies seasonally according to the amount of precipitation, relative proportions of rain and snow, topography, geology and vegetation. Streamflow also fluctuates on interannual time scales. Changes in snowpack accumulation and melt from climate warming are expected to influence streamflow, but these effects will be more pronounced where streamflow patterns are controlled by snowmelt. Glacial melt and retreat also may affect streamflow, but only in very small, high-elevation basins, and this effect will diminish as basin size increases. Streamflow also depends on the human-controlled factors of vegetation cover, urbanization, and river regulation (e.g. by dams); changes in these factors have significantly altered streamflow in the past century. Therefore, it is extremely challenging to disentangle long-term trends in streamflow from temporal variability. It is also easy to mistakenly attribute observed trends to climate, when they may be due to flow regulation (dams) or land use changes.

3.2.1 Annual and Seasonal Surface Flow and Variability

3.2.1.1 Water budget

The water budget indicates the potential mechanisms and magnitude of various hypothesized streamflow changes in response to climate variability. The conceptual water budget for Oregon watersheds involves multiple components, including precipitation, cloudwater interception, canopy evaporation, transpiration, snow storage, and snowmelt. Climate change and variability potentially affect all these components.

3.2.1.2 Spatial patterns of annual runoff

The spatial patterns of runoff in Oregon pose significant challenges for detecting climate change effects on historical streamflow. Most of Oregon is forested, strongly influencing runoff patterns through evapotranspiration, which may exceed 50% of precipitation. Precipitation is orographic, and highest in mountains and in western Oregon (see Chapter 1). Because precipitation is concentrated in mountainous areas and in western Oregon, large drainage basins in the eastern two-thirds of Oregon produce much less streamflow than the Willamette and coastal basins (see Figure 3.1 for major river basins in Oregon). Additionally, the lower Columbia, Willamette, and Oregon Coastal watersheds produce higher peak flows and water yields than the eastern Oregon watersheds, although they are partially covered by forests. The highest peakflows occur in southern and northern coastal Oregon, reflecting the high precipitation and steep drainages (see Figure 3.2).

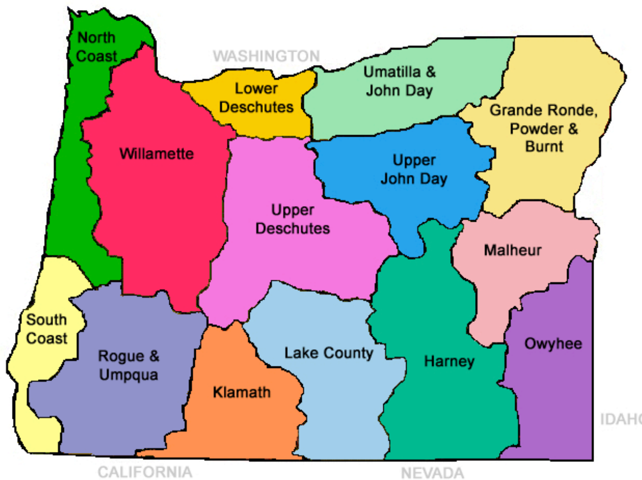


Figure 3.1 Major river basins in Oregon

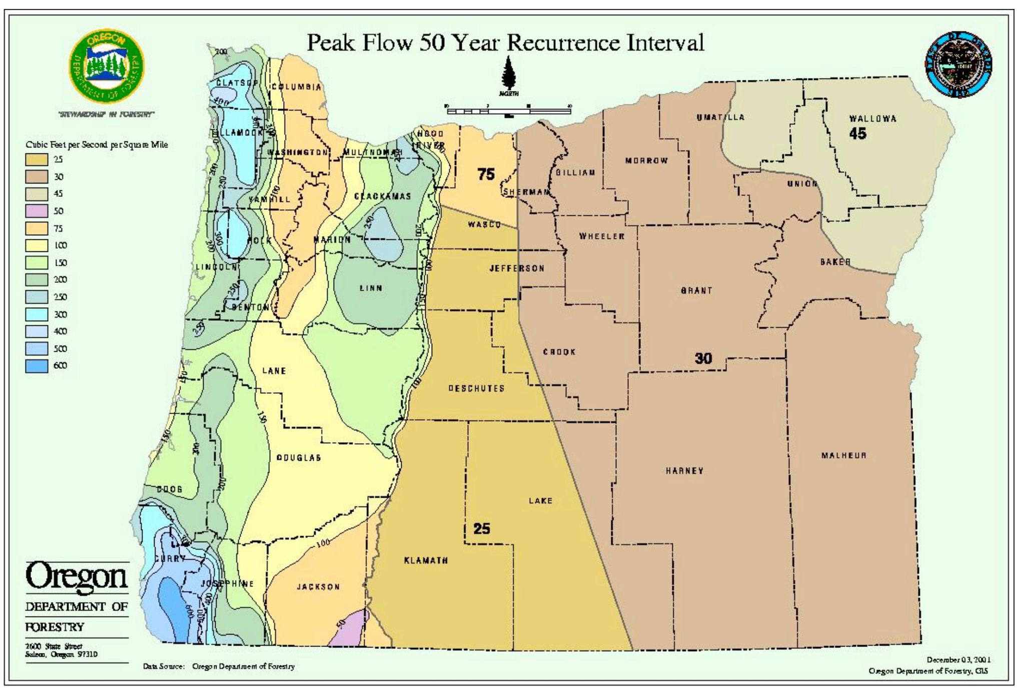


Figure 3.2 Peak flow 50 year recurrence interval (source: http://www.odf.state.or.us/atlas/maps/peakfl75.jpg).

The seasonal cycle of the Columbia River discharge has already been modified significantly by major dams and deliberate management: peak discharge formerly occurred in late spring, but now occurs in autumn (Sherwood et al., 1990). The annual average discharge shows large interannual variability and some interdecadal variability, but no significant long-term trend between 1928 and 2009 (Figure 3.3). In contrast, the average May-through-July discharge has decreased by about 30%; most of this decrease occurred between 1950 and 1990, as a result of management for flood control, irrigation and hydroelectric power. In recent years, concern for salmon smolt survival has led to increased spillage over the dams in spring and early summer; if this concern continues to prevail, the summer discharge might recover or at least stabilize.

Most populated areas occur in the lower reaches of large basins, but upstream dams and land use regulate streamflow at downstream gages. Basins above dams provide records that are unaffected by dams, but these watersheds are mostly in areas of low population density, and streamflow in these basins has been affected by forest harvest and other land use changes over the past century. The construction of dams for flood control and irrigation in the middle part of the 20th century throughout much of western Oregon greatly diminished peak discharges and altered the seasonal pattern of discharge in large basins, such as the Willamette River. A hydrologic simulation model of the natural flow regime (Figure 3.4) illustrates the impact of dams between 1977 and 2008 for three stations in the Willamette River: late summer flow is augmented by water released from dams.

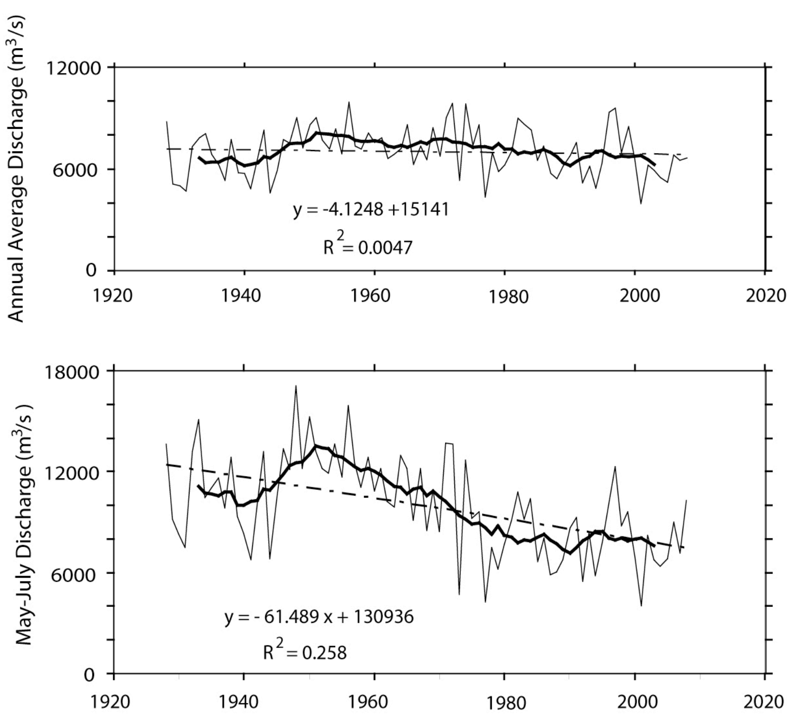


Figure 3.3 Annual average and May – July discharge in the lower Columbia River, 1928-2009

Forest harvest significantly and persistently increased winter and spring water yields in small watersheds of western Oregon (Jones and Post, 2004), and also altered peak discharges of at least small peaks, and (arguably) large peaks in small and intermediate basins (Jones and Grant, 1996, Thomas and Megahan, 1998, Beschta et al., 2000, Jones ,2000, Grant et al., 2008).

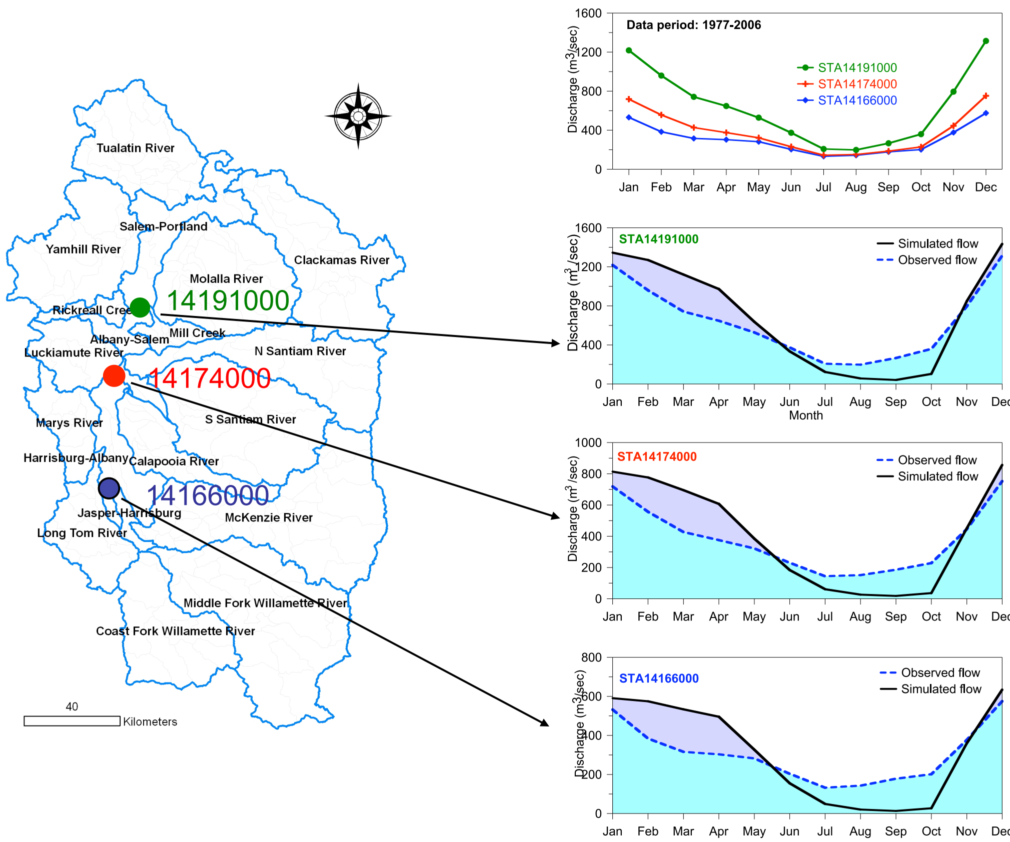


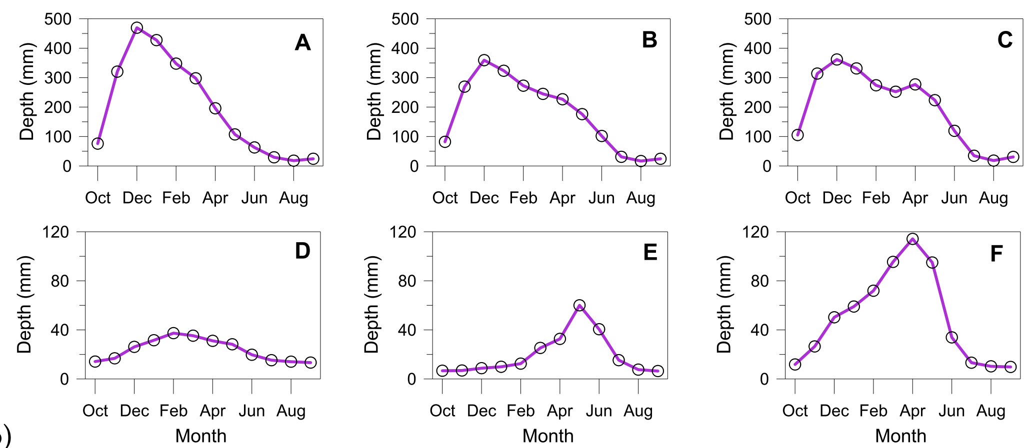
Figure 3.4 Comparison of the observed flow and the PRMS simulated flow for the three monitoring stations in the Willamette River (Chang et al., 2009)

3.2.1.3 Temporal patterns of streamflow

Seasonal patterns of runoff vary across Oregon depending on precipitation type (rain vs. snow), basin size, topography, and geology. Runoff in Oregon is strongly seasonal: over 75% of streamflow occurs in the six months of October to April (Willamette River, John Day River, mean monthly discharge, Oct to Sep). In small basins on highly weathered old volcanic rocks in western Oregon streamflow varies even more by season. In contrast, streamflow from basins on recent, porous lavas of the High Cascades (e.g., Clear Creek) have low seasonal variability because deep groundwater augments summer low flows (Tague et al., 2008; Chang and Jung, 2010). In contrast, flow in the western Cascades (e.g., Lookout Creek), primarily fed by shallow subsurface flow, diminishes rapidly during dry summer season.

Figure 3.5 Comparison of late summer streamflow in Clear Creek (groundwater fed) and Lookout Creek (shallow subsurface-fed). Photo credit: Chang.

Figure 3.6 illustrates monthly hydrographs for six representative basins in Oregon. They are located in different hydrologic and ecoregions, which reflect different climate and vegetation regimes. Basins A (coastal basin) and B (Willamette Valley) are primarily fed by rainfall, while flow in basin C (Hood River) is contributed by a mix of rain and snowfall, and basins east of the Cascade Range (D,E, and F) are fed by snowmelt (Fig. 7a). Basins A and B have a rainfall-dominated peak in December, basin C has a rainfall-dominated peak in December and a snowmelt-dominated peak in April, and basins D, E, and F have a single snowmelt-dominated peak in late winter and spring (Figure 3.7b). Total annual runoff amounts in basins in eastern Oregon, which received much less precipitation, are much smaller than those in the Valley or coastal areas. Geology also controls the timing and amount of runoff in the Deschutes basin (Figure 3.7b-d).



(b)

Figure 3.6 Monthly mean runoff for annual total runoff and the ratio of summer flow to annual flow (Source: Chang et al. in preparation). A = Wilson River near Tillamook; B = Little North Santiam River near Mehama; C = Blazed Alder Creek near Rhododendron; D = Warm Springs River near Kahneeta Hot Springs; E = Donner und Blitzen River near French Glen; F = Umatilla River above Meacham Creek near Gibbon.

3.2.2 Trends in annual and seasonal flow

Observed interannual trends in annual discharge in very large basins can be seen from 100-year records at the Willamette River (Salem) vs. John Day (McDonald). The lowest streamflow in 100 years of record was 1977 on both the west and east sides of the Oregon Cascades (Figure 3.7). The wettest years were in the early 1970s on the west side, and early 1980s (ENSO) on the east side. On the west side, 2001 and 2005 were among the six lowest-ranked streamflow years, but these were not unusually lowflow years on the east side.

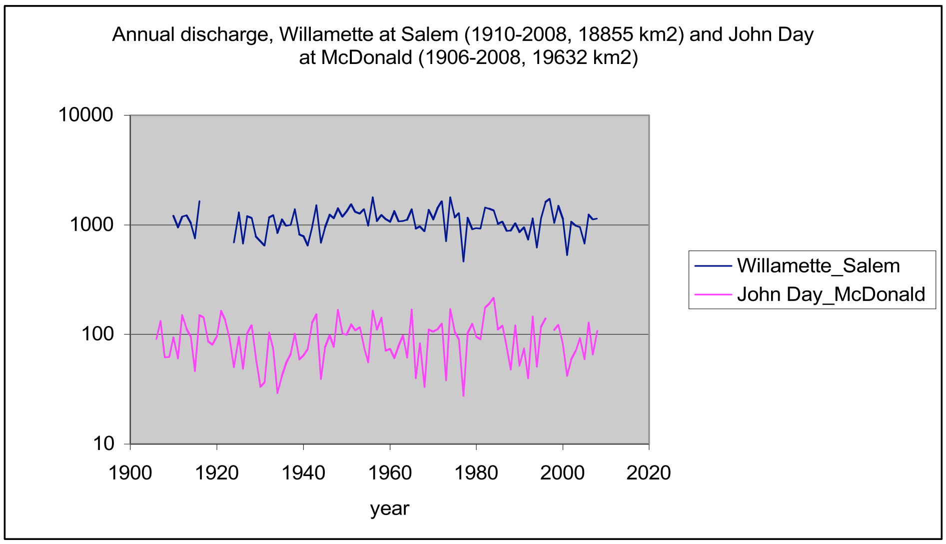


Figure 3.7 Annual discharge 1906 - 2008 on the west side (Willamette) and east side (John Day) of the Cascade Range in Oregon

Lins and Slack (1999) found decreases in streamflow in the Pacific Northwest streams, particularly in low flow regimes during the 20th century. Subsequent studies in the PNW also show declining streamflow trends (Hamlet et al., 2007; Stewart et al., 2004, 2005; Barnett et al., 2008). Similarly, Luce and Holden (2009) found significant decreases in the magnitudes of the lowest 25% of streamflow years over the period 1948-2005 in Idaho, Washington, and Oregon, and speculate that on the east side of the Cascades these declines may be due to declining precipitation. However, precipitation is not declining in the central western Cascades of Oregon (Jones, unpublished data from the Andrews Forest, and PRISM maps/data from C. Daly). More work is needed to relate streamflow trends to precipitation in large basins.

Warming air temperatures are expected to shorten snowpack duration and speed snowmelt timing, resulting in earlier peak annual streamflow. Based on a study of the western United States, Stewart et al., (2004, 2005) found that peak streamflow timing now comes one to four weeks earlier than it did in the the middle of the 20th century, and attribute this change to earlier spring snowmelt. However, the temporal center of mass of snowmelt-dominated streams in Oregon historically occurs in March, whereas the western basins most affected by warming are those with peak streamflow in April to June. Oregon streams in this study mostly experienced shifts of <10 days, and most of these streams were in eastern and southeastern Oregon (Stewart et al., 2004, 2005).

To assess climate variability influences on streamflow in Oregon, we selected USGS and Oregon Department of Water Resources stream gauging stations that have more than 30 years of record and have not been affected by upstream dams or significant diversions. Thirty stations in Oregon meet such criteria and are analyzed for trends; 21 were analyzed for years 1958 - 2008, and 9 with shorter records were analyzed for years 1975 - 2008. The Mann-Kendall's test was used to detect the direction and significance of trend in each station. While summer flow declined in over two thirds of the stations during the study period, spring flow increased in one third of the study stations. Twenty-five stations exhibit declining trends in mean annual flow, while only 4 of the 25 stations show significant trends (Table 3.1) (Chang et al. in preparation). September flow declined significantly at most of the studied stations, while March flow increased significantly for only two stations (see Figure 3.8). Decreasing September precipitation appears to be responsible for the declines in September flow.

Table 3.1. The number of positive and negative trend stations for 30 stream gauging stations (21 with period 1958-2008, 9 with period 1975-2008). Numbers in parenthesis show statistically significant trend stations ($P < 0.05$).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
+	9 (0)	1 (0)	14 (1)	17 (0)	7 (0)	11 (0)	6 (0)	4 (0)	3 (0)	4 (0)	7 (0)	13 (0)	5 (0)
–	21 (1)	29 (2)	16 (2)	13 (3)	23 (5)	19 (1)	24 (2)	26 (9)	27 (16)	26 (3)	23 (2)	17 (2)	25 (4)

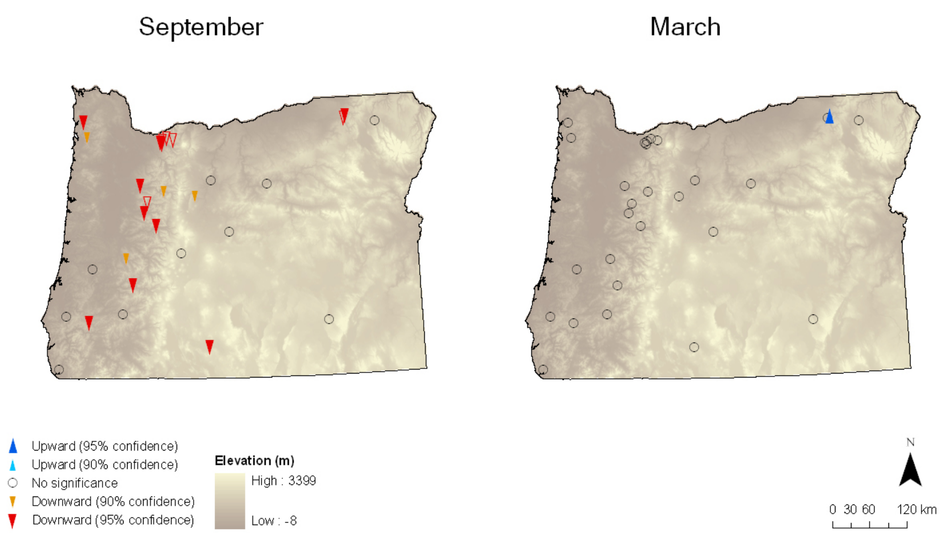


Figure 3.8 Trends in average runoff for March and September for 30 stream gauging stations. Numbers in parenthesis show statistically significant trend stations ($P < 0.05$).

The Umatilla River above Meacham Creek (USGS station number 14020000) illustrates a case of increasing flows in early spring, and declining flows in September over the period 1958 and 2007 (see Figure 3.9). The increase in March streamflow may be due to earlier spring snowmelt. The interannual variability of September flow also declined during the study period.

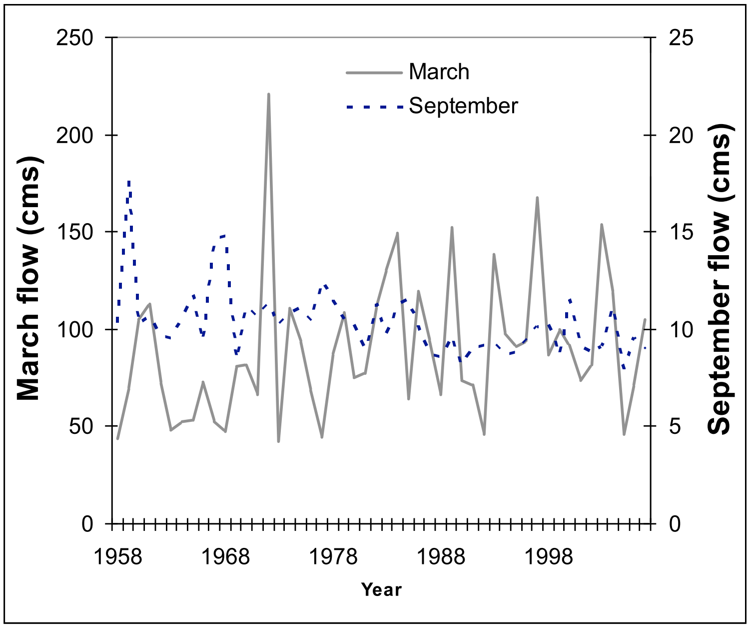


Figure 3.9 Trends in March and September flow for Umatilla River above Meacham Creek, near Gibbon

In the Upper Klamath River basin, dry season (April to September) and summer streamflow (July to September) declined 16%, and 38%, respectively during the period between 1961-2009 (Mayer and Naman 2010). This decline is closely associated with decline in April 1st snowpack, which decreased approximately 40% during the same study period for snowcourse sites located below 1820 m elevation.

Streamflow trends vary according to the underlying geology and the importance of snow in the annual hydrograph. In the Cascade Range of western Oregon, Jefferson et al., (2006) found that relative streamflow in August (i.e., August streamflow as a proportion of annual flow) decreased significantly over the past century in two snow-dominated basins, but not in two rain-dominated basins. Basins draining the High Cascades (Clear Lake and McKenzie River) experienced significant declines in August streamflow from the early 1920s (McKenzie River) or early 1950s (Clear Lake). However, basins draining the highly-weathered western Cascades (South Santiam, Smith River) did not experience declines in relative streamflow in August over similar periods of record.

In small, undisturbed forested basins, runoff ratios and baseflow have declined significantly during spring, but they have not changed during summer or winter in the Andrews Experimental Forest in the Willamette basin, over the period 1952 - 2006 (Moore, 2010: Figure

3.10). These patterns suggest that declining spring streamflow is explained by increasing air temperatures and corresponding declines in snowpack accumulation and spring melt, as well as increased evapotranspiration from increased spring air temperatures. Corresponding increases in winter rain have not produced detectable increases in winter runoff in these small basins, either because the increase in rain is relatively small compared to interannual variability, or because warming temperatures have increased photosynthesis and transpiration in winter, mitigating any effect of increased ratio of winter rain to snow. Declining spring discharges also were not associated with declining summer discharges, either because the decline in spring runoff is not sufficiently large to influence summer soil moisture storage and runoff, or because dominant conifer trees are adapted to intra- and interannual variations in moisture availability and adjust transpiration accordingly (Moore, 2010).

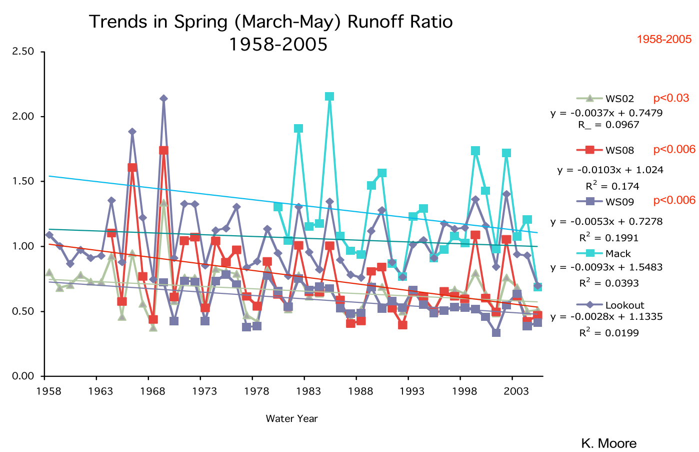


Figure 3.10 Declining spring runoff ratios from small, forested reference basins in the Andrews Forest, western Oregon.

In the Portland metropolitan area, there are no significant trends in annual mean flow between 1950 and 2000 regardless of urban development during the study period, suggesting that shift in climate regime may have masked the urban influence on hydrology, although urban streams show the flashiness and dryness (Chang 2007).

Overall, despite apparent increases in spring air temperatures and corresponding decreases in snowpacks, few consistent trends are apparent in long-term streamflow records.

3.2.3 Trend in Snow Water Equivalences

The timing of streamflow depends on snowpack size and the timing of melt in much of the western US, including many parts of Oregon. Annual precipitation in western Oregon is high (above 2500 mm in mountainous areas), but 70 - 80% of this precipitation occurs in winter (November to April). Hence, summer streamflows are dependent upon snowmelt. Therefore, climate warming effects on snowpacks may reduce streamflow during spring and summer periods, when water yield is limited.

Analysis of historic data show that warmer temperatures at higher elevations result in a shift in the form of precipitation toward more rain and less snow. Significant declines in snow water equivalent (SWE) in the Pacific Northwest and a shift from snow to rain coinciding with increases in temperature since the 1950s are well documented (Mote, 2003; Mote et al., 2005; Knowles et al., 2006), and this change has been related to trends in hydrologic response (Mayer and Naman, 2009).

Throughout the intermountain West, current analyses of projected climate change impacts predict that rising temperatures will diminish snowpacks, and these studies predict future summer water shortages (Folland et al., 2001; Service, 2004). Knowles and Cayan (2002) predict that the April to July fraction of total annual flow will be reduced by 30% in the Sierras by 2060 as a result of reduced snow accumulation and earlier melt. More recent climate simulations taking different greenhouse gas emission pathways into account predict future snowpack reductions of 30 – 90% (Hayhoe et al., 2004).

Snowpacks in the Pacific Northwest are expected to be particularly sensitive to warming. Climate models predict continued winter warming of 0.2 to 0.6°C per decade in the Pacific Northwest (Mote and Salathé 2010), and Cascade snowpacks are projected to be less than half of what they are today by 2050 (Leung **et al., 2**004). Lower elevations of the Cascade Ranges, for example, are predicted to exhibit the greatest differences in the timing and magnitude of snowmelt (Hayhoe et. al., 2004; Payne et. al, 2004). Because snow in much of the Cascades accumulates close to the melting point, future warming would mean that large areas could shift from a snow-dominated to a rain-dominated winter precipitation regime (Nolin and Daly, 2006), potentially increasing winter peak flows and reducing summer low flows as discussed above in Section 3.2.2.

In response to temperature increases in the Pacific Northwest (Cayan et al., 2001; Regonda et al., 2005), snowpacks in western North America have declined over the past 50 years (Mote et al., 2005). Using measurements of April 1 snow water equivalent (SWE) dating back to 1950, Mote et al. (2005) noted that the Pacific Northwest has experienced the largest declines in snowpacks in the western United States. A similar decline in April 1 snow water equivalent has been identified in the Clackamas River basin of Oregon between 1948 and 2000 (Graves and Chang, 2007). This change can be primarily attributed to an increase in winter temperatures (Mote, 2003; Mote et al. 2005; Barnett et al. 2008).

Some large portions of the mountains of Oregon may lose their snowpack, converting the hydrograph from a snowmelt to a rain-dominated pattern. Knowles et al. (2006) documented a significant trend towards increased rainfall and decreased snowfall (corrected for changes in precipitation) over the western United States from 1949-2004. The Pacific Northwest demonstrated a strong connection between Pacific Decadal Oscillation and temperature for days on which precipitation occurred. However, longer-term temperature trends also appear to be responsible for the shift from snowfall to rainfall. Most watersheds on the western slope of the Oregon Cascades encompass elevations that receive winter precipitation as a mixture of rain and snow. These watersheds have complex winter hydrographs that are dependent on the distribution of rain and snow during individual events, which in turn is controlled by storm temperatures and catchment hypsometry. Snow cover typically accumulates at temperatures close to the melting point, and thus is at risk from climate warming because temperature affects both the rate of snowmelt and the phase of precipitation. With a projected 2°C winter warming by mid-century, 9200 km^2 of currently snow-covered area in the Pacific Northwest would receive winter rainfall instead (Nolin and Daly, 2006).

Regional climate models predict that Pacific Northwest summers will become hotter and drier over the next century (Christensen et al., 2007), exacerbating existing stresses. Tague et al. (2008) used a hydro-ecological model named RHESS to examine the influence of geology on Cascadian streamflow response to warming scenarios. Their model showed that warmer temperatures resulted in greater reductions in August discharge and annual minimum flows for the High Cascades than the Western Cascade watershed, both in terms of absolute volumes and normalized by drainage area. The Western Cascade streams, however, showed greater relative reductions in these summer streamflow metrics. Model results illustrate that differences between the responses of the two sites were primarily due to differences in groundwater flow, as manifested in drainage efficiency of the watersheds. Spatial differences in recharge characteristics and the timing of snow accumulation and melt were shown to be important, but secondary, in terms of explaining responses at the two sites.

3.2.4 Trend in Glacier Mass Balance

Glacier runoff contributions to streamflow provide critical water supply in many mountainous regions (e.g. Singh and Singh, 2001; Barnett et al., 2005). Historical records and future climate projections point to the loss of midlatitude glaciers throughout the world (Oerlemans, 2005; Lemke, 2007), resulting in significant changes to both total annual and summer streamflow downstream (Chen and Ohmura, 1990; Barnett et al., 2005; Hock et al., 2005; Juen et al., 2007). Glacier runoff supplies fresh water to numerous communities in throughout the world and is highly sensitive to changes in temperature (Chen and Ohmura, 1990). Warmer temperatures cause increased glacial melt but as glaciers recede, their potential contributions to water supplies are diminished (Barnett et al., 2005; Hock et al., 2005). Glaciers also moderate intra- and inter-annual flow variability by storing water in the form of ice during years of high precipitation and releasing melt water during seasons and years of high temperature (Fountain and Tangborn, 1985). The hydrologic properties of glaciated watersheds differ from glacier-free watersheds in several ways. Glaciers release an estimated two to ten times more water than neighboring catchments of equal area and altitudes in the United States (Mayo, 1984). Runoff variability in glaciated watersheds is controlled primarily by surface energy fluxes whereas runoff variability in glacier-free watersheds is dominated by precipitation patterns (Jansson et al., 2003). There is a lag effect caused by glacial storage and the delayed networking of englacial and subglacial conduits (Jansson et al., 2003) such that runoff from glacier melt is delayed until later in the summer, when other contributions to streamflow are much reduced. Glacier melt decreases streamflow variation, bolsters late season runoff, and is especially important in drought years (Fountain and Tangborn, 1985). Under negative mass balance conditions, glaciers discharge a greater volume of water than is input in the form of precipitation and this “excess discharge” can be substantial, even for watersheds having less than 15% glacier coverage (Lambrecht and Mayer, 2009).

In the northwestern United States, glaciers diminished throughout the 20th century and model simulations suggest this trend will continue through the next 100 years (Dyurgerov and Meier, 2000; Hall and Fagre, 2003). Recent studies document that Mount Hood's glaciers have decreased in length as much as 61% over the past century (Lillquist and Walker, 2006). Coe Glacier has diminished at a rate 27% slower than that of the Eliot in the last century (Jackson, 2007), and we estimate that by about 2057 its area will be about 61% of its present day area. On a regional basis, temperatures are expected to increase by a range of 1.1 – 6.4°C in the next 100 years (Lemke et al., 2007). Nolin et al. (in review) showed that for the Upper Middle Fork Hood River, 74% of late summer streamflow is derived directly from glacier melt, most of which goes to irrigation of high value crops in the Hood River Valley. Their model simulations indicate that, while increased temperature leads to more rapid glacier melt and therefore increased streamflow, glacier recession ultimately overcomes this effect, leading to substantial declines in streamflow. These results show that the disappearance of Mount Hood's glaciers will likely result in the loss of about 27% of total late summer discharge in the Upper Middle Fork Hood River.

Glaciers in Oregon, like much of the west (e.g., Nylen, 2004; Hoffman et al., 2007) have been receding since the start of the last century when observations first began (Lillquist and Walker, 2006; Jackson and Fountain, 2007). The glaciers rapidly retreated since about 1910, slowed and advanced during the 1960s to middle 1970s before retreating again in the early 1980s. Since the late 1990s glacier retreat has accelerated. Between 1900 and 2004, the glaciers in Oregon have lost about 40% of their area. Some glaciers have lost as much as 60%. No glaciers are advancing in Oregon. (details about glacier change in Oregon: http://glaciers.research.pdx.edu/states/oregon.php)

Generally speaking, glaciers respond to variations in snow accumulation which nourish the glacier and to variations in summer air temperatures which cause melt. No long term trends in precipitation exist but summer air temperatures have been warming. Consequently, the shrinkage of glaciers in Oregon is due to warming air temperatures (Jackson and Fountain, 2007). This supports other work regarding the thinning of seasonal snowpack in Oregon (Mote, et al., 2005; Nolin and Daly, 2006). We expect that as the climate continues to warm, the glaciers will continue to recede.

Glaciers are locally important contributors to water supplies, and their contributions are important for augmenting summer lowflows. However, the area of glacial cover is very small, and the proportion of total water yield in Oregon that originates from glaciers is extremely small.

3.2.5 Trend in Extreme Hydrologic Events

In an analysis of climate change impacts for the State of Washington, Rosenberg et al. (2009a) found that peak flows and total annual precipitation have decreased over time while the magnitude of large, low frequency events of all durations has increased in some areas. In this study, trends in high flow (top 5% daily flow) and low flows (low 5% daily flow) were examined for the same 30 gaging stations in Oregon that were used in section 3.2.1. There are no significant trends in high flow for most of the stations examined (not shown). The average of the driest 5% of years, however, decreased at 25 sites, and 12 of these trends were significant (see Figure 3.11). Seventeen out of the 21 sites with longer records showed decreases in the average of the driest 5% of years, and the M-K test showed that 9 of these negative trends were significant. Most of the stations that exhibit significant negative trends are located in high elevations, suggesting that diminishing spring snow covers and consequent low summer flows may explain the declines in low flows in those stations. However, increased water use by young forest plantations, which were established during the period of streamflow record in these basins, also may be a factor (e.g., Perry, 2007). Only two stations show a significant increase in low flow.

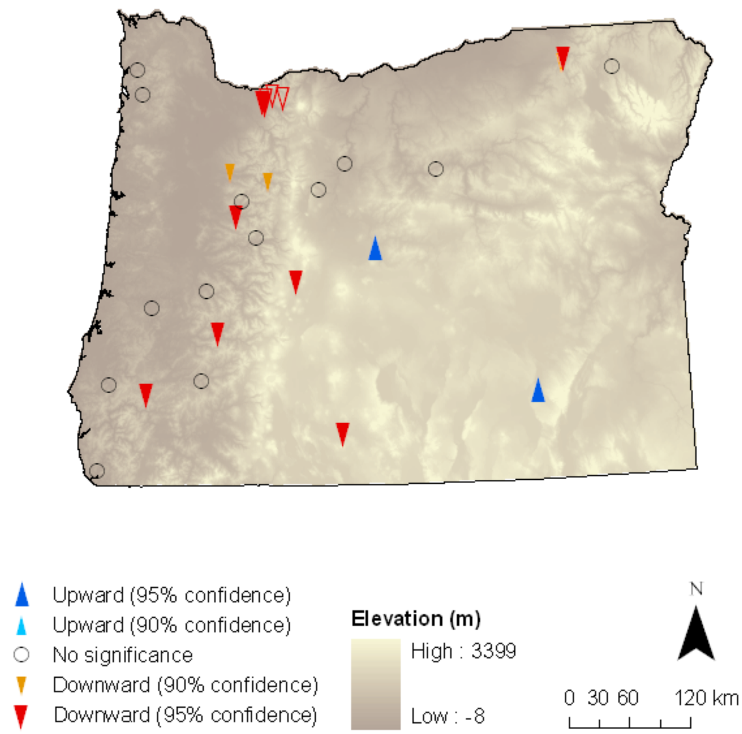


Figure 3.11 Trends in the average flow for the driest 5% of years, with significance determined by the M-K test (Source: Chang et al., in preparation).

The largest peak flow events in Oregon are produced by rain-on-snow events, when warm rain and winds contribute to rapid snowmelt (Harr, 1981, 1986). The Cascade Range of Oregon produces the highest 1% of floods on record in >500 km² basins in the United States, because large storms produce sustained rainfall and sometimes snowmelt for multiple days over broad areas of mountain ranges (O'Connor and Costa, 2004). Changes in forest cover significantly and persistently increase peak discharges in forested basins upstream of dams in western Oregon, especially for small events (<1-yr return intervals), but also, arguably, of large events (>1-yr return periods) (Jones and Grant, 1996; Thomas and Megahan 1998; Jones, 2000; Beschta et al., 2000, Grant et al., 2008).

If extreme rain-on-snow events are sensitive to the area of simultaneous snowmelt, climate warming could have a range of effects on extreme floods. Hamlet and Lettenmaier (2007) speculated that a climate warming-induced reduction in snow-covered area could reduce flood risk, but an increase in the effective basin area contributing to runoff from rainfall could increase flood risk. Climate-warming effects on extreme rain-on-snow floods are likely to depend on changes in atmospheric circulation and air mass behavior. Extreme rain-on-snow events occur when a rare sequence of marine polar air masses is followed by marine tropical air masses, creating simultaneous melt in large snow-covered areas and producing large effective contributing areas and extreme floods.

The probability of the sequence of events leading to an extreme rain-on-snow flood is already very low, and will only be affected by climate change if climate change alters (1) the occurrence of widespread snowpacks or (2) the energy of warm, wet tropical air masses.

3.2.6 Relation Between Climate Variability (ENSO & PDO) and Hydrology

This seasonal variability of heavy rainfall has implications for the quantity and quality of water resources in the Willamette River Valley.

In the western Cascades of Oregon, winter air temperatures, April snowpack, and winter streamflow are strongly related to the Pacific Decadal Oscillation. Over the period 1958 - 2007, in years with positive PDO (warm ocean temperatures near the coast of Oregon), air temperatures were significantly higher than average, snowpacks were significantly lower than average, and winter streamflow was significantly lower than average (Jones, in preparation).

These relationships—lower than average December and April streamflow in years with warm ocean conditions (WP/EP) – also are apparent in streamflow from basins in the Willamette Valley (Figure 13). The relation between wintertime precipitation intensity, as measured by both simple intensity and number of heavy precipitation days per year, and climate variability as measured by different phases of ENSO and PDO, shows some mixed results for the eight stations in the Willamette basin between 1972 and 2006. While the relation between ENSO phase and precipitation intensity is generally negative in November and positive in April, the relation between PDO and intensity is generally negative and strongest in January and March. These varying seasonal associations with ENSO/PDO phase may be associated with the Willamette Valley's location in the transitional zone between positive and negative El Niño response and to the moderating effects of out-of-phase ENSO/PDO (Praskievicz and Chang, 2009a). Figure 3.12 , illustrates the relation between different phases of ENSO/PDO and streamflow variability in April and December for four stations (A, B, D, F) shown in previous Figure 3.6. As shown in this Figure, December streamflow is high during the cool phase of PDO and La Niña years. In April, three sites show lowest median flow during the warm phase of PDO and El Niño years.

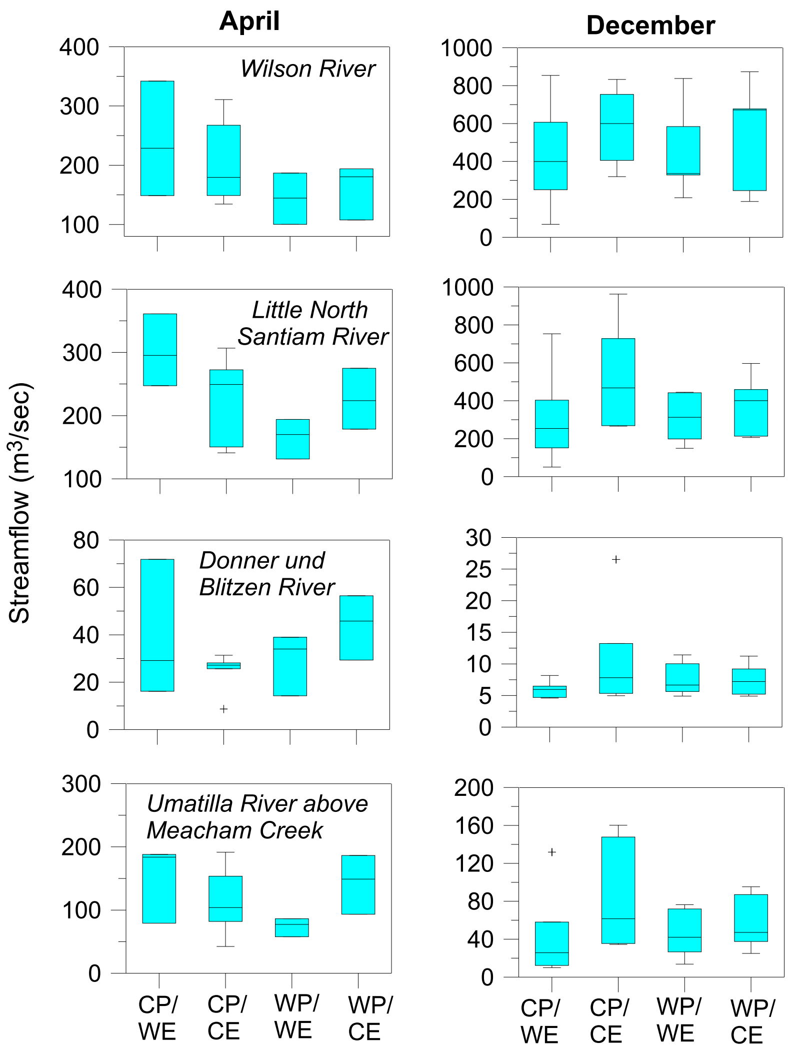


Figure 3.12 Differences in April and December streamflow among four combinations of warm and cold PDO/ ENSO phases for 4 USGS stations. Box and whiskers represent all years in category. CP/WE = cold PDO and warm ENSO; CP/CE = cold PDO and cold ENSO; WP/WE = warm PDO and warm ENSO; WP/CE = warm PDO and cold ENSO.

3.2.6 Climate Variability and Water Resources

The overall effect of climate variability on water resources in Oregon depends on hydrologic mechanisms operating at multiple spatial and temporal scales (snow water storage and melt, evapotranspiration). Three aspects of Oregon geography and hydrology will critically determine whether climate change effects exceed interannual variability of climate: (1) the extent of basin area affected by changes in snow water storage and snowmelt, which is associated with basin size, topography, and geology, (2) ecosystem adaptation and resilience to climate variability and trends, and (3) the relative magnitude and rate of climate-induced changes compared to historical effects of anthropogenic activities, such as dams and land use change on the magnitude and timing of streamflow.

In general, we expect the following.

- Climate change effects on streamflow will be largest close to melting glaciers or in seasonal snow zones, and decline in increasingly large basins as the snow-affected zone decreases as a proportion of contributing area.

- Climate change effects may be mitigated by ecosystem adaptations to climate variability, such as increased water uptake by vegetation during winter, which could offset predicted increases in rain:snow and winter discharge, and decreased water uptake by vegetation during summer, which could offset predicted declines in summer discharge.

- Historical effects of land use change (forest harvest, forest expansion after fire suppression) and dam management (winter water storage and summer releases) may be larger than as-yet-observed streamflow responses to climate change.

These issues will be discussed in more detail in section 3.3.

3.3. Projected Future Changes in Surface Water Hydrology

Future changes in surface water hydrology will depend on a range of factors. Hydrologic and climate models have been used to explore a range of possible outcomes from expected climate changes. Most of the model efforts have focused on the first three of these four hypothesized mechanisms for streamflow response to climate change.

- Increased air temperatures lead to decreases in the ratio of snow to rain, which decreases snow water equivalent (water stored in snowpacks), which decreases the snowmelt contribution to runoff in the spring;

- Decreased spring runoff carries over into summer, leading to decreased summer streamflows;

- Increased air temperatures decrease the ratio of snow to rain, which increases winter streamflow; and

- Increased air temperatures increase evapotranspiration and decrease spring and summer streamflow.

The overall effect of these mechanisms on water resources depends on (1) the extent of basin area affected by changes in snow water storage and snowmelt, (2) ecosystem adaptation and resilience to climate variability and trends, and (3) the relative magnitude of climate-induced changes compared to historical effects of dams and land use change on streamflow.

Future changes in climate factors that will affect streamflow include changes in peak flows, summer low flows, and seasonal water yield. These future changes will depend on future precipitation (not predicted to change much) and future temperature and its effects on snow storage and ET. Future temperatures are expected to reduce snow-covered area in much of Oregon, especially in the forested mountains. Reductions in snowpack are expected to increase winter flows (higher rain:snow) and reduce water delivery in spring and summer. However, these streamflow changes will also depend on forest vegetation response to future warming. For example, if future warming increases photosynthesis and respiration in the winter, that may offset some of the expected future increases in winter water yield and peak flows. Also, if future warming and reduced summer streamflows enhance hydrologic drought, drought-adapted conifers may be able to compensate by reducing ET, which in turn may offset some of the expected future declines in summer lowflows. Such changes in flow regime will have significant economic impacts for basin-wide water uses (Franczyk and Chang ,2007). Future changes in runoff will also be affected by land use changes, which should be factored into future climate change impact studies (Praskievicz and Chang, 2009b). The spatial variability of the current water use patterns could then be factored into adaptive water resource management in a changing climate (Franczyk and Chang, 2009b).

A variety of studies have developed quantitative estimates of the expected future impacts on surface water hydrology associated with climate change for hydrologic systems in the Western US. The hydrological response to projected future shifts in climate conditions has been described in parts of northwestern Oregon by Graves and Chang (2007) and Franczyk and Chang (2009a) Context: "by Graves and Chang (2007) and Franczyk and Chang (2009a), in the Oregon Cascades by Tague et al. (2008) and Tague and Grant (2009), and in California by Dettinger et al. (2004), Hanson and Dettinger (2005), and Dettinger and Earman (2007a). All of these studies show that the general hydrologic response to warming and the resulting reduction in the ratio of snow to rain will be increased winter runoff, earlier snow melt, and diminished spring and summer runoff. An analysis of the hydrologic response to climate change in the upper Deschutes Basin based on ensemble GCM predictions coupled to hydrologic models shows similar changes in runoff (Waibel et al., 2009)

This chapter summarizes key findings of the available literature and suggests research directions that may serve to increase the capacity to adapt to changing future conditions in Oregon.

3.3.1 Changes in snow water equivalent

Hydrologic systems in Oregon are relatively sensitive to changing climate, in large part because of the presence of seasonal snowpack. The snowpack develops in the mountains each winter, storing water through the period, and releasing it during spring, as air temperatures increase. This spring melt is channeled through a system of storage reservoirs, which are operated to both reduce downstream flooding and to provide water supply across much of the state over the relatively dry summer months. The amount of water stored as snow and the timing of melt depend very directly on spring air temperatures. As outlined earlier in this report, a wide variety of research has evaluated trends in historic snowpack data, with an emerging consensus that the snowpack throughout the West has experienced measureable declines over the period for which measurements are available.

The trajectory with which these observed changes will continue into the future is of particular interest to managers and stakeholders, particularly in light of the projected increases in air temperatures which have consistently arisen from global climate change research. The impact of projected future climate on freshwater resources is most frequently evaluated through the use of modeling. While results from these modeling-based impact studies vary depending upon the particular area of study and the study methods, a number of common themes emerge from studies developed in snowmelt dominated systems in the western US. The most significant result is that the warm snowpack that exists throughout the Washington and Oregon Cascade mountains is particularly vulnerable to commonly projected increases in winter temperatures. Peak stream flow volumes, which characterize snowmelt peaks in snow-dominated watersheds, are commonly used to summarize and assess the snowpack dynamics.

In one such study, Stewart et al. (2004) evaluated changes in the timing of peakflows under Business as Usual (BAU) emissions using PCM (Parallel Climate Model) and the VIC (Variable Infiltration Capacity) model of hydrology. They focused on the centroid of yearly stream flow as an indicator of snowmelt, and consistently projected statistically significant earlier peak runoff values in Washington. Supporting this work, Barnett et al. (2005) suggest that in the snowmelt dominated regions of the Western US, spring peak streamflows are likely to consistently occur up to a month earlier by 2050. Using PCM and a BAU scenario, Dettinger et al. (2004) employed the PRMS hydrologic model to provide more direct estimates of the future snowpack. They found that for the American River basin, in California, the average April 1 snowpack will approach 15 percent of historical values at the end of the 21st century. More recent modeling work by Elsner et al. (2010) also supports the notion of continuing snowpack decreases, in this case in Washington, suggesting statewide decreases in April 1 snow pack of 27 - 29% by 2020,

37 - 44% by 2040 and up to a 65% decrease by 2080. They focus on two emissions scenarios and used both the VIC and DHSVM (Distributed Hydrology Soil Vegetation Model) hydrological models.

In the Willamette River basin, the ratio of April 1st SWE to Precipitation (SWE/P) declined substantially from the reference period of 1970-1999 under two GHG emission scenarios with a greater reduction in the 2080s. The decline in the ratio is most pronounced under the high emission A1B scenario (see Figure 3.13). This is a combined result of increase in precipitation falling as rainfall in winter and earlier snowmelt caused by rising temperature. Snowmelt, estimated by the PRMS model, was projected to decrease gradually over time. For example, models of the upper Mckenzie River sub-basins indicate a decrease in snowmelt of up to -52% for the 2040s and up to -78% for the 2080s relative to the reference period, 1960 - 1989 (Chang and Jung, 2010).

3.3.2 Spatial and Temporal Variations of Changes in Runoff

Available research consistently projects reductions in winter snowpack in the Northwest US, as well as earlier runoff in snowmelt dominated basins, yet many regions in this area do not develop a winter snowpack and are rainfall dominated. While many of these lower elevation basins are influenced by higher elevation, snowmelt dominated areas, the runoff response is characterized by a wider range of variables, including potential changes in precipitation and groundwater contributions.

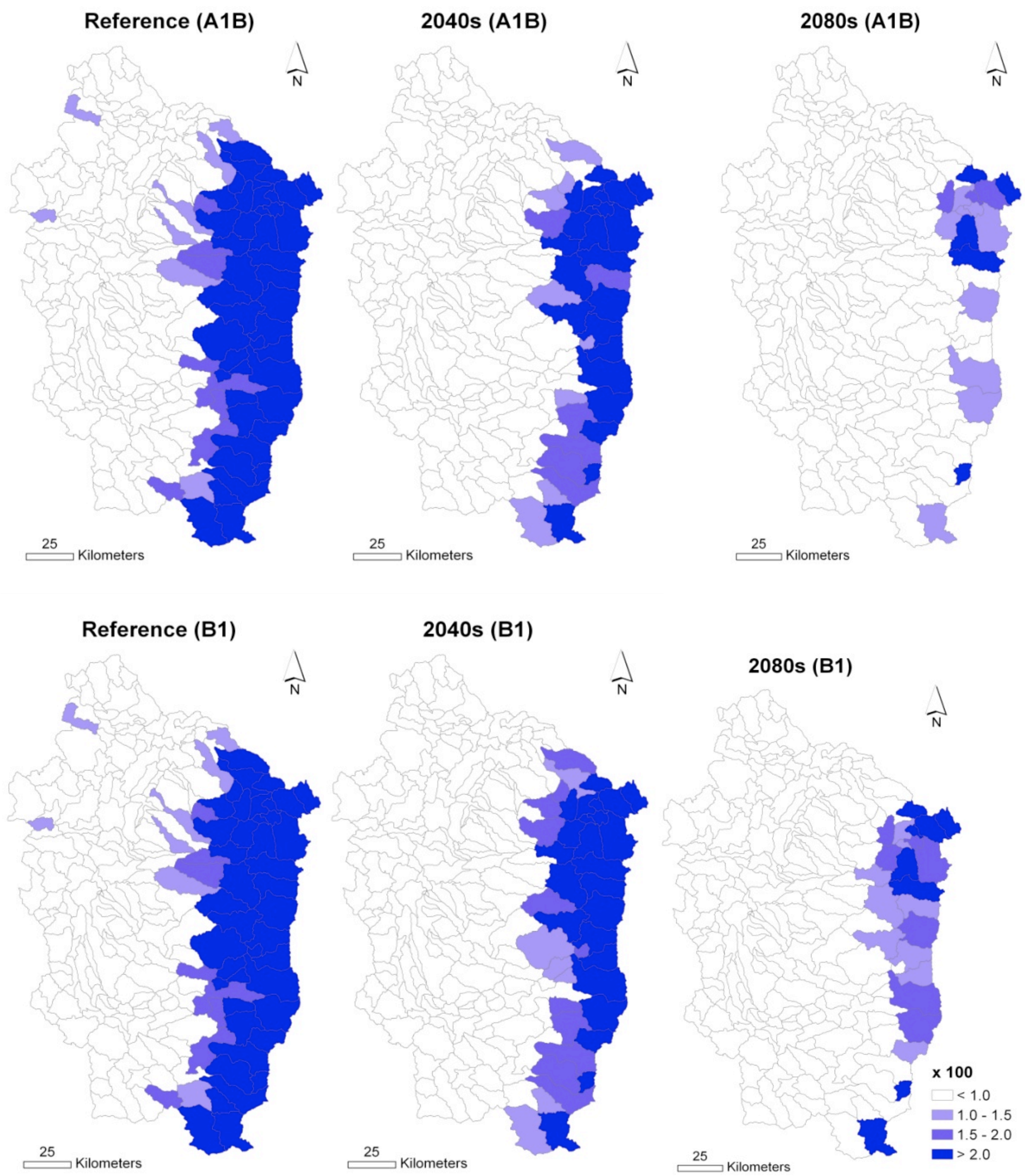


Figure 3.13 Ensemble mean changes (averaged over eight GCMs) in SWE/P in the Willamette River basin for reference, the 2040s, and the 2080s by GHG emission scenario. The ratio is multiplied by 100 for representation, Source: Chang and Jung 2010.

As the seasonal distribution of precipitation changes and temperature rises, watershed hydrology is likely to be modified at multiple spatial and temporal scales. Latitude and elevation control the sensitivity of particular regions to a changing climate, primarily because of the strong relationship between these factors and the presence of winter snowpack. While seasonal runoff will be more affected by increases in temperature in snow-melt dominated basins (Graves and Chang, 2007), in rainfall-dominated basins it will be more affected by changes in precipitation (Franczyk and Chang, 2009a).

In the Willamette River basin, the complex topography and geology also partially control the sensitivity of each sub-basin response to changes in climate. In the Western Cascades, snow-water equivalent is predicted to decline and peak runoff is predicted to occur earlier by the 2080s. In the High Cascades, with relatively gentle slope and young volcanic rocks, summer runoff may be sustained by existing large groundwater reservoirs (Tague and Grant, 2009; Jefferson et al., 2006). However, the uncertainty of projected future runoff is high, particularly for the High Cascade basins where groundwater is a big component of the seasonal water cycle (Chang and Jung, 2010).

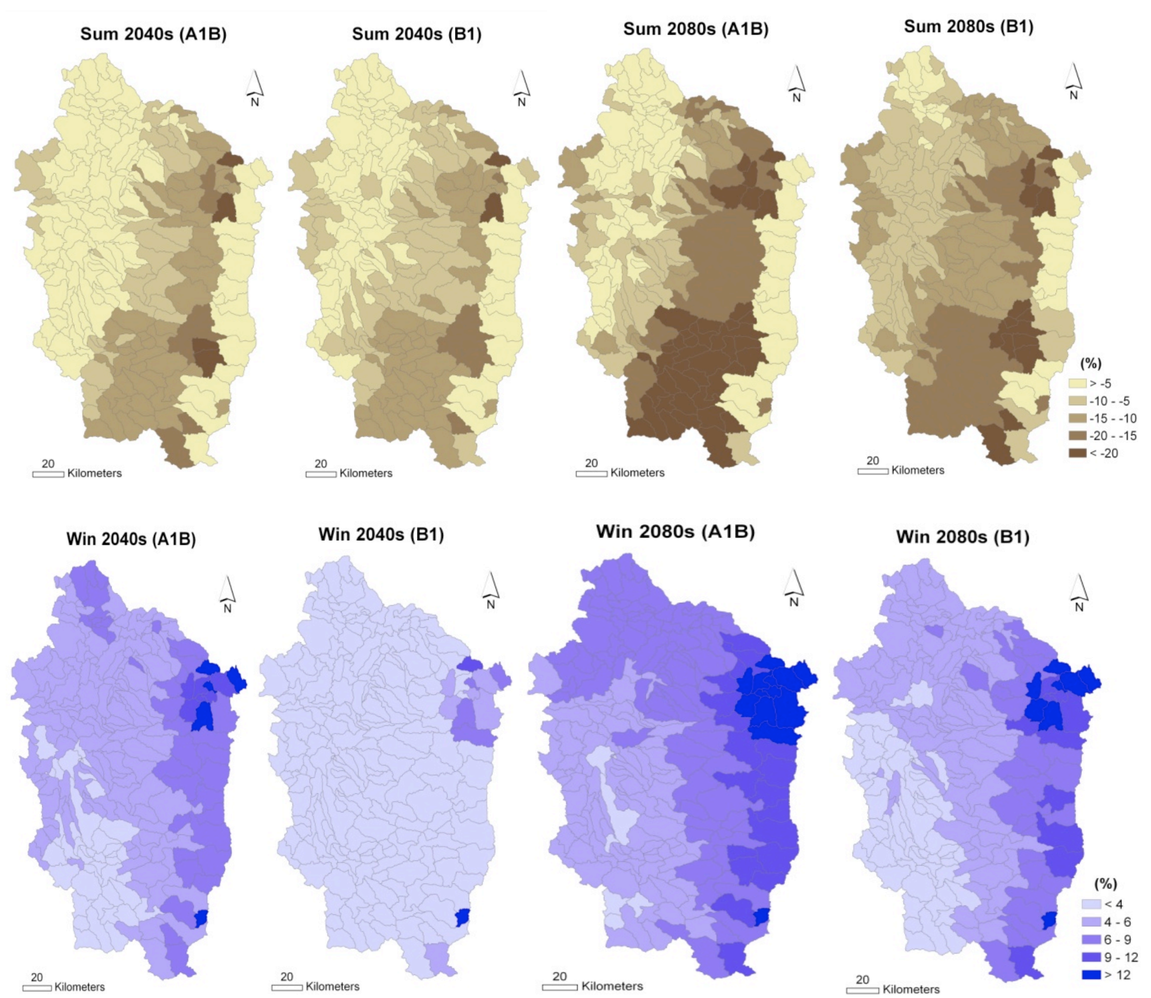


Figure 3.14 Ensemble mean changes in summer runoff (upper panel) and winter runoff (lower panel) for the 2040s and the 2080s by each emission scenario (Source: Chang and Jung, 2010).

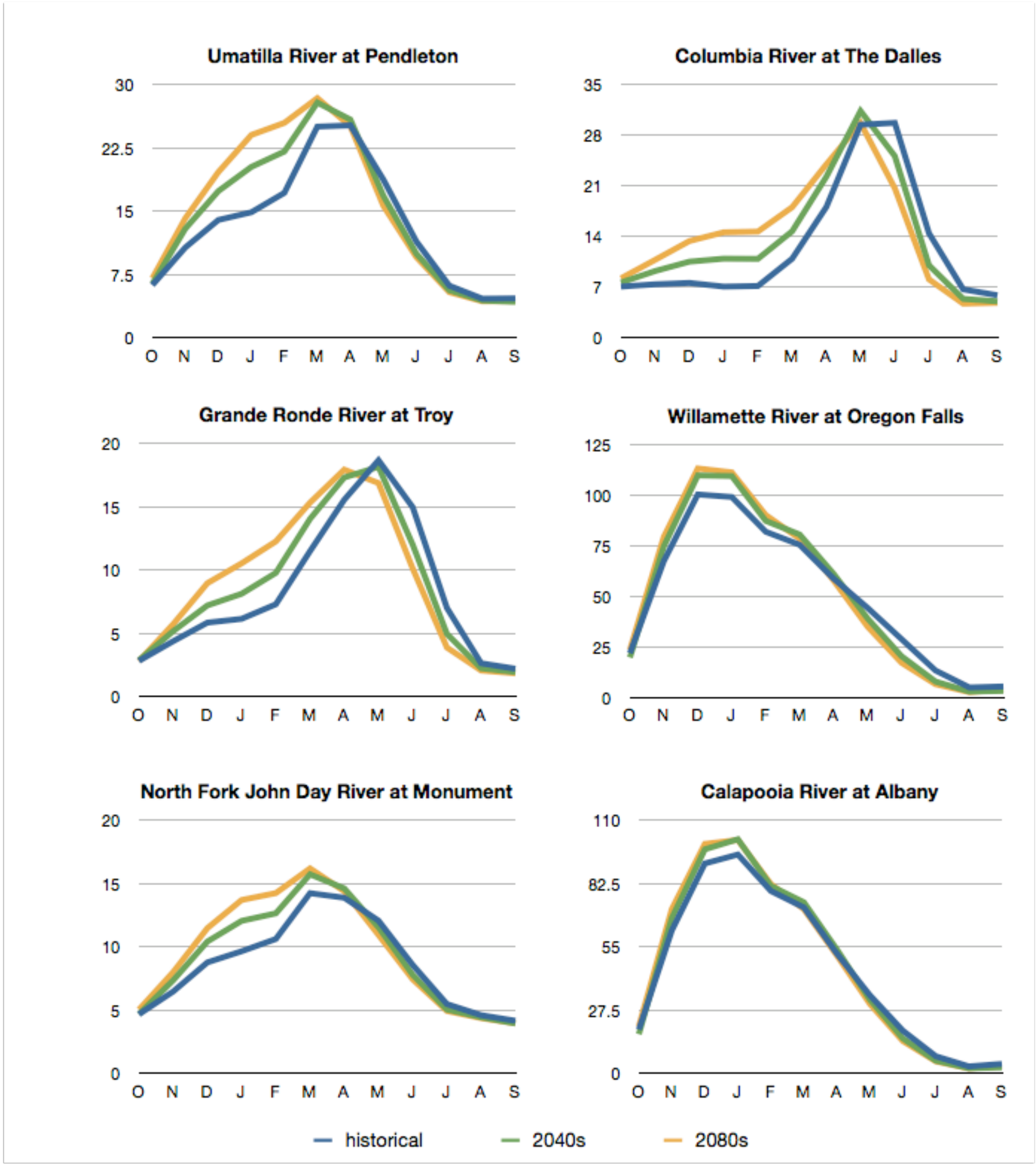


Figure 3.15 Hydrographs of combined flow for selected locations in Oregon using VIC outputs (hybrid delta, ensemble mean of 10 GCMs, A1B scenario) credit Hamlet et al, 2010, Climate Impacts Group, www.hydro.washington.edu/2860.

The University of Washington Climate Impacts Group produced 297 hydrologic scenarios for the Columbia River Basin using the Variable Infiltration Capacity (VIC) model. For this assessment, combined flows were downloaded from the website for the A1B scenario for the historical period, the 2040s and the 2080s. Combined flow is average total runoff and baseflow as an average depth (mm). These hydrographs are constructed using an ensemble average of 10 GCMs that were downscaled using the hybrid delta method. To read more about the project, downscaling techniques, and to download the data, visit the project website at http://www.hydro.washington.edu/2860/.

The six Oregon sites used for this assessment were selected based on two factors: their spatial distribution and their Nash-Sutcliffe efficiency. An effort was made to select sites that were distributed well across the larger Columbia River Basin and the state. Additionally, each site selected for this assessment had a Nash-Sutcliffe efficiency of 0.5 or greater. Nash-Sutcliffe efficiency is used to determine the predictive capabilities of a hydrologic model. The coefficient is a number between 0 and 1. The closer to 1 that the coefficient is, the better the model is at simulating flows. For applications such as these, a N-S efficiency of 0.5 is considered good.

Each hydrograph shows, with varying degrees of magnitude, a shift in streamflow largely consistent with climate projections. In snowmelt-dominated sites such as the Columbia River at the Dalles and the Grande Ronde River at Troy, flows are projected to increase in the winter months and decrease in the summer months through the 21st century. Peak flow shifts earlier into the spring at both sites in this scenario. At sites where the peak flows occur in the wetter winter months (Willamette and Calapooia), flows are projected to increase in the winter and decrease slightly in the summer. Both the Umatilla and North Fork John Day River project a significant increase in winter flows, but only a slight decline in summer flow. Diminished summer flows have implications for many sectors including agriculture, water resources and recreation, among others.

While changes in winter runoff volume and timing are commonly reported as potential impacts of projected temperatures, increased variation in hydrological response is also a potential response. Hamlet and Lettenmaier (2007) simulated runoff response and flood risk to explore impacts of documented (Mote et al., 2005) 20th century temperature increases. They used the VIC hydrological model and while they note significant variability in the flooding response, the results suggest that much of this variability can be constrained by regional differences in midwinter temperatures. In cold areas with a winter snowpack, flood risks have decreased, and in warm rainfall-dominated areas, flood risk appears to have significantly increased. Mote et al. (2003) also project an increased volume and earlier peak of winter runoff due to a lack of snowpack storage and an increase in rainfall (as opposed to snowfall), and also predict decreases in summertime low flows. They attribute the decreases in low flows directly to the lack of projected spring snowmelt peak. While changes in peak flows have significant implications, the associated changes in low flows are of potentially greater consequence in that water use is at a maximum during the summer period, while at the same time water availability is, even in the coolest years, at a minimum. The balance between these two quantities is more fully explored in other sections of the report, and we note here that it is an important component in the distribution runoff pathways, and that modifications to it may have potentially far-reaching effects.

While there are no significant trends in winter precipitation intensity in the Willamette River basin since 1972 (Praskievicz and Chang, 2009a), according to the IPCC fourth assessment report, climate change is likely to bring more extreme hydrologic events such as floods and droughts in the region. Urban areas are particularly vulnerable to these changes as impervious areas do not efficiently absorb storm water and infrastructure is densely concentrated (Chang and Franczyk, 2008). A case study of Portland shows that climate change will bring more frequent storm events with a return period of less than 25 years, which means that nuisance flooding is likely to become more common at road cross-sections that have a history of chronic flooding (Chang et al., 2010a).

It is also important to recognize that these examples focus on basins in the Willamette River where precipitation is relatively abundant. In other regions of the state, different processes control the response (rainfall dominance, groundwater contributions, semi-arid hydrology, etc). Additionally, changes in water use by vegetation along with management-based adaptation strategies would also be important features of any future impacts work. An impact assessment for the state would need to be significantly broadened in scope to capture the large degree of hydrologic variability and possible secondary responses to climate change from vegetation and management expressed statewide.

3.3.3 Interactions Between Climate and Land Surface Hydrology

The interactions between climate system and land surface hydrology are rather complex in the Willamette River basin. While elevation is a primary control of basin runoff, other basin characteristics such as geology and topography also affect basin runoff. Elevation is an important determinant of change in basin runoff because it affects the amount of precipitation falling as snow in winter and the snowmelt rate in spring. While winter runoff change is more sensitive to changes in winter temperature than winter precipitation in high elevations, the relative influence of winter temperature declines with elevation, and winter precipitation becomes more important in projecting future winter runoff in low elevations (< 1000m). This is associated with whether the basin runoff generation is dominated by either rainfall or snowmelt, suggesting that the elevation threshold may be associated with other basin characteristics such as geology. Geology could buffer the sub-basin hydrological response to climate change. Basins in the High Cascade Range with significant groundwater exchange may be less sensitive to changes in climate than those in the Western Cascade Range in the near term 2040s (less than 10% reduction in summer runoff) (Chang and Jung, 2010).

3.3.4 Uncertainty in Projecting Future Runoff

Uncertainty is an inherent component of projections related to future runoff. It is an additive property of the modeled system, with each individual component contributing to the overall predictive uncertainty of the system, and as such the degree of uncertainty associated with each model component should be evaluated as a mechanism to communicate confidence in projected results. There are several sources of uncertainties in climate change impact studies. The GCM structural uncertainty is the main source of uncertainty as recognized in several studies (Praskievicz and Chang, 2009b; Graham et al., 2007). Although many investigations have shown that the highest uncertainty is attributed to the GCM's structure, the other sources are not negligible (Wilby, 2005; 2006; Wood et al., 2004). Other uncertainty sources include the emission scenarios, the downscaling methods, the hydrologic model structure and the hydrologic model parameters.

The importance of each source of uncertainty depends on hydrologic characteristic of the basin under study (Kay et al., 2009; Prudhomme, 2007). For example, two sub-basins of the Willamette watershed, one rain-snow dominated and one rain-dominated, showed different sensitivities to uncertainty. The snow-dominated basin was more influenced by uncertainty in hydrologic parameterization than the rain-dominated basin, although climate model uncertainty was still the main source of uncertainty in both basins (Chang and Jung, 2010).

To date, many hydrologic models have been used to project the possible consequences of the climate change on streamflow, ranging from simple conceptual lumped models to comprehensive physically-based distributed models – e.g. NWSRFS (Nash, 1991), WatBal (Yates, 1996), macro-scale hydrological model (Arnell, 1999), VIC (Lettenmaier, 1999), MODFLOW (Kirshen, 2002), CATCHMOD (Wilby, 2005), PDM (Kay et al., 2009) and PRMS (Jung and Chang, 2010) among others. Most of the hydrological models show reliable and accurate results under historical climate conditions (natural variability). However, they have often projected mixed results in runoff change even under identical climate change conditions. This could be attributed to differences in the models' structures (Bae, 2009; Bloeschl and Montanari, 2010; Kay et al., 2009; Wilby, 2006). Bae et al. (2010) employ three semi-distributed models to investigate uncertainty resulting from hydrologic model selection; they conduct their study using 13 GCMs simulations with 3 emission scenarios. They conclud that monthly and seasonal runoff change simulated by a single hydrological model is within ±10% difference from those of a multi-model ensemble except in the low flow season.

Elsner et al. (2010) acknowledge the need to evaluate the uncertainty around modelderived hydrologic projections. While they do not provide estimates of predictive uncertainty, a sensitivity analysis using simulated runoff to estimate precipitation elasticity, or the fractional change in runoff as compared with a fractional change in precipitation, is developed. They also calculate modeled temperature sensitivity as the percent change in projected runoff for a 1 degree increase in temperature. The sensitivities are estimated for 12 different basins in Washington and represent 2 different hydrologic models. The results indicate low sensitivity across this range of simulations, providing additional quantitative evidence that the uncertainty of climatic projections dominates the overall uncertainty of impact projections.

Hawkins and Sutton (2009) state that the uncertainty in regional climate predictions varies with time but there is no constant positive trend because emission scenario uncertainty increases over time but GCM and internal variability uncertainties decrease. Also, the uncertainties vary across the seasons. In the summer, small changes in flow are much more significant than they would be in the high-flow wet season.

The uncertainty associated with hydrologic model selection was studied over the Tualatin river basin (Najafi et al., in review). Figure 3.16 shows the results of each model based on 8 GCM forcing data that are expressed as bias percentage between the future and reference periods. The figures show the runoff results for the winter (Dec-Jan-Feb) and summer (June, July, August) respectively for the two A1B and B1 emission scenarios. The TM model's (the simplest model) summer result shows the highest uncertainty due to the GCMs compared to the other hydrologic models simulations. The uncertainties vary between models for different emission scenarios and time periods. Therefore, the hydrologic model structural uncertainty would be another considerable uncertainty in addition to the climate model, downscaling and emission scenario as the main sources of uncertainty reported in the literature.

The representation of vegetation response to water availability in most hydrologic models is a further source of model uncertainty in hydrologic projections under climate change scenarios. The dominant tree species in Oregon forests are capable of significant adjustments of transpiration rates in response to environmental factors, and these adaptations are not included in most hydrologic models. In addition, vegetation may undergo succession in response to changes in air temperature and/or soil water availability, further altering vegetation water use and hence streamflow, in ways not currently captured by hydrologic models.

As projections of future impacts of climate change on hydrology continue to develop, it is important to recognize uncertainty; but perhaps more important to recall, as outlined by Bloeschl and Montanari (2010), that while projections of future conditions will always be uncertain, the presence of uncertainty does not indicate a lack of understanding.

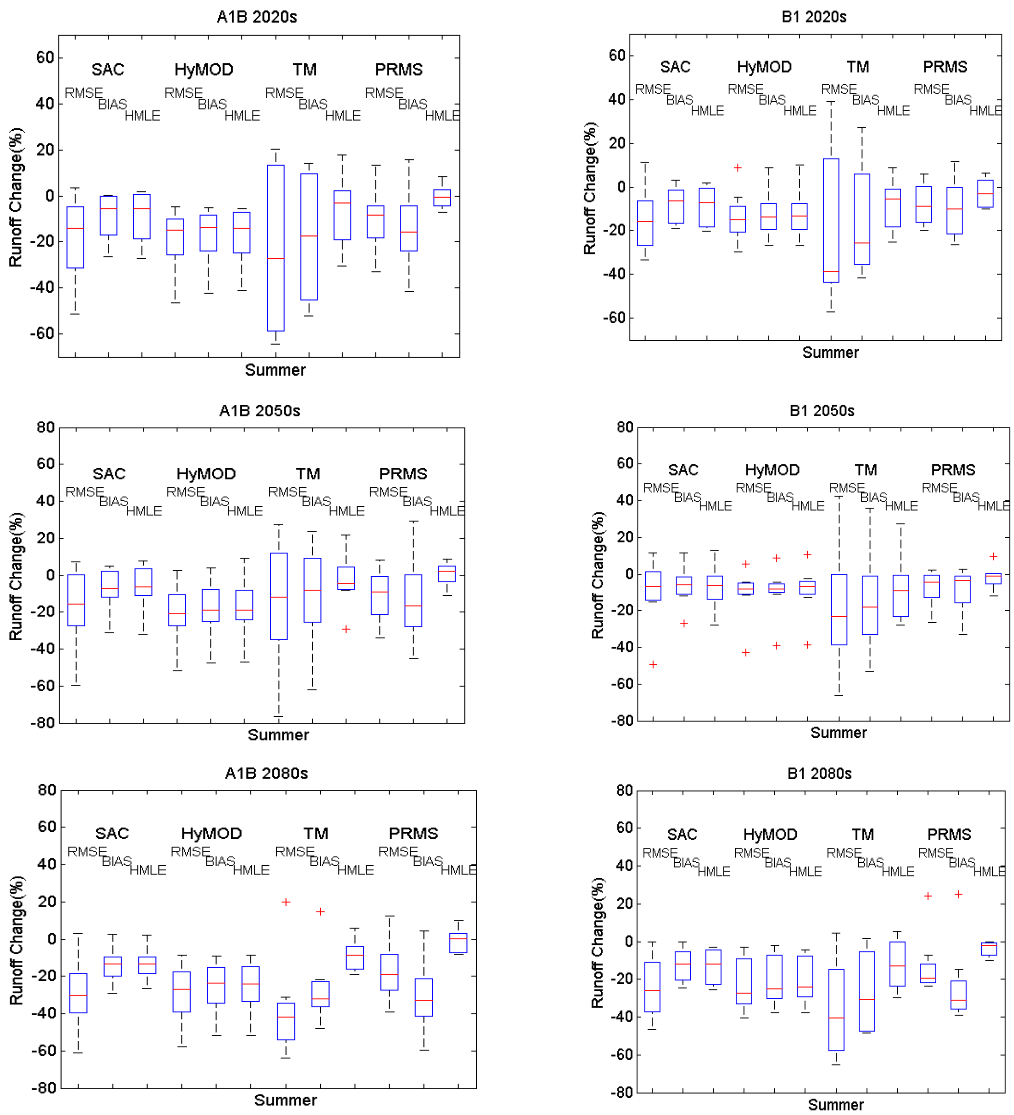


Figure 3.16 Runoff change relative to the reference period obtained by four hydrologic models with different complexities (source, Najafi et al., in review)

3.4 Potential Changes in Groundwater Hydrology

Projected future changes in temperature and precipitation will affect groundwater hydrology. Projected changes in climate will result in alterations of the timing and amount of recharge, increases in evapotranspiration, lowering of heads in boundaries such as streams, lakes, and adjacent aquifers, sea-level rise, and increased pumping demand. Increase pumping demand due to climate change will be exacerbated by population growth. This section presents a brief overview of groundwater hydrology, summarizes ways in which groundwater systems can be affected by projected climate changes, describes the likely response in key geographic settings in Oregon, and suggests directions for future research.

3.4.1 Overview of Groundwater Hydrology

Groundwater originates as precipitation that infiltrates into the ground. The infiltration of rainfall or snow melt into the groundwater system is called recharge. The largest amount of recharge typically occurs in upland areas where precipitation is greatest, although recharge can occur anywhere that precipitation exceeds evapotranspiration and available storage in the root zone. Water percolates downward until it reaches the water table, which generally defines the top of the region in which rock materials are completely saturated with water. In areas where streams are above the water table, leakage from streams can also recharge the groundwater system. Groundwater can also be recharged artificially through deep percolation of irrigation water, particularly in areas irrigated using surface water, and leakage from irrigation canals. Once in a groundwater system, water moves through permeable geologic materials in response to gravitational forces at a rate proportional to the permeability of the material through which it is moving and the hydraulic head gradient (which can be thought of as the slope of the water table). Groundwater eventually discharges back to the surface typically through springs or as diffused seepage to streams, lakes, and wetlands. In areas where the water table is very close to land surface, plants with roots extending to the water table can also be an avenue of discharge. Groundwater can also be removed artificially through wells. Groundwater discharge can occur naturally almost anywhere the water table, or saturated zone, intersects land surface including in uplands, where it supports perennial flow in low-order streams, and in lowlands and major stream valleys.

Groundwater discharge is an important component of streamflow along with surface runoff. Most critically, groundwater is the principal source of streamflow in the late summer and fall when there is little precipitation or snowmelt to supply runoff. In cold regions and at high altitudes, groundwater maintains winter flows critical to many groundwater dependent ecosystems, for example maintaining winter flows over salmonid redds. The portion of streamflow supplied by groundwater is known as baseflow. The proportions of groundwater and runoff in a stream vary seasonally, but also depend on the geology. Streams in areas of very permeable rock with substantial groundwater systems (as is common in parts of the Cascade Range) (figure 3.18) may consist almost entirely of groundwater discharge and have only a small component of runoff. Such streams are termed "groundwater-dominated," and they are common in young volcanic areas. Groundwater-dominated streams have constant flows with very small seasonal variation (figure 3.18). Streams in relatively impermeable areas such the

Coast Range, in contrast, have a very small component of groundwater and are runoff dominated. Runoff-dominated streams have large seasonal variability and commonly go dry, or nearly so, in the late summer (figure 3.18).

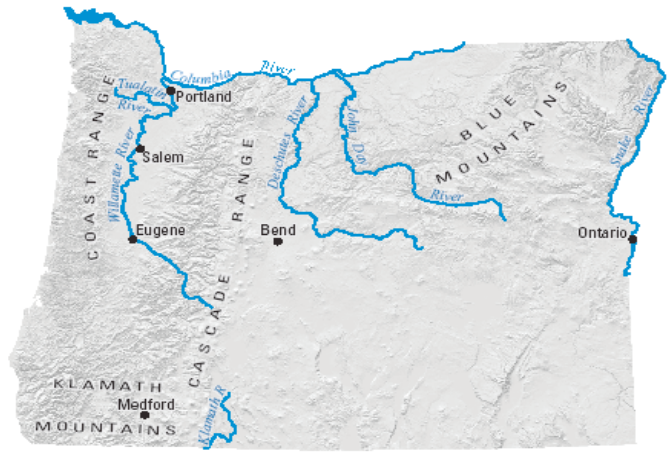


Figure 3.17 Selected physiographic and geographic features in Oregon

Because groundwater systems are recharged by precipitation, they are sensitive to changes in the amount, timing, and form of precipitation. Potential negative responses to climate change could include lower water levels in wells (water table elevations) and reductions in groundwater discharge to streams. Lower water table elevations can reduce the amount of water available for human uses by reducing the saturated thickness of aquifers and the amount of water in storage. Reductions in groundwater discharge to streams limit water available for human uses (such as municipal and agricultural diversions) and the in-stream needs of aquatic ecosystems.

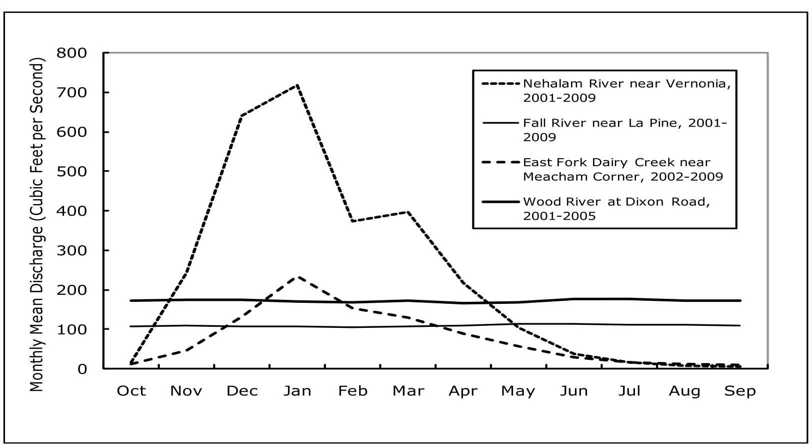


Figure 3.18 Mean monthly discharge of selected runoff dominated streams (dashed lines) and groundwater dominated streams (solid lines) with overlapping periods of record in Oregon. Nehalam River and Dairy Creek data from the U.S. Geological Survey, Fall and Wood River data from the Oregon Water Resources Department.

Because groundwater systems are recharged by precipitation, they are sensitive to changes in the amount, timing, and form of precipitation. Potential negative responses to climate change could include lower water levels in wells (water-table elevations) and reductions in groundwater discharge to streams. Lower-water table elevations can reduce the amount of water available for human uses by reducing the saturated thickness of aquifers and the amount of water in storage. Reductions in groundwater discharge to streams limit water available for human uses (such as municipal and agricultural diversions) and the in-stream needs of aquatic ecosystems.

Alexander and Palmer (2007) summarized studies of the impacts of climate change on groundwater resources in eight regions in the US and Canada. Most of the studies involved model analyses and incorporated multiple climate models and emission scenarios. Results differ between models, but tend to show that recharge varies in proportion to precipitation. Groundwater systems can be affected by changes in total precipitation, as well as changes in the spatial and seasonal-to-daily distribution of precipitation. Other climate-related factors that are shown to be important include changes in stream stage, increases in evapotranspiration, and increases in groundwater pumping.

3.4.2.1 The response of groundwater systems to climate warming

As surface hydrologic processes respond to climate change, so will groundwater recharge. The same rainfall and snowmelt events that drive runoff also provide groundwater recharge. Most groundwater recharge in Oregon occurs in place, meaning at the location where rainfall or snow melt occurs. Groundwater recharged from anthropogenic sources, such as deep percolation of irrigation water and canal leakage, is usually secondary to in-place recharge at the watershed scale. The close relation between runoff and groundwater recharge is demonstrated by Manga (1997), who successfully uses runoff as a proxy for groundwater recharge in models of groundwater-dominated streams in the Oregon Cascades. This means that changes in the timing of runoff that will occur under warmer climate conditions will result in changes in the timing of groundwater recharge. This is of practical importance where the timing of discharge of groundwater-fed streams is important for reservoir operations or irrigation.

Increased evapotranspiration due to warmer temperatures may also result in reductions in total annual recharge, especially at lower altitudes, as less water will percolate below the rooting depth of plants (Dettinger and Earman, 2007a). Variations in recharge resulting from changes in evapotranspiration are likely to vary geographically. Studies in the Yakima Basin of Washington show a 20% reduction of groundwater recharge (and stream discharge) in some subbasins resulting from a 3.6 °F increase in temperature (J.J. Vaccaro, U.S. Geological Survey, written commun., 2010). Preliminary results from modeling studies in the upper Deschutes Basin in Oregon suggest that total annual basin-wide changes in recharge resulting from warming will be much smaller (M. Scott Waibel, Portland State University, written communication, 2010).

3.4.1.3 The response of groundwater systems to changes precipitation

In general, increases or decreases in total precipitation will be reflected in groundwater recharge. The relation between total precipitation and groundwater can be seen by comparing the cumulative departure from average precipitation and long-term water level trends in wells (figure 3.20). Fluctuations in upland recharge areas can range from several feet to tens of feet in response to, and generally coincident with, decadal drought cycles. This suggests that groundwater levels in many aquifers will reflect any long-term changes in total annual precipitation more or less as they occur. Historic streamflow records show that groundwater discharge to streams also varies with annual precipitation (figure 3.21). If precipitation decreases, groundwater levels will decline and discharge to streams will diminish proportionally. If average annual precipitation increases, groundwater levels will rise and discharge to streams will increase. However, the effects of increased groundwater recharge resulting from the small projected increases in precipitation in Oregon are likely to be offset by other factors such as increases in pumping demand and evapotranspiration resulting from warmer temperatures.

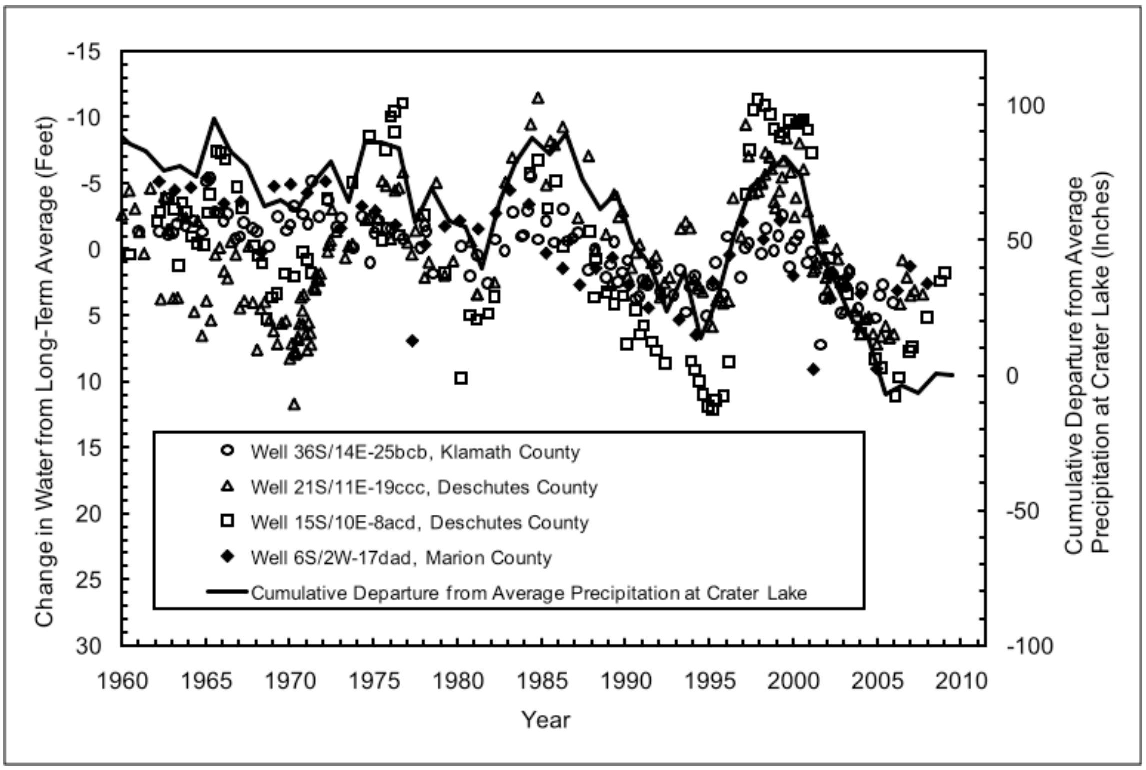


Figure 3.19 Comparison of water level fluctuations in selected wells and cumulative departure from average precipitation at Crater Lake Oregon. Well data from U.S. Geological Survey and Oregon Water Resources Department.

Changes in the seasonal distribution of precipitation will affect seasonal water table fluctuations and of groundwater discharge to springs and streams. If seasonal shifts are sufficiently large and total annual precipitation remains constant, the result could be less annual recharge in some areas. This is because some shallow aquifer systems, such as in parts of the Willamette Valley, fill to capacity and recharge during the winter is already "rejected" and shunted off to streams (Conlon et al., 2005). Increased winter precipitation, therefore, may not result in increased groundwater recharge.

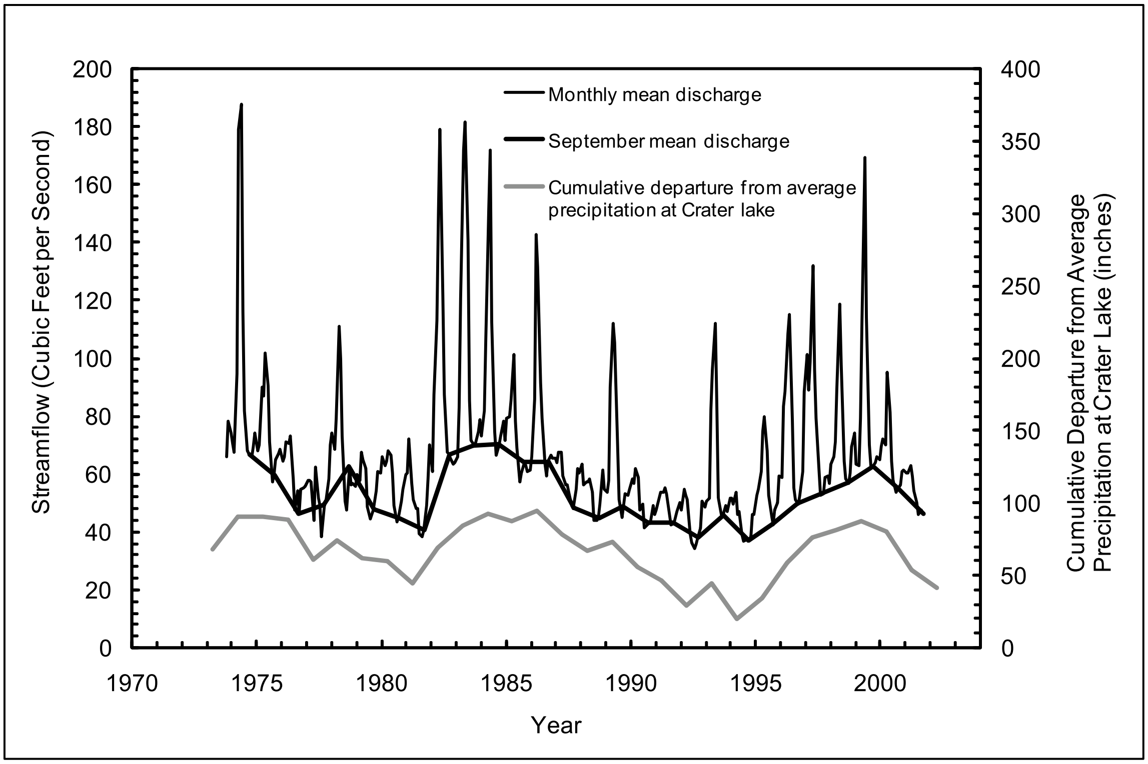


Figure 3.20 Monthly mean discharge of the Williamson River near Lenz, Oregon. Note the relation between the September mean discharge (a proxy for baseflow) and the cumulative departure from average precipitation at Crater Lake.

3.4.2.3 Other factors influencing the response of groundwater to climate change

Groundwater recharge can be affected by factors other than changes in precipitation and evapotranspiration. Studies have also shown that recharge can be affected by changes in the temporal and spatial distribution of frozen ground (Jyrkama and Sykes, 2007) and rainfall intensity (Mileham et al., 2009) resulting from climate change.

In addition to changes in recharge, other factors will influence the way in which groundwater systems respond to climate change. Aquifer systems in alluvial deposits that are in direct hydraulic connection to streams can be affected by the lowering of stream and lake stages resulting from diminished flows. Lower stream and lake stages can result in lower water levels in adjacent aquifers. Reduced streamflow may also result in reduced irrigation diversions and in less artificial recharge from deep percolation of irrigation water and canal seepage. Artificial recharge may also be reduced by conservation measures such as the use of more efficient irrigation methods or lining irrigation canals.

Sea-level rise resulting from climate change also could affect groundwater in coastal regions. Sea level is an important boundary condition affecting water levels in the extensive sand-dune aquifers along the coast such as found near Coos Bay, Reedsport, Florence, and in Clatsop County (Rinella et al., 1980; Brown and Newcomb, 1963; Hampton, 1963; Frank, 1970). A rise in mean sea level will result in a comparable rise in water-table elevations in sand dune aquifers as well as alluvial aquifers hydraulically connected to tidally influenced estuaries. This could result in water-level rises and expansion of groundwater-fed lakes and wetlands in sand dune areas and other low-lying coastal settings. Sea level rise will exacerbate any existing saltwater intrusion problems, as will warming-related increases in groundwater pumping in coastal areas.

Groundwater systems are also susceptible to the effects of increased water demand resulting from climate change. Warmer temperatures typically result in increased groundwater pumping by both municipalities and irrigators. Diminished late season streamflow predicted by most analyses will reduce the surface water available for irrigation which will also increase demand for groundwater. The very small increase in precipitation projected by the ensemble average of climate models for Oregon is unlikely to offset increased pumping due to warmer temperatures and diminished late-season streamflow.

3.4.2 The Influence of Geographic and Geologic Settings on the Response of Groundwater Systems to Climate Change

The response of groundwater systems to climate change will vary with geographic and geologic settings. Principal variables that will influence the response of groundwater systems to climate change include the permeability of the underlying geologic deposits, the geographic setting within the watershed (upland versus lowland aquifers), and the degree to which recharge originates as snow.

The permeability of geologic materials is the most basic factor controlling the presence or absence of groundwater systems and how those systems will respond to climate change. Low permeability units such as the marine sedimentary rocks Coast Range, pre Cenozoic rocks Klamath Mountains, and Mesozoic and early Cenozoic rocks of the Blue Mountains Province in northeastern Oregon, have generally low bedrock permeability and do not host large regional groundwater systems. Aquifers in such areas are largely limited to localized zones of bedrock fractures and alluvial deposits in valley bottoms. The largest impacts to the limited groundwater systems in such settings are likely to result from increased pumping demands and increased ET due to warmer conditions (Loáiciga, 2003; Hanson and Dettinger, 2005; Dettinger and Earman, 2007a). Streams in low permeability areas have very limited baseflow and typically go dry, or nearly so, in late summer and fall (figure 3.19). Late season water needs in such areas are commonly provided by storage in reservoirs that are filled during the winter and spring.

Areas dominated by permeable material such as fractured lava or extensive coarse-grained sedimentary deposits typically contain substantial groundwater systems that can be large enough to be of regional importance (Gannett et al., 2001, 2007; Tague and Grant, 2004). Such areas include the younger (high) Cascade Range, volcanic areas of central and eastern Oregon, and large sedimentary basins such as the Willamette Valley and Portland basin. Most large river basins in Oregon include both high permeability and low permeability areas. An exhaustive analysis of the potential response of groundwater to climate change in geographic settings across the state is beyond the scope of this chapter. Instead, this section discusses the probable response in selected settings to provide general insights. For simplicity of discussion, regional groundwater systems are divided into upland and lowland settings in the following sections. The processes described in upland and lowland settings, such as recharge and discharge, occur at a range of spatial scales.

3.4.3.1 Groundwater systems in upland settings

Upland settings where permeable deposits dominate recharge areas tend to have substantial groundwater systems and a large proportion of groundwater-dominated streams (and associated groundwater dependent ecosystems). The most prominent permeable upland in Oregon is the geologically youngest region of the Cascade Range, often known as the "High" Cascade Range which encompasses the upper parts of the Deschutes, Klamath, and Willamette Basins. The importance of groundwater to the hydrology of basins flanking the Cascades has been recognized for many decades going back to the work of Russell (1905), Meinzer (1927) and Stearns (1929, 1931). More recent work characterizing the importance of groundwater contribution to streams emanating from the Cascades includes that of Grant (1997), Gannett et al. (2001, 2003, 2007), Tague and Grant (2004, 2009), and Jefferson et al. (2006, 2007).

Many permeable upland areas in Oregon, and in the Cascade Range in particular, rely on snowmelt for a large part of their groundwater recharge. As was previously described, warming will result in a shift in the form of precipitation toward less snow and more rain, and consequently more runoff in the winter, earlier (and less) snow melt in the spring, and less runoff during the summer. The timing of groundwater recharge will shift in the same manner as runoff. The shift in timing of recharge will affect groundwater-dominated streams, increasing winter flow and reducing late season flow (Manga, 1997; Tague et al., 2008). Runoff-dominated streams are expected to experience larger changes in the seasonality of flow than groundwater-dominated streams. This is because the groundwater system acts as a reservoir, storing seasonally variable recharge and releasing it to streams at a more constant rate throughout the year. Groundwater discharge from permeable upland areas, therefore, has the potential to moderate the effects of warming to some degree (see, for example, Tague et al., 2008; Tague and Grant, 2009; Chang and Jung 2010; Mayer and Naman 2010). Although groundwater-dominated streams may experience small percentage reductions of late season flow, the changes may be volumetrically large (Tague et al., 2008; Chang and Jung, 2010). In runoff-dominated low-order streams, a small-volume/large-percentage reduction in flows may be catastrophic for some groundwater dependent ecosystems, particularly if those reductions cause perennial streams to become ephemeral.

While the effects of changes in the seasonality of recharge may be moderated by groundwater storage in permeable uplands, such areas will respond to changes in total annual precipitation. Water levels and groundwater discharge to streams will vary in proportion to any long-term increases or decreases in total precipitation. Total recharge likely will also be reduced by increased evapotranspiration under warmer conditions.

3.4.2.2 Groundwater systems in lowland settings

Groundwater recharge in lowland areas (such as the Willamette Valley, Portland Basin, and stream valleys and lake basins in central and eastern Oregon) will respond differently from uplands to warming and to possible changes in the seasonality of precipitation. Moreover, additional climate-related stresses may affect groundwater in lowland areas. Natural recharge in lowland areas is primarily from rain and intermittent snowmelt and does not rely on large, spring snowmelt events. Therefore, changes in the form of precipitation are not likely to have as large an influence on the seasonality of recharge in lowland areas as they will in upland areas. Most climate models do, however, project a shift in the timing of precipitation toward wetter fall and winter seasons and dryer summers (Mote and Salathé, 2010). These shifts will affect seasonal groundwater fluctuations, possibly resulting in lower water levels in wells in the summer which could increase pumping costs and limit well yields. This is an important consideration for irrigation and municipal wells. As mentioned previously, if the shift toward winter precipitation is sufficiently large and total annual precipitation remains the same, total annual recharge could diminish in shallow aquifers that reach capacity and "reject" recharge during the winter.

Groundwater is much less likely to moderate the effects of climate change on streams originating in lowland settings than streams originating in permeable uplands for several reasons. Recharge rates in lowlands areas are generally less because of the smaller amount of precipitation, groundwater discharge to streams from lowland areas is generally less than in upland areas, and groundwater originating in lowlands generally makes up a smaller component of streamflow. For example, groundwater-dominated streams rarely originate in lowland areas except at the bases of uplands.

Groundwater systems in lowland areas are more susceptible to increases in pumping than upland areas. Farms and cities, the largest users of groundwater, tend to be located in lowlands. In addition, some lowland groundwater systems may be susceptible to changes in boundary conditions. Shallow alluvial aquifers in lowland stream valleys tend to be hydraulically connected to streams, and, because of the low head gradients, groundwater levels can be influenced by stream stage over significant areas (for examples in the Willamette Valley see Conlon et al., 2005). Decreases in stream stage resulting from smaller late-season flows could result in proportional water-level declines in hydraulically connected aquifers.

3.4.2.3 Columbia River Basalt Group aquifers

Aquifers in the lava flows of the Columbia River Basalt Group constitute a unique class of aquifers in Oregon. Because of their high transmissivity, Columbia River Basalt Group lavas are productive aquifers. However, these aquifers are susceptible to large pumping-related water level declines due to their low specific storage and recharge that is limited by low vertical permeability. Columbia River Basalt aquifers underlie much of north central Oregon and parts of the Tualatin and northern Willamette valleys.

Poorly-confined aquifers at shallow depths in the Columbia River Basalt Group allow infiltration of water and are often in a state of dynamic equilibrium with climate, and the temporal variations caused by seasonal recharge events and decadal drought cycles are apparent in water-level trends (Conon et al., 2005; Vaccaro et al., 2009; Kenneth E. Lite Jr., Oregon Water Resources Department, oral communication, 2010). Highly confined aquifer systems such as found at depth in the Columbia River Basalt Group, in contrast, have very limited recharge. Consequently, climate signals are often not prominent in water-level data in Columbia River Basalt wells deeper than about 600 feet (Conlon et al., 2005; J.J. Vaccaro, USGS, written communication, 2010). Water level fluctuations in such highly confined systems are usually dominated by anthropogenic influences such as pumping, and, in some areas, head changes due to progressive interconnection of aquifers at different depths by wells (Burns et al., 2009). In an analysis of water level trends in the Yakima Basin in Washington, Vaccaro et al. (2009) show that water level declines are largest in deeper aquifers, indicating diminished recharge with depth. Generally speaking, climate signatures are apparent in upper basalt zones but less so in deeper zones (John Vaccaro, USGS, written communication). Therefore, climate change will affect Columbia River Basalt aquifers to different degrees (or at least with different timing) depending on depth. In deep basalt aquifers, the effects due to changes in recharge are likely to be small in comparison to the effects of increased demand, particularly if average annual precipitation remains largely unchanged.

3.4.3 Strategies for Improving the Understanding of, and Responding to, Changes in Groundwater Hydrology Resulting from Climate Change

Several actions could be taken to improve the understanding of the probable response to groundwater systems in Oregon to climate change and to help in development of adaptive management strategies. Efforts should include additional analysis of historic data to improve understanding the relation between groundwater systems and climate across the state, improved monitoring of groundwater to quantify the current and future response to climate variability, and continued development of hydrologic models to improve understanding of the linkages between climate and groundwater and to improve predictive capabilities.

Considerable information is contained in historic records of groundwater levels and streamflow; these records could be evaluated along with historic meteorological data to improve understanding of the coupling of climate and groundwater. Such an analysis could provide new insights, highlight particularly vulnerable regions or hydrologic settings, and provide useful information for development of new models.

Monitoring of groundwater and streamflow in Oregon has historically been done for specific regulatory or management purposes so present networks, while supplying considerable valuable information regarding the possible effects of climate change, are not optimally suited for that purpose. Hence, water level trends in monitored wells are often dominated by pumping effects that overwhelm the climate signature. The US Geological Survey (USGS) has developed a groundwater climate response network to "portray the effect of climate on groundwater levels in unconfined aquifers or near-surface confined aquifers that are minimally affected by pumping or other anthropogenic stresses" (Cunningham et al., 2007). Of the 500 wells in the national network, eight are in Oregon. It is possible that many of the hundreds of wells presently monitored by the Oregon Water Resources Department (OWRD) and the USGS for other purposes would be suitable for including in a climate response network. It is probable that there are aquifers that are not presently included that should be monitored.

Considerable information on the state of groundwater systems can be provided by monitoring the groundwater discharge to streams and springs using standard stream gaging techniques. Many gaging stations throughout Oregon, operated primarily by the USGS and OWRD, can be used to estimate discharge from some major aquifer systems. These estimates can be compared to climate records as in Figure 3.20 to provide insights into climate/groundwater connections. Most streamflow monitoring, however, is done to assist in operations of dams and reservoirs or for managing irrigation water. There are, therefore, many groundwater systems for which discharge is not monitored. A systematic review of stream gaging networks and large springs in Oregon could identify sites that would provide information on groundwater conditions as well as aquifer systems that are not presently adequately measured.

Developing networks specifically for monitoring changes in groundwater recharge caused by climate change is a topic of growing interest in the western US, however no standard techniques and protocols presently exist. Summaries of existing and emerging techniques for monitoring groundwater recharge are provided by Dettinger and Earman (2007b) and Earman and Dettinger (2008).

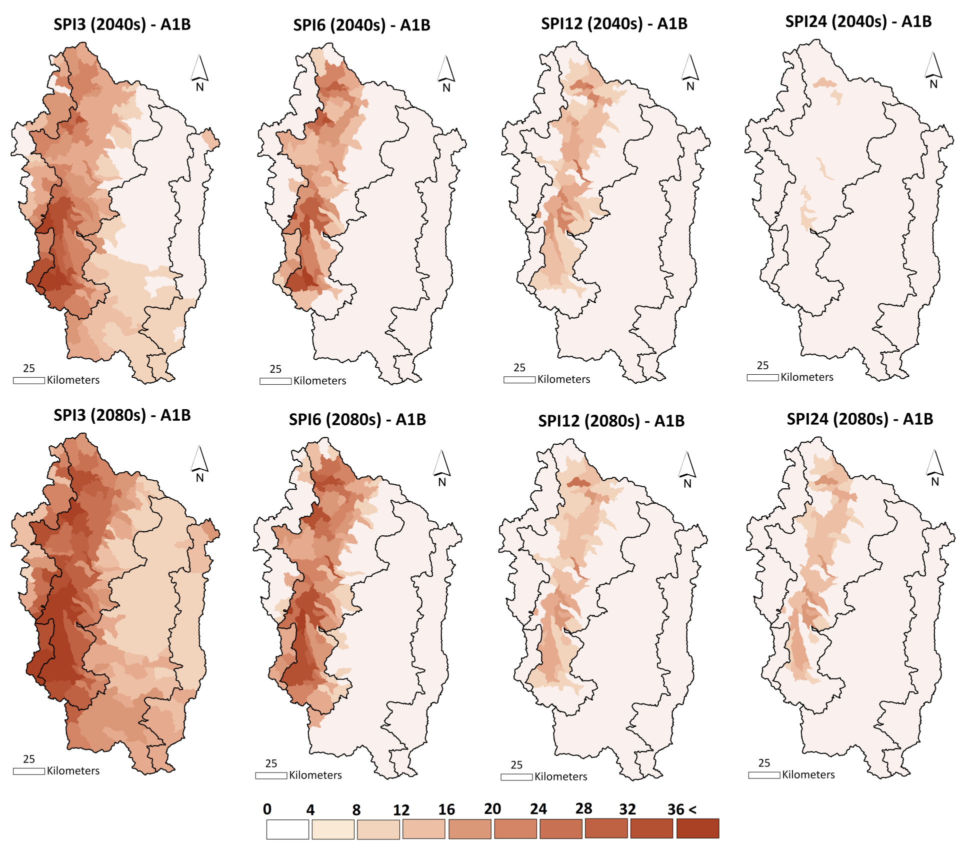
Insight into the probable hydrologic response to the range of projected climate changes in Oregon and the western US has come from modeling studies. Models not only provide important insights, but also predictive capability. Modeling studies of the hydrologic response to climate change in Oregon include work in the northern Willamette Valley by Graves and Chang (2007) and Franczyk and Chang (2009a), in the McKenzie River watershed by Tague and Grant (2009), and in the Deschutes Basin by Waibel et al. (2009). Some of these studies incorporate existing hydrologic models, developed for reasons other than climate change research, coupled with downscaled climate model output or other predictions of future climate. Continuation and expansion of modeling efforts will provide additional insights and predictive capability. Emerging techniques for coupled groundwater/surface-water models (such as the USGS GSFLOW code) are particularly promising. Groundwater models exist for a number of major basins in Oregon (for example, Morgan, 1988; Davis-Smith et al., 1988; Morgan and McFarland, 1996; Gannett et al,, 2004) that could be coupled with climate models to gain insights into the hydrologic response of the basins to projected climate change. Coupling hydrologic models with management models using optimization techniques can help identify strategies for resource management under uncertain and changing conditions.

3.4.4 Summary

Groundwater systems in Oregon will be affected by warming and possible changes in the amount and seasonality of precipitation projected by climate models. The principal mechanisms for change in groundwater are expected increases in evapotranspiration, which will decrease groundwater recharge, and increase pumping of water from groundwater wells to compensate for increased evapotranspiration. Secondary mechanisms include small changes in groundwater resulting from small projected changes in precipitation and localized changes in sea level in coastal areas. Responses include changes in the timing, amount, and spatial distribution of recharge, as well as changes in pumping demands and other boundary conditions. The response of groundwater systems will vary among geographic and geologic settings. All groundwater systems are sensitive to changes in the amount and timing of precipitation, from those in humid regions to systems in semiarid regions. Regional groundwater systems in the Cascade Range, important to streamflow in the adjacent basins, may moderate the effects of climate change somewhat but are likely to experience changes in the seasonal distribution of recharge. Lowland groundwater systems are probably most susceptible to increases in groundwater pumping resulting from warmer temperatures. Understanding the linkages between groundwater systems and climate can be improved with expansion of collection and analysis of groundwater data. Continued development of hydrologic models can improve understanding of the likely response of groundwater systems to the range of possible future conditions, and help in development of water management strategies.

Case study: Possible future climatological drought in Willamette River Basin

Drought is a natural hazard that can have severe impacts on regional water sector. The extreme seasonality of precipitation in the Pacific Northwest has induced frequent seasonal water shortage problem, especially at the rain-dominated region in summer. However, more winter rainfall and earlier snowmelt by increasing temperature is likely to increase drought risk at a transient region and snow-dominated region because of reduced water storage for summer use. We investigated possible changes in future climatological drought over the Willamette River Basin. The statistically downscaled 16 climate simulations derived from eight GCMs with two emission scenarios (Chang and Jung, 2010) were used to calculate relative Standardized Precipitation Index (SPI) (Vidal and Wade, 2009; Dubrovsky et al., 2009). The relative SPI can assess the spatial and temporal change of drought frequency at different lasting time scales, 3-, 6-, 12-, 24-month. Multimodel ensemble results projected increase in drought frequency under the A1B and B1 GHG emission scenarios. In particular, short-term 3- and 6-month droughts are likely to increase highly over the Willamette Valley region and the Western Cascade region for the 2080s (2070-2099) due to decreased summer precipitation. Long-term droughts, 12- and 24-month, however, are not projected to change except some of the Willamette Valley region because winter precipitation is projected to increase in these areas.



3.5 Impacts of Climate Variability and Change on Water Quality

3.5.1 Water Temperature

Although numerous studies have examined potential consequences of climate change on river flow (Arnell 2004; Payne et al., 2004), relatively few studies have investigated how river water quality might change in response to warmer air temperature and changing patterns of precipitation distribution (Murdoch et al., 2000, Chang et al., 2001). Water temperature is the most important indicator of stream health; it directly affects the amount of dissolved oxygen in water, which is critical for fish survival. Water temperature also indirectly affects the overall health of streams through its influence on in-stream biogeochemical cycles. In the Pacific Northwest (PNW), summer water temperature is critical for the survival of cold-water species like salmon. Studies have shown that ranges for cold-water fish would be displaced northward with a loss of habitat because cold-water species cannot adapt quickly to abrupt environmental changes (Mohseni et al., 2003).

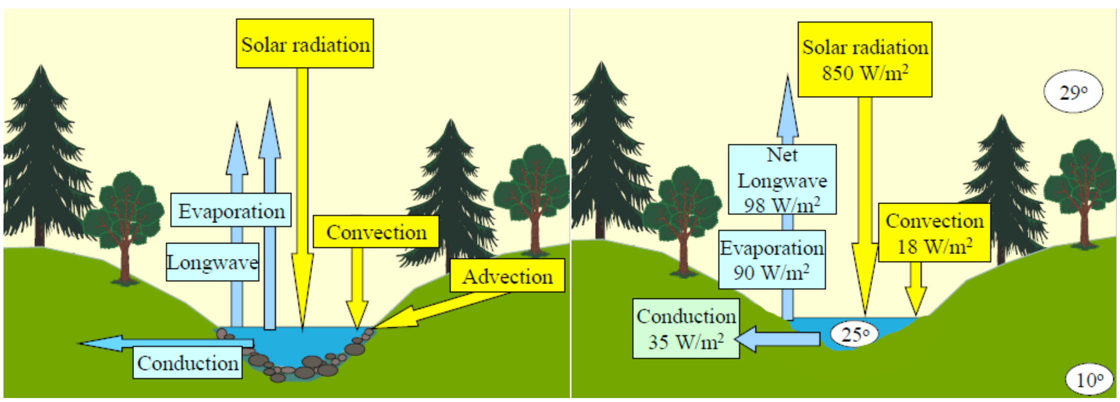


Figure 3.21 Major factors influencing stream temperature and example of heat budget for hot summer day at noon.

Changing climate could affect stream temperature through several mechanisms (Figure 3.21). Although air temperature and water temperature are correlated (Webb, 1996), variation in air temperature alone does not lead to major changes in stream temperature in Oregon streams (Johnson, 2003; Johnson, 2004). The largest effect of climate change on stream temperature may occur indirectly through climate-induced modification of riparian vegetation (although it might take a while), which provides shading for streams, and influences streamflow timing and amount. In the Willamette River basin approximately 35% of runoff comes from the snow pack. This results primarily from increased soil moisture earlier in the spring (Burns et al., 2007). Declining snowpacks could reduce spring and summer streamflow, which thus could increase summer stream temperatures. Low streamflows coincide with maximum summer air temperatures, and if streams become standing pools, temperatures can greatly increase. The degree of temperature change will depend on how much streamflow will decrease in the future and the degree to which stream temperature depends on discharge. Stream discharge could further decline as elevated summer air temperature accelerates the rate of evapotranspiration, which will have harmful effects on freshwater habit of Pacific Salmon (Mantua et al., 2010).

Land use also affects stream temperature (Krause et al., 2004; Johnson and Jones 2000). A reduction of riparian buffers, whether from urban, agricultural or forest land use practices, and the shade they provide leads to increased levels of solar radiation and increased stream temperatures. Urbanized landscapes with high levels of impervious surfaces can absorb more heat energy than rural landscapes, which also increases surface air temperatures. This effect may be more pronounced during the spring and early summer months with runoff flowing over the hot surfaces into streams. These overland flows can cause short-term spikes in water temperature (Nelson et al., 2007).

While there is a growing concern about potential changes in water quality resulting from climate change, only a few studies have investigated this topic in the Pacific Northwest (PNW). Based on an analysis of two PNW streams, Cristea and Burges (2010) showed that stream temperature increases depend on reductions in summer streamflows rather than increases in air temperature. Johnson and Jones (2000) documented a return to preharvest stream temperatures with recovery of riparian vegetation. Tague et al. (2007) examined water temperature variations in a High Cascade and a Western Cascade basin using historical water temperature data. Their results suggest that geology and the source of stream water controls summer water temperature dramatically, with less seasonal variations in water temperature in sub-surface flow- dominated High Cascade watersheds.

Water temperature in Oregon is highest in the summer, with forested headwaters generally having cooler temperatures than larger downstream sites (Figure 3.22). Winters are times of lowest temperatures, and maximum temperatures generally occur in July, August or September, depending on year-to-year weather patterns, discharge trends and timing of shading.

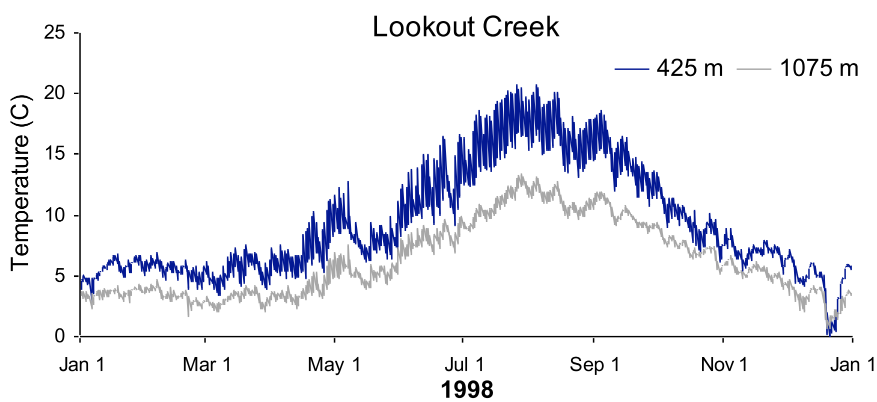


Figure 3.22 Daily maximum and minimum water temperature during 1998 for 1st and 5th order Lookout Creek in the Cascade Mountains.

Figure 3.23 illustrates a general spatial pattern of maximum water temperature during summer (June to September) for selected stations for a period of 1999 and 2008. As shown in this Figure, most basins draining the Cascade Range experience low maximum water temperature, while urban and mixed watersheds (e.g., Johnson Creek and the Tualatin River Basin) exhibit higher than average water temperature. Basins located in southwestern Oregon also experience higher than average water temperature.

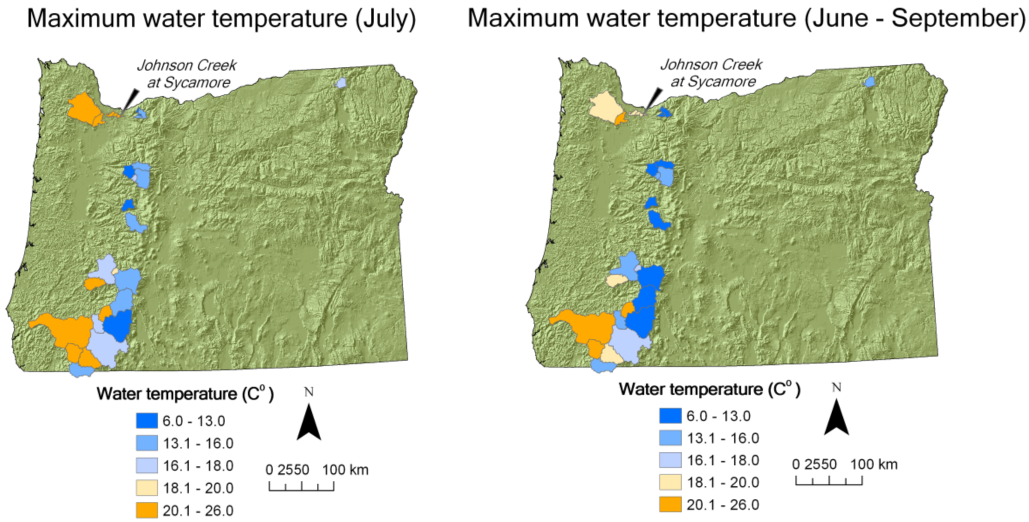


Figure 3.23 Average annual maximum daily water temperatures for July and summer (June to September) for 31 basins in Oregon, 1999-2009.

Long-term trends of water temperature in undisturbed watersheds are rare. Many sites with long-term data have been impacted during the period of record by upstream impoundments or land use changes, which confounds our ability to detect climate related changes. Data from stream gaging stations in the Rogue River basin (Rogue River near Mcleod, station #14337600) and in the Willamette River basin (Blue River at Blue River, station #14162200, and North Santiam River at Niagara, station #14181500) show general increasing trends in maximum water temperature for two of the three stations, particularly in the North Santiam River (Figure 3.25). High variability in August and September water temperature at Blue River appear to be associated with flow regulations in late summer months.

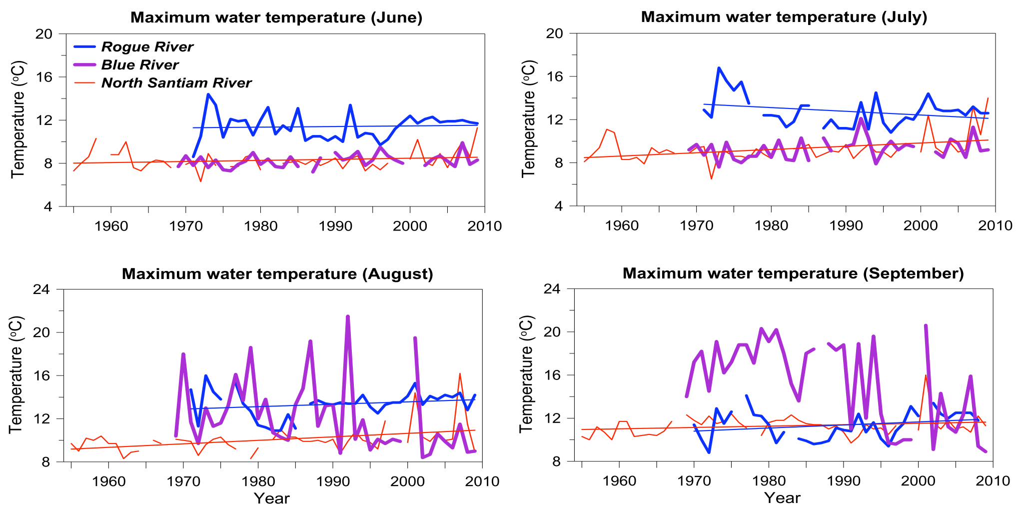


Figure 3.24 Long-term trends of maximum water temperature for Rogue River near Mcleod, Blue River at Blue River, and North Santiam River at Niagara.

Figure 3.25 shows trends over time in maximum water temperature in summer, based on records from 1999 to 2009. Only 6 of 36 stations show increasing trends. According to Mann-Kendall's test, one station located in the Willamette Valley shows a downward trend in summer maximum water temperature. The 7-day average daily maximum temperature, currently used for assessing water temperature threshold for fish habitat (e.g., lethality and migration blockage conditions), increased at 5 stations which are all located in the Portland metropolitan area. As shown in Figure 3.26, the variability of water temperature in Johnson Creek increased over the past 10-year period, suggesting that the stream frequently exceeds the threshold level of 18°C. A comprehensive assessment would be required to determine the degree of disturbance to fish habitat in urban streams.

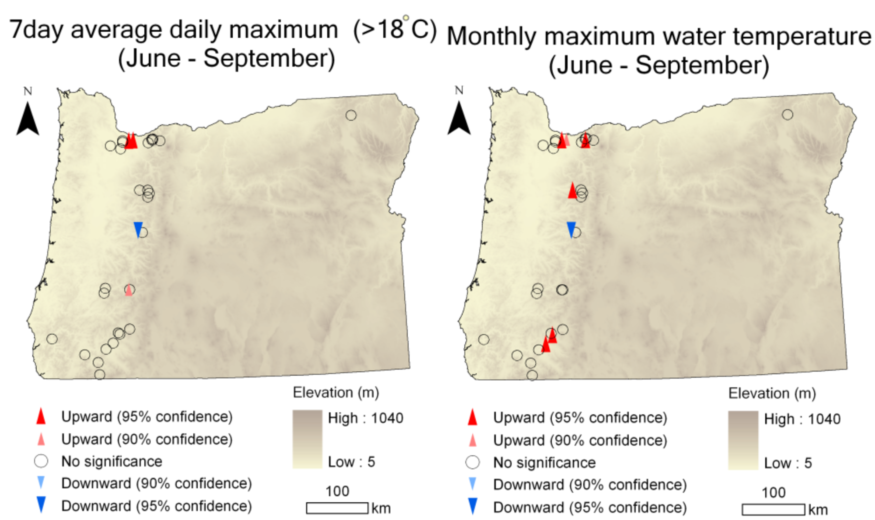


Figure 3.25 Trends in maximum summer water temperature and 7-day average daily maximum temperature for 31 stations in Oregon

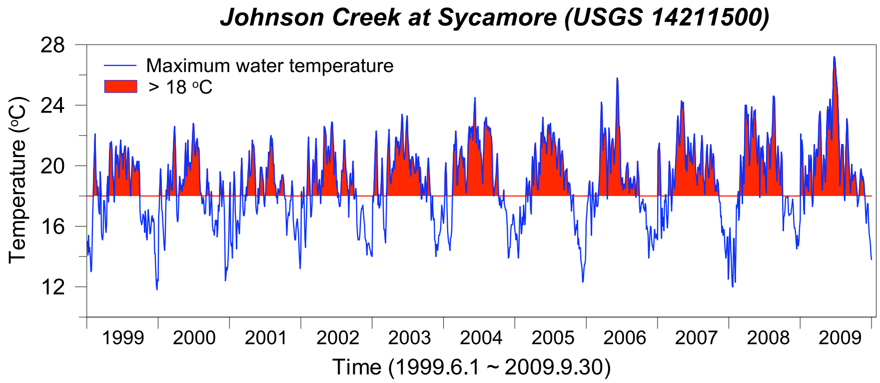


Figure 3.26 Maximum water temperature for Johnson Creek at Sycamore, 1999-2009

A preliminary study of the three streams - Tualatin, Johnson and Clackamas River - in the Portland metropolitan area shows that the degree of landscape disturbance further elevates stream water temperature (Chang and Block 2009). While lagged air temperature can explain approximately 66% of variations in summer water temperature on average, the size of stream, the amount of flow, and the upland hydrological processes also affect water temperature variations (see Figure 3.27).

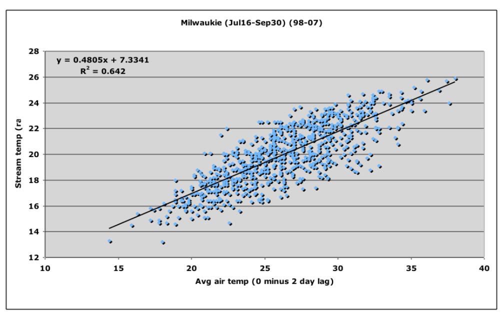


Figure 3.27 Relation between streamflow and water temperature and lagged air temperature and water temperature at Milwaukee in Johnson Creek, 1998 - 2007.

Major controls on stream temperature are riparian vegetation (through shading) and streamflow (which influences heat exchange). Climate warming may increase stream temperatures by reducing riparian vegetation, or by reducing snowpack and spring and summer discharges. Low elevation watersheds in areas of agricultural or urban land use, which are already temperature limited, may be most susceptible to climate-warming-induced increases in stream temperature.

Figure 3.28 shows potential changes in water temperature in the mainstem of the Tualatin River located in the Portland metropolitan area. These results are based on CE-QUAL-W2 simulations for 154 segments in the lower Tualatin River under three combinations of temperature, flow, and riparian scenarios. The nine maps show the number of days that 7-day daily average water temperature exceeds 20˚C between May 15 and October 15 under each scenario. Under the baseline scenario (top left), only the lower segments of the drainage experience water temperature above 20˚C. Under water temperature reduction scenarios, with reductions due to revegetation in tributary riparian zones, only a few immediate segments are affected. Under 5% flow reduction and 1.5˚C air temperature rise scenarios (representing the 2040s), segments with water temperatures in excess of 20˚C for more than 60 days expand to include some upstream areas. Under 10% flow reduction and 3˚C air temperature rise scenarios (which represents the 2070s), they expand further into upstream areas. Riparian vegetation scenarios have the most direct impact on middle segments of the drainage under the highest warming scenario.

In summary, there is little evidence to date of increasing stream temperatures over time in Oregon, except in urban streams, where temperatures may have increased because of cumulative loss of shading from riparian vegetation associated with urban and suburban development. Only a few dozen long-term records of stream temperature exist in Oregon. Existing studies have demonstrated that stream temperatures depend on riparian vegetation cover as well as air temperatures and discharge, which are inversely related. Future changes in stream temperature in response to climate change in Oregon will depend on the degree to which warming results in a reduction of late summer streamflow and how warming influences riparian vegetation. The resulting effects are complex. Warming temperatures may increase late-summer evapotranspiration from riparian vegetation, potentially reducing late summer flow; smaller snowpacks and earlier snowmelt may further reduce late summer streamflow. If streamflow in late summer is reduced, with no changes in riparian vegetation cover, stream temperatures may increase. However, increases in riparian vegetation cover (from stream restoration) could partly counteract these effects. In addition, stream temperature increases from typically forested headwaters, where groundwater contributions are important, to typically agricultural or urban downstream areas, so stream temperatures in downstream areas may be more sensitive than headwaters to future climate-related warming.

3.5.2 Sediment and Nutrients

As sediment and phosphorus loadings typically increase during high flow events, changes in flow variability are expected to alter temporal variability of sediment and phosphorus loadings. A case study in the Tualatin River basin (TRB) of Oregon illustrates that winter sediment nutrient loadings are expected to increase under climate change scenarios as winter flows are projected to increase (Praskievicz and Chang, 2011). Although diminished summer flow is likely to reduce summer nutrient loading, the annual load is expected to increase further with urban development scenarios.

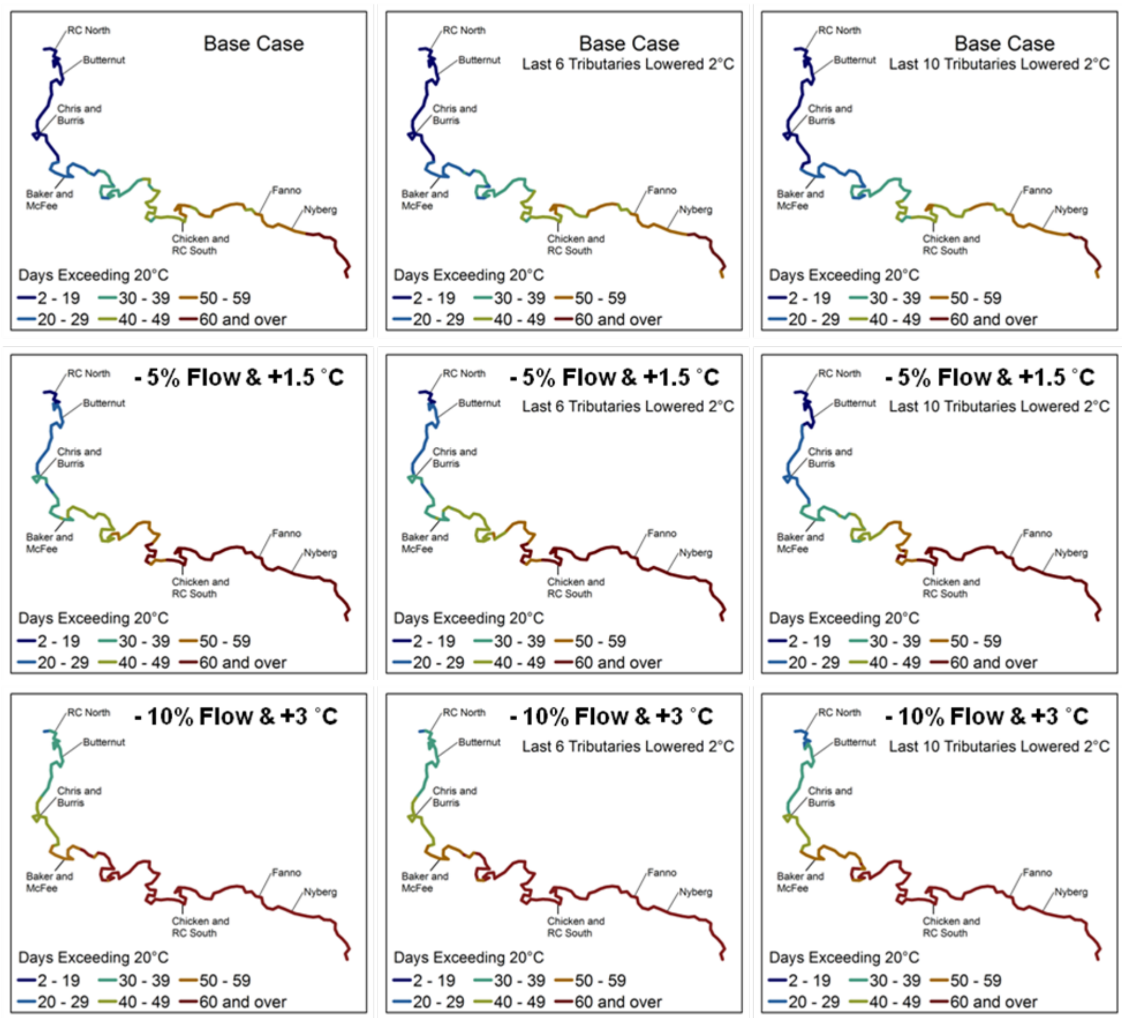


Figure 3.28 Change in water temperature under climate change and tributary riparion vegetation scenarios (Source: Chang and Lawler 2010).

However, conservation-oriented development could reduce erosion and phosphorus loading substantially compared to conventional development. The combination of climate change and urban development scenarios generally produce hydrological and water quality results that track the results from climate change alone, suggesting that the water resource impacts from climate change are more significant than those from land use change in the TRB. The development and conservation scenarios do differ in their hydrological and water quality outcomes, thus representing a potential opportunity for local adaptation to climate change by pursuit of sustainable forms of urban development.

3.6 Impacts of Climate Variability and Change in Water Demand

Municipal water demand patterns have progressively become a greater concern to urban water resource managers due to changes in climate and the expansion of urban areas in many parts of the world during the 20th and early 21st centuries. The recent Intergovernmental Panel on Climate Change report (IPCC) also projected an increase in temperature and spatial and temporal variability of precipitation, which may increase water demand but reduce seasonal water supply (Kundewicz et al., 2007). Although many North American cities have recently implemented conservation measures which have reduced water consumption per capita (Gleick, 2003), growing municipalities located in arid or semi-arid regions or areas prone to drought are increasingly apprehensive about the sustainability of their water resources (Morehouse et al., 2002; Kenney et al., 2008). Even for cities located in relatively temperate climates, such as the Pacific Northwest of North America, potential seasonal changes in runoff due to climate change pose another stress in the sustainability of water resources (Palmer and Hahn, 2002; VanRheenen et al., 2003; Palmer et al., 2004; Graves and Chang, 2007). Residential water consumption is a key factor that could affect water availability at the local and regional scale (Gutzler and Nims, 2005; Balling and Gober, 2007).

While previous studies suggest the existence of threshold values of climate variables that affect the sensitivity of urban water consumption, few examined the complex relation between water consumption and climate variables at multiple temporal scales. Water consumption research is typically constrained by a lack of detailed data to draw from; however, a rich dataset of long-term daily water data was available for the preliminary investigation of Portland water consumption. To draw meaningful inferences on water consumption as it relates to climate variability and projected climate change, multi-scale analysis is needed. Multi-scale temporal analyses allow us to project short-term and long-term water demand forecasting based on the fluctuations of climate variables. Water resource managers need not only seasonal climate but also daily weather information as they relate to water supply and demand (Steinemann, 2006).

Here we examined the relationship between urban water consumption and climate variables at daily, monthly, seasonal, and annual scales using 50 years of historical water production data from Portland, Oregon as a case study. Additionally, we also used customer demand monitoring data for a finer temporal analysis at a household level for one specific summer year. This study is a unique investigation concerning the sensitivity of urban water consumption to climate variables as the scale of analysis changes. It will provide useful climate information for urban water resource managers as it relates to water consumption. Urban water managers may be able to use such information to establish proactive plans under increasing pressure from climate change (Ruth et al., 2007; Praskievicz and Chang, 2009c).

3.6.2 Inter-annual Climate Variability and Water Consumption

Water consumption in the Pacific Northwest is highly dependent on weather variations. The annual consumption pattern shows increase in water consumption in warmer and drier months, and in warmer and drier years. Figure 3.29 shows average annual water consumption by retail and wholesale customer classes of the Portland Water Bureau (PWB) along with maximum daily temperature, averaged over the year, measured at the Portland Airport (PDX) weather station. Although consumption is related to population, conservation, land use, and other economic and demographic factors, the inter-annual fluctuations in consumption also are related to maximum air temperature. One exception is the spike in temperature in 1992, which coincided with a dip in consumption. This dip was the result of mandatory curtailment imposed by the PWB during the summer of 1992, when a water shortage occurred due to lack of access to the existing groundwater supply along the Columbia River South Shore, an issue which has now been resolved.

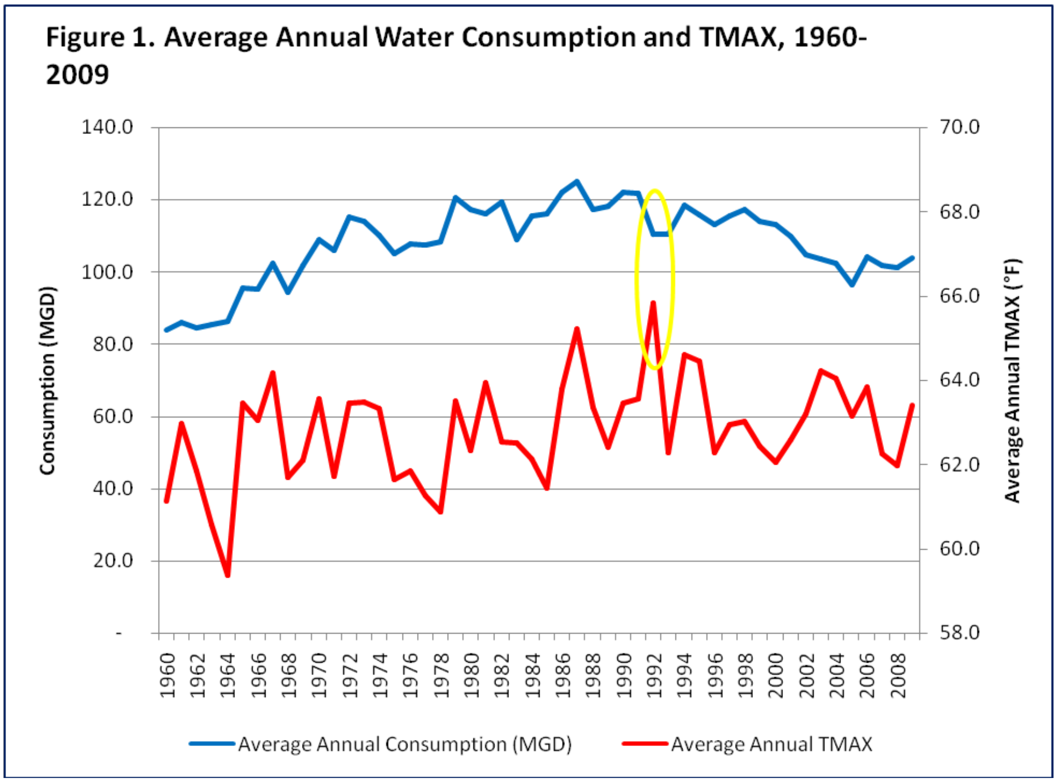


Figure 3.29 The relation between average annual water consumption and average annual maximum temperature.

Consumption has an inverse relationship with total annual precipitation, however, not as strong as that of temperature. Figure 3.30 shows dips in average annual consumption in years that are very wet.

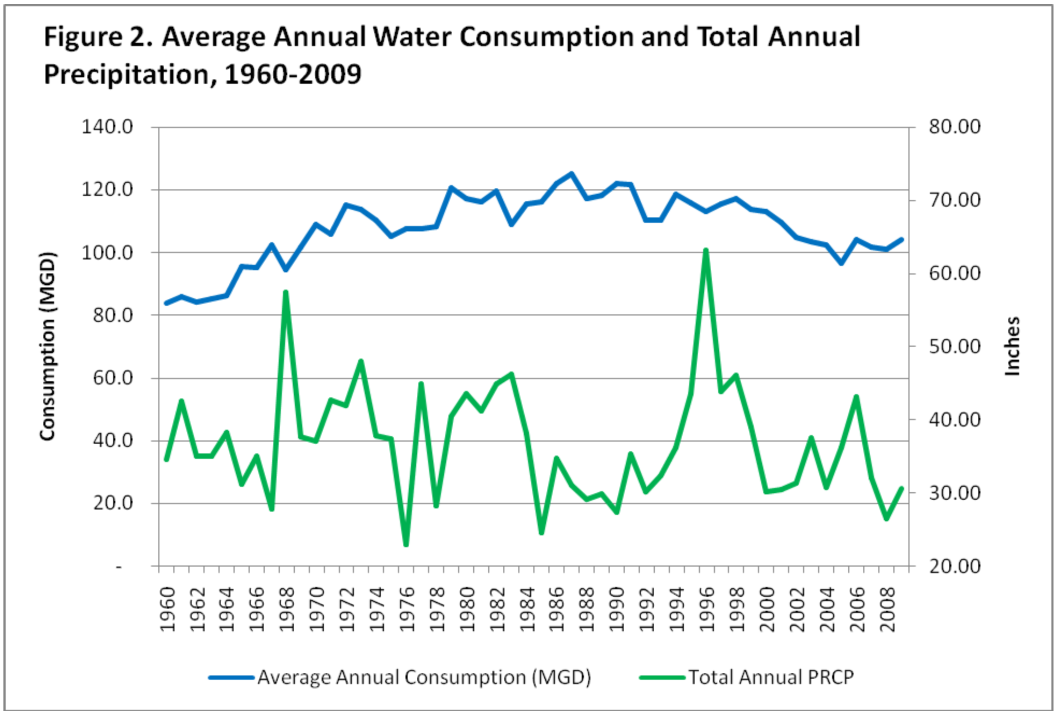


Figure 3.30 Average annual water consumption and total annual precipitation, 1960-2009

3.6.3 Seasonal Climate Variability and Water

Water consumption shows a strong seasonal pattern in the PWB service area. The Bureau recognizes June to September as peak season based on empirical data observations. The annual figures over the 1960 - 2009 period show higher consumption during peak season relative to off-peak in the range of 113% - 176%. Although peak season consumption also depends on economic and demographic factors, it is affected by inter-annual climate variability as well. Figure 3.31 depicts the Peak/Off-Peak ratio and maximum daily temperature, averaged over the year. Again, with the exception of 1992, spikes in the relative peak-off-peak consumption mostly coincide with those of the TMAX.

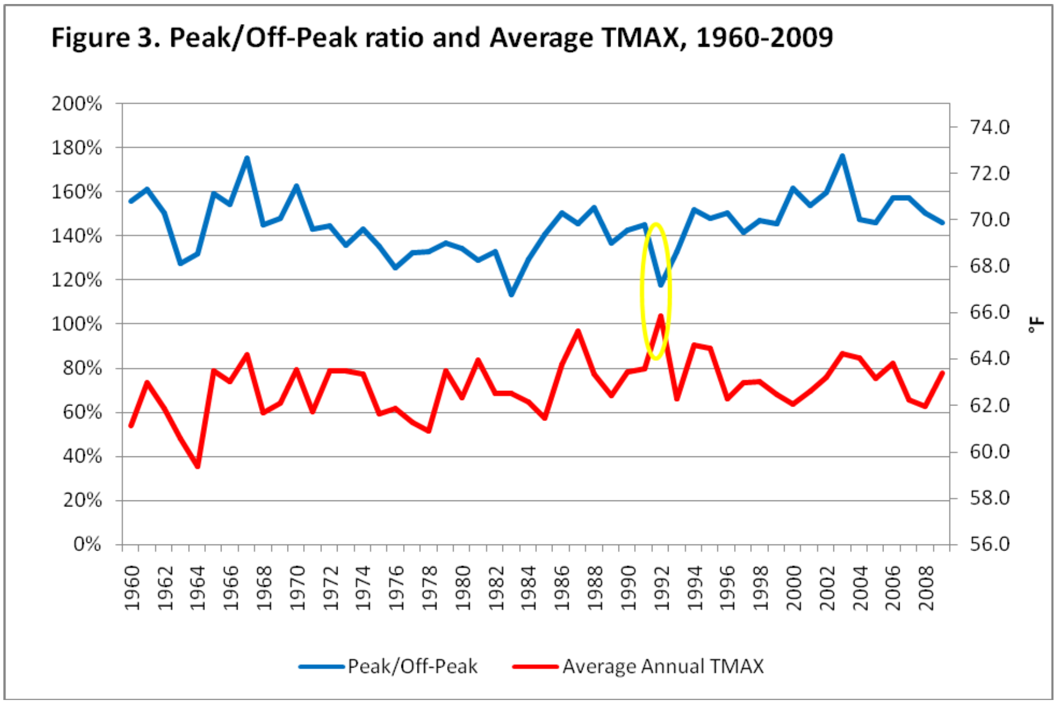


Figure 3.31 Peak/off-peak ratio and average maximum temperature, 1960 - 2009. The peak/offpeak ratio is water consumption in June to September (dry season) divided by water consumption in October to May (wet season).

3.6.4 Daily weather variability and water consumption

Daily fluctuations in consumption are closely related to daily fluctuations in weather. In fact, a simple regression of daily consumption on maximum daily temperature and total daily precipitation shows that 51% of variation in daily water consumption can be explained by total daily temperature and precipitation. Obviously, part of the explanatory power is due to seasonal patterns in both consumption and weather. That is, no matter how hot or cold the summer months are, there will be increases in water consumption due to change in the season. The daily effect of weather above and beyond the seasonal effect can be measured by considering the deviations of daily temperature and precipitation from their historical mean. A more sophisticated regression model, which includes seasonal, economic, demographic, and weather variables in form of deviations from historical means, shows how variations in consumption can be disaggregated to show the effects of these variables. A model developed by PWB shows that daily weather variations explain about 13% of the daily variations in consumption, above and beyond seasonal changes.

There was also wide variation in the average amount of water used by individual households from day to day. Overall, the average daily volume of water used by a household was greater in summer months than in winter months. This corresponds with Portland's cool, wet winters and dry, temperate summers. Average daily household water consumption was also greater on weekend days, which is logical given our sample of residential properties: some residents likely spend much of their weekday time out of the home at work or other locations. Consequently, water-consumptive activities of maintenance (washing clothes and cars) and recreation (gardening and water play) are more likely to take place on weekends.

A multilevel model results suggest that the most important determinants of household water consumption is daily maximum temperature, followed by day of the week (weekend or not), building size and building age. These factors correspond to other previous studies in the same region (Shandas and Parandvash, 2010; Chang et al., 2010). A model suggests that water use increases by 27 liters/household for every 1º C increase with an increase in daily maximum temperature. It requires an 86.5 ft^2 increase in building area to increase water use by an amount equivalent to a 1º C rise in daily max temperature. Larger houses have a greater water consumption than smaller houses on hot days. Thus the larger the house, the greater the increase in water use with rise in daily maximum temperature.

Case study: water demand in the city of Hillsboro: a spatially-explicit assessment

Urban residential water consumption is significantly affected by both interannual seasonal climate variability and periods of drought. In Hillsboro, Oregon, a rapidly growing suburb of Portland, a statistical analysis of single-family residential water records for the period 2004-2007 found that water consumption throughout the entire study area exhibited significant sensitivity to interannual climate variation (House-Peters et al. 2010). Sensitivity to interannual climate variability was manifested as increased household water consumption during the summer season, as compared to the winter season, due to increased external water use for irrigation, pool maintenance and car washing during hot, dry weather. Furthermore, sensitivity to interannual climate variability was spatially heterogeneous throughout the study area. Census blocks displaying the largest magnitude of increased summertime water use, up to 2.2 times greater than winter use, had newer and larger homes, higher property values, and more affluent and well-educated residents. This research also examined water consumption during a drought summer in 2006 when the study area recorded only half as much precipitation as the 30-year mean and exceeded the 30-year mean's average maximum temperature by one degree Celsius (National Climatic Database, station #353908). Although water use across the entire study area did not demonstrate sensitivity to the drought conditions, particular census blocks were highly sensitive to the drought, consuming up to 1.85 times more water for external purposes during the drought summer than an average summer. Interestingly, during the summer characterized by reduced precipitation and higher maximum daily temperatures, external water use was found to be more dependent on physical property characteristics and less dependent on socio-economic characteristics. These results suggest that strategic urban planning and neighborhood design may be able to reduce stress to the water supply system during peak summer demand and future drought episodes.

3.6.5 Conclusions

Statistical analysis of daily water consumption per capita in the studies cited above shows that determining which climate factors are the most influential to consumption per capita is highly dependent on the scale of study. While both precipitation and temperature are significantly associated with water consumption at all scales, the influence of temperature is stronger than that of precipitation on water consumption at the monthly scale. Other hydro-climatic and social behavior variables, such as humidity and social activities, could be also potential factors that affect the variations in water consumption. As soil moisture depends on both precipitation and evaporation, it is important to include humidity as part of water demand modeling, particularly outdoor water use such as lawn irrigation and recreational activities. Changes in lawn irrigation behavior thus can also be an important factor that might influence irrigation water demand (House-Peters et al., 2010). At a daily scale, our multilevel model can provide more nuanced information about the interacting effects of water use, structural attributes, day of the week, and temperature. These results imply how changing temperatures and demographics can lead to development patterns that exacerbate or conserve regional water resources.

This multi-scale analysis of urban water consumption illustrates complex interactions between urban water consumption and climate variables depending on the scale of analysis. It demonstrates what climate information would be useful for short and long-term water consumption forecasting. Urban water resource managers may be able to use such information for establishing proactive water resource management strategies under increasing pressure from potential climate change. While many municipalities in Oregon have prepared water management and conservation plans with supply focus (Bastasch, 2006), now is a time to put climate change into water resources planning at multiple levels.

3.7 Projected and Observed Impacts of Climate Change on Hydrosystems

Oregon is blessed with a varied and ecologically diverse environment; consequently, parts of the state are either too wet or too dry to support many human activities without modifying the natural water supply. These modifications include an extensive series of engineering projects, including reservoirs, dikes and levees, and diversions, to meet a number of sometimes conflicting objectives for Oregon's hydrosystems, including flood control, irrigation and municipal supply, hydropower production, recreation, and recovery of threatened and endangered species. Meeting these objectives in the future is likely to become increasingly difficult as climate and land use change, combined with population growth, alter the demands on and supplies of the water system.

A number of groups have investigated the projected impacts of a changing climate on hydrology and streamflow that represent changes in supply (Udall and Bates, 2007; US Geological Service, 2005; Stewart et al., 2005; Regonda et al., 2005; National Assessment Synthesis Team, 2001; Knowles et al., 2006; Ray, 2008; Baxter and Hauer, 2000; Warren et al. , 1964). Also relevant are projected changes in water demands (NWPCC, 2005; Voisin et al., 2006).

These changes in supply and demand are likely to have important impacts on water infrastructure and the built environment. Regional frequency results indicate that an increased frequency of higher streamflow events (i.e. Figure 3.32) can be expected for most areas of the PNW region, though this pattern is expected to vary spatially (Rosenberg et al., 2009a; Kunkel et al., 1999; Pryor et al., 2009; Madsen and Figdor, 2007). Small basins with a large proportion of their area at the midwinter or transient snow line are likely to be most vulnerable to climate changes (Mote et al., 2003).

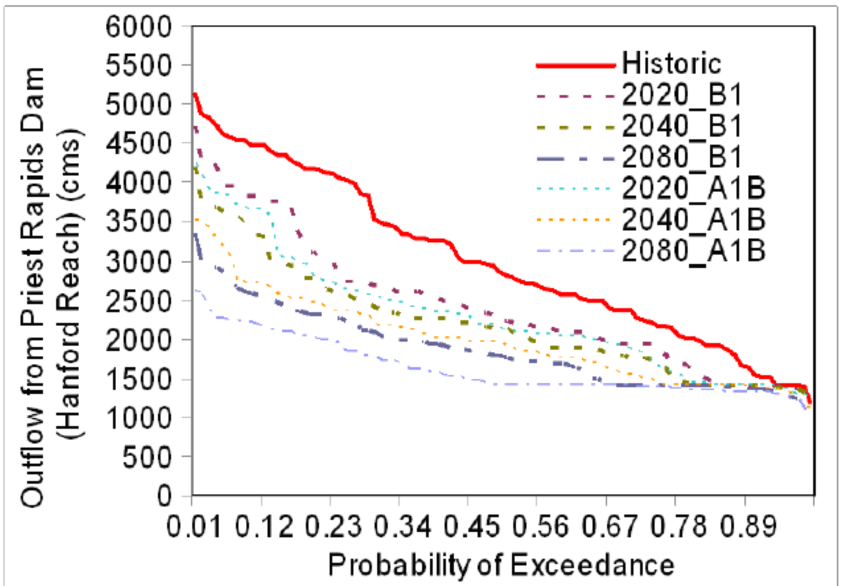


Figure 3.32 Predicted changes in extreme events for the Columbia River Basin. Figure reprinted from Hamlet et al., 2009.

Despite the value of trends projections from GCMs, the variability between GCMs challenges the design of some urban infrastructure (Rosenberg et al. 2009b). As an example, the variability between models represents one characteristic challenge in designing new and retrofit infrastructure (e.g. stormwater) based on the magnitude of the 24-hour extreme. Further, the anticipated changes are likely to be beyond what the current water infrastructure can reliably manage. For example, achieving a reduction of winter flood risk with future increases in peak flows will likely require strengthening dikes and levees, restoring floodplains, improving flood forecasting, changing reservoir management, improving emergency management, and modifying land use policies and flood insurance. With regards to low flows, it is projected that a reduction of summer water will require diversification and development of water supplies, reducing demand, improving efficiency, operational changes at reservoirs, increasing water transfers between users, and increasing drought preparedness (Binder et al., 2009). Thus, maintaining water infrastructure in future climates and land uses is likely to require new design and management approaches to address the potential challenges posed by uncertain changes in both supply and demand.

In this section we further explore these potential impacts of climate and land use changes on water infrastructure in Oregon, leading to questions regarding: How might water management objectives (e.g. hydropower production, flood protection, recreation, municipal and irrigation supply, and instream flows) be impacted by climate change? What indicators and measurements are relevant to evaluating climate change impacts on meeting water management objectives? What adaptation strategies are groups considering and what tradeoffs may be necessary for new water management objectives?

3.7.1 Impacts on Water Infrastructure

A number of climate-related impacts could have important consequences for water infrastructure and management. For example, fish recovery plans may need to be revised, fire risk may increase due to vegetation shifts, infrastructure (e.g. crossings, conduits, landslide risks) could be impacted by increased peak flows, and water and/or reliance on groundwater could increase.

In some areas, impacts to water infrastructure include (also see Miller and Yates, 2007).

- intrusion of bromine/iodine from seawater, leading to problems meeting disinfection by-product rule compliance (AWWA, 2001)
- increasing potential for floods to exceed stormwater systems, leading to water contamination from combined sewer overflows (Ashley et al., 2001)
- increased potential for floods to damage infrastructure (Filion, 2000)
- increased fire frequency leading to increased sediment loads to water treatment plants

Recent work has focused on the development of hydrological projections for the PNW in the context of water resources management (Vano et al. ,2009a and 2009b; Wiley and Palmer, 2008; Trayham, 2007; Polebitski et al., 2008). Together, these studies indicate that shifts in hydrology towards higher flows in fall are likely to variably impact dam operating objectives. For example, Wiley et al., (2008) predicted that April snowpack will decline from 2000 to 2040 and that peak snow accumulation will shift from March to earlier in the year. This is anticipated to result in a decline in fall reservoir storage. In another example, Vano et al., (2009a) used downscaled GCM A1B and B1 emission scenarios as inputs to DHSVM to produce streamflow simulations for the 2020s, 2040s, and 2080s. These results were then input into water resources model run at a daily time step. Their results project a transition from a double peaked hydrograph (December and mid-May snowmelt peak) to a single peak in December (elevated winter runoff). By early April to the end of March, all future scenarios show less water than historical conditions, due to earlier snowmelt. Despite this change, reliability (the ability of the system to meet demands including instream flow and consumptive use) remains at 100% for historical simulations of Seattle, Tacoma, and Everett reservoirs and only drops below 98% for the warmest and driest scenarios (CCSM3 and ECHO_G). However, in their models, reliability decreased markedly if increases in demand are factored into analyses.

Most models agree that instream flow requirements will be increasingly difficult to meet in the more distant future as demands increase and available storage declines. In Puget Sound reservoirs, Vano et al. (2009a) and Wiley and Palmer, (2004) found that instream flows in summer will not be significantly impacted by climate change in the near future as instream flow requirements set by the Habitat Conservation Plan (SPU, 2000) are lower than typical observed flows. However, instream flows are projected to be adversely impacted for the most severe climate scenarios for the 2020s and for A1B and B1 scenarios in the 2040s and 2080s. Without substantial infrastructure changes, tradeoffs are likely to be necessary between hydropower generation, instream flows for fish, reservoir storage, and flood protection. For example, regarding instream flows, the Hamlet et al. (2009) studies suggest that the use of larger reservoir storage will be required to mitigate/supplement summer low-flows for reducing tradeoffs between fish flows and firm energy resources. Along these lines, Payne et al. (2004) found that trade-offs were unavoidable in the winter due to limited reservoir storage level.

It is likely that changing supply and demand of water will require reconsideration of established rule curves to more reliably meet flood protection, instream flows, and hydropower objectives. For example, projections (Figure 3.34) indicate that increased potential for hydropower production exists through the winter months while decreased production is likely through the summer months as we move further into the future. These results are based on simulation of streamflow for the Columbia River Basin (Hamlet et al., 2009) using the VIC hydrologic model (Liang et al., 1994) and methods described by (Elsner et al., 2009). Their objective was to investigate adaptive responses with regard to flood control, using fixed (assuming no change in demands) energy targets for firm and non-firm energy. They found that, for the 2020s, winter hydropower increases 0.5-4% and summer hydropower decreases 9 - 11%, with net decreases of 1 - 4%. By the 2040s, winter production will increase 4% and summer production will decrease 2.5 - 4%. By 2080s, winter production will increase 7 - 10% and summer production will decrease 18 - 21%. The largest reductions in hydropower generation, as compared with 20th century values, are likely to occur July-Sept, coincident with peak seasonal air conditioning loads (Voisin et al., 2006; Westerling et al., 2008).

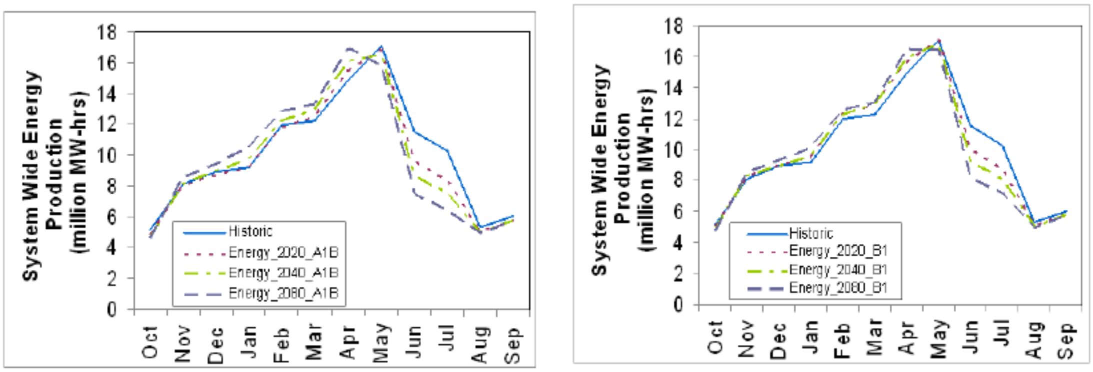


Figure 3.34 Projected Impacts to hydropower production on the Columbia River. Simulated long-term mean, system-wide hydropower production from the Columbia River basin for A1B scenario (top panel) and the B1 scenario (bottom panel). Figure reprinted from Hamlet et al., 2009.

Mote et al. (2003) found that the reliability of energy production remains high in future scenarios but that reliability of flood control diminishes with increased precipitation (Figure 3.34).

In addition to direct changes in flow, synergistic changes in water temperature are likely to influence reservoir operations (Battin et al., 2007; Mantua et al., 2010). Thermal stress periods are predicted to be minimal until 2020s and then subsequently increase (Mantua et al. ,2009). These stress periods will occur during reduced summer flows and are likely to influence both dam operations and infrastructure needs (e.g. temperature control devices). The complex and variable nature of hydrologic, and consequent ecosystem changes, suggests that current strategies and regulations that govern operations of reservoirs in static and uncoordinated ways may inhibit the necessary flexibility required to manage water resources in a changing climate.

3.7.2 Adaptations and Tradeoffs

As agencies and communities adapt to a changing climate, tradeoffs are going to be inevitable. Some of these tradeoffs will be specific to the local hydrogeology and climate while others will be based on social values or existing legal requirements (e.g. ESA). For example, while hydropower is a very inexpensive energy source and accounts for 70% of energy use in the PNW (Hamlet et al., 2009; Binder, 2009) the amount of hydropower generated is controlled by water availability and not demand (Hamlet et al. 2009). Thus, some are considering additional storage (Snover et al., 2007) to meet competing water demands. Indeed, important trade-offs between fish flows and firm energy resources in winter may require the use of much larger reservoir storage (Hamlet et al., 2009; Barnett et al., 2004). In one example, researchers (Payne et al., 2004) examined tradeoffs in alternative reservoir operation strategies. They found that greater storage to capture earlier reservoir refill could help meet instream targets, though at a cost (9 - 35% loss) of firm hydropower production.

3.7.2.1 System optimization

Optimization has been applied to evaluate tradeoffs in operations for multiple-reservoir, multi-purpose hydrosystems for many years (Needham et al., 2000). However, some major challenges exist in basing operations solely on optimization outcomes. Labadie (1997) reviews reservoir optimization models, with discussion on the lag between theoretical developments and implementation. Some of these challenges include establishing relative value or priority among multiple objectives, scaling and time steps/lags (changes in flow now vs. responses of ecosystems vs. other costs/benefits), defining and measuring system health/impairment and response/performance. These factors require a high degree of model complexity, which significantly increasing costs of model development, ease of use, the reliability of its output (Van Lienden and J. Lund, 2004), and the difficulty in addressing deviations and risk. Further, an increase in the frequency of extreme events (floods or droughts) will make it more difficult to meet multiple objectives under an optimized system. For example, reservoirs in the Willamette Basin, designed to meet flood protection, municipal water supply, and Biological Opinions requirements are generally in concert. However, during high flow events, conflict between objectives could occur when, for example, ramping rates required by the Biological Opinions may not be met to satisfy flood protection objectives.

3.7.2.2 Current planning and design practices

Fundamental challenges emerge for water managers when applying the results of GCMs in water infrastructure design. These challenges result from the current design paradigm for water resources engineering, which is based on frequency distributions of precipitation and runoff and assumes stationarity. For example, design of stormwater infrastructure is frequently based on precipitation events of 1-hr to 24-hr duration, and 2 to 25 year return frequency (Osman, 1993). Predictions at this scale are especially important in urban areas, where smaller lag-to-peak and flashy streams are common (Rosenberg et al., 2009). Continuing to design stormwater facilities in this way may require GCMs to be downscaled to hourly precipitation timestep and low spatial resolutions (e.g. ~20km) before input into rainfall-runoff models (Rosenberg et al., 2009), a process that is highly vulnerable to uncertainty. The alternative is the development of a new design paradigm that is not based on frequency distributions. Advantages of various downscaling approaches in the Pacific Northwest have been reviewed (Salathé et al., 2005), and Avise et al., (2006) present some advantages of using regional climate models for various impacts applications. Neither solution has been comprehensively demonstrated or is without uncertainties. Thus, managers will need to consider the resolution of data required for hydrodynamic and management models and either downscale (with a quantitative understanding of uncertainty) or adjust their management models to operate at a coarser scale.

A second challenge regarding engineering design practices is the assumption of stationarity. In addition to key challenges in assuming hydrological stationarity (Milly et al. 2008), nonstationarity in ecological and social drivers is also likely. For example, planning for future energy demands is challenged by unpredictable changes in carbon pricing and policies that may influence where and when power is produced from reservoirs, the availability of alternative energy supplies, the increased importance of managing reservoirs for temperature in both the summer and winter, changes in populations and/or demographics, and the lack of stationarity in ecological systems' responses to changing landscapes and hydrology.

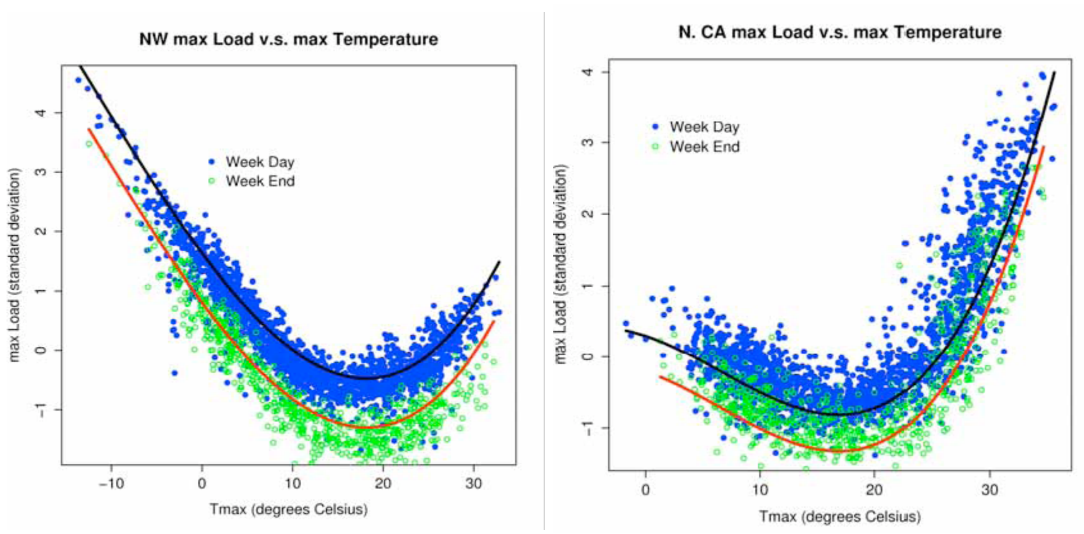


Figure 3.35 Nonlinear relationships between maximum daily temperature and peak energy demand in the PNW and Northern California. (Figures from Westerling et al., 2008).

An example of nonstationarity in social drivers is demonstrated by Hamlet et al. (2009), who investigate the uncertainty in the relationship between daily maximum temperature and peak energy demand in the PNW and northern California. By investigating projected increases in population, heating degree days, cooling degree days, and air conditioning market penetration, this research attempted to address heating and cooling energy demand indices (for residential, not industrial use) for three projected climate periods (2010 - 2039, 2030 - 2059, 2070 - 2099) using IPCC emission scenarios A1B and B1. Their studies projected that peak electricity demand in summer in the PNW would likely remain similar to current demands, but would be higher in CA (Figure 3.35). Their work also emphasized a highly non-linear relationship between demand and maximum temperature. For example, despite warmer temperatures, heating energy demand is projected to increase with increasing population: 22 - 23% for the 2020s, 35 - 42% for 2040s, and 56 - 74% for 2080s. Cooling energy demands will increase by a factor of 2.6 - 3 for the 2020s, 4.6 - 6.5 for 2040s, and 10.8 - 19.5 for 2080s. This work also identified key sources of error in these analyses to be 1) decadal scale precipitation associated with the PDO, and 2) population growth predictions and related heating and cooling energy demand.

3.7.2.3 Addressing uncertainty in water resources impact assessment

In this unpredictable water future, water resource management may become increasingly complex as new objectives and multi-facility coordination requirements are added to reservoir rule curves and water infrastructure. This complexity will be driven by a number of key uncertainties, including the loads and market price of power, hydrologic variability, water demands, environmental and biological requirements, aging infrastructure, and science and policy changes. These uncertainties pose important challenges to the management of hydrosystems.

The uncertainty in climate and hydrology is important for a number of management decisions around water infrastructure, including Biological Opinions, ESA and NEPA, flood risk management, FERC relicensing, evaluating resource adequacy and rates, infrastructure studies and policy (e.g. 2014/2024 Columbia River Treaty) reviews. While decision making under uncertainty is not new (Loucks et al., 1981), the non-linearity of changes associated with climate change presents some new challenges in a) using, interpreting, and communicating data based on climate projects, b) grasping the scope of policy/economic changes, c) resolving inconsistency in timesteps between social change and environmental change, d) meeting new and varied demands on the water system, and d) identifying control points in social-economic-ecological systems. Using dam operations as a specific example, uncertainties in reservoir operation models include fisheries objectives (flow augmentation and spill), forecast errors, hydropower loads, and runoff distributions. These challenges are further complicated by inconsistencies between the temporal and spatial scales of GCM and water resource models. Some (Barsugli et al., 2009) argue that GCMs need better model agreement on key parameters, a narrowing of the range of model output, and climate model output that matches the spatial and temporal resolution needed for water utility models, improved short-term climate model projections that fit water utility planning horizons.

Model uncertainties emerge from a variety of sources, including both the projections of future climate and the hydrologic response to changing climate. Based upon work in the United Kingdom, Kay et al. (2006) suggest that the largest source of uncertainty in estimated future runoff is introduced by the choice of GCM, followed by the chosen emission scenario, and then by the hydrological model which produces estimates of future runoff. This ranking of uncertainty has been supported by others (Praskievicz and Chang, 2009b; Bloeschl and Montanari, 2010) who have suggested that the greatest uncertainty emerges from the fact that the GCM projections cannot be evaluated against measured data for the future. Hydrological models, on the other hand, can be evaluated against historical conditions, and calibrated to ensure that the model captures measured dynamics, albeit historical, of the hydrological system.

The assessment of uncertainty in climate and hydrological predictions is becoming an integral component of climate forecasting (e.g. Solomon et al. 2007). The most common implementation of uncertainty analysis in climate modeling focuses on the utilization of an ensemble of climate results, including both multiple emissions scenarios and the results from multiple GCMs, as input into a single hydrological model. A variety of studies have utilized this model for impact assessment in California and Washington watersheds (Vano et al., 2009a and 2009b; Miller et al. , 2003; Hayhoe et al., 2004; Leung et al., 2004; Dettinger, 2004; Maurer and Duffy, 2005; Maurer, 2007). This procedure makes direct use of the uncertainty methods that are commonly employed by the atmospheric modeling community and climate change impacts research. In addition, Bloeschl and Montanari (2010) make the case that uncertainty introduced into water resource assessment through hydrological modeling should also be acknowledged and quantified. Techniques exist for evaluating hydrological model uncertainty (e.g. Beven and Freer, 2001; Vrugt et al., 2003), which can support climate change planning and designs.

3.7.3 Evaluating vulnerability of infrastructure to climate change

Measuring and communicating the impacts of climate change on water infrastructure is critical as water resource managers reflect on future infrastructure needs and risk. Several metrics may be useful in evaluating the vulnerability of water infrastructure across basins, political governances, and management approaches. Indirectly, measures of a landscape's hydrologic sensitivity to climate change may include percent of watershed with transient snow (resulting in a two peaked hydrograph due to rain and snow) (Swanson et al. 1992), and Hydrologic Landscape Regions (Wiggington et al. in review), which are based on measures of seasonality, climate, aquifer permeability, terrain, and soil permeability.

More directly, minimum reservoir storage, as the ratio of annual runoff to total storage, is another measure of system vulnerability or stress. Studies by Vano et al. (2009a, 2009b) indicate that active storage capacity drops by 50, 25, or 10% in October, when reservoir storage is typically lowest, under the A1B and B1 scenarios as compared to historic conditions. This could result in lower reservoir storage available late spring through early fall in the future. Similarly, Mote et al. (2003) found that basins with higher storage-to-flow ratios may be less vulnerable to stress than those with minimal storage. Another direct measure of storage vulnerability is the projected timing of reservoir filling. Medellín-Azuara et al. (2007) predict that dry-warm climate scenarios, given projected water demands and land use for 2050, will increase the seasonal storage range, with peak storage occurring around one month earlier.

3.7.4 Conclusions

As Oregon's population and economic activity increase over time, and as changes in climate increasingly impact the hydrological and ecological systems of Oregon, management of water resources will become increasingly complex. Difficult decisions regarding tradeoffs, modifications to current water infrastructure, and coordinated, thoroughly-analyzed operations of hydrosystems are going to be necessary.

3.8 Conclusions and Recommendations

As illustrated by several case studies, climate change will affect various sectors of water resources in Oregon in the 21st century. First, the amount and seasonality of water supply is expected to shift as seasonal distribution of precipitation changes and temperatures rise. While annual total precipitation may not change or even increase under some climate change scenarios, hotter summers accompanied by reduced precipitation will decrease stream flow. Although there are no anticipated spatial patterns of precipitation and temperature change across the state for the 21st century (temperature is projected to increase uniformly across the region), significant regional variations do exist. Models suggest that spring and summer streamflow in transient rain-snow basins, such as those in the Western Cascade basins, will be sensitive to these changes in precipitation and temperature; analyses of existing long-term streamflow data in western Cascade basins reveal declining spring streamflow, but no changes in summer or winter streamflows, since the 1950s. The High Cascade basins that are primarily fed by deep groundwater systems are expected to sustain low flow during summer months despite declining snowpacks, although the absolute amount of summer flow will decline. Basins in the east of the Cascades underlain by the Columbia River basalts are expected to have low summer flow in a distant future as groundwater recharge declines over time. April 1 snow water equivalent (SWE) will decline and the center timing of runoff will become earlier in transient rain-snow basins as snowpack is projected to decline consistently in the 21st century.

Second, water temperature is projected to rise as air temperature increases in the 21st century, particularly in urban streams where natural riparian vegetation is typically lacking. A decline in summer streamflow is expected to exacerbate water temperature increases, because the low volume of water will absorb solar radiation or blackbody radiation from the streambed and banks more quickly than during times with larger instream flows. Changes in water temperature can have significant implications for stream ecology and salmonid habitat in many Oregon streams. Lower order streams in transient rain-snow basins and in semi-arid eastern Oregon will be the most vulnerable to rising summer air temperature and diminished low flow. A new dam or reservoir might be required to maintain environmental flow in summer.

Third, as shown in the Portland water use study, when other demand factors are constant, increases in temperature alone would result in higher demands for peak season water. While demand during winter months is expected to remain constant, urban water demand is positively correlated with air temperature, particularly among single family residential (SFR) households. These impacts are also evident at multiple scales, including the household, neighborhood, and region. At the regional scale, urban land uses have different water demands, and will have varying impacts on water availability. Overall, people living in single-family residential areas are the largest consumers of water. At the neighborhood scale, the density of development helps to predict future water use, where higher density residential developments have lower water demand. Finally, at the household scale, the results of empirical research in the Portland region suggests a coupling of structural attributes (e.g. building and lot area) and temperatures that affect water demand. For the competing demands on regional water resources, if this development had contained smaller homes, and higher densities, other land uses would likely have more total water available.

Uncertainty is still high in projecting future changes in runoff, urban water demand, and water quality in Oregon. While the main source of uncertainty stems from the choice of global circulation models, additional sources of uncertainty include GHG emission scenarios, downscaling methods, hydrologic model structure and parameterization, and impact assessment methods. Multi-ensemble models that take into account all sources of uncertainty with different weights might provide a means of quantifying different sources of uncertainties. Communicating uncertainty to water resource decision makers is another challenge for adaptive water resource management in a changing climate. While a more sophisticated hydrologic impact assessment model yet to be developed, climate adaptation strategies can be implemented at multiple spatial scales.

Since one objective of land use planning is to coordinate regional activities, planning is one tool that may be helpful in meeting the future water needs of the State. Currently, land use and water resource management agencies have limited coordination in their responsibilities. The analyses provided here suggest that two characteristics of land-use plans, namely zoning and public involvement, can be instrumental to improving the coordination between land and water management agencies. Zoning can be used to link types of future development (e.g., for 2030 and 2040) to include a combination of infill, expansion, connecting existing developments, with explicit identification of water demands on different land uses in the region. To date, few plans have explicitly included dimensions of water management. Outreach and education campaigns can help inform the public about the relationship between water demand and supply, but can also assist in adapting to a future with increasingly limited resources. The details of those plans and the precise nature of the outreach and education campaigns will require further investigation, and will likely be part of the second assessment of Oregon's water resources.

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