A GIS Analysis of Climate Change and Snowpack on Columbia Basin Tribal Lands

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Abstract

Salmon and steelhead of the Pacific Northwest are dependent on the delivery of abundant, cool water from seasonal snowmelt to support their migration, spawning, incubation, and rearing. The anthropogenic release of greenhouse gases, which is raising global air temperatures, poses a threat to the seasonal accumulation and melt of snow in the Pacific Northwest. As temperatures have warmed, the region has experienced a greater proportion of precipitation falling as rain and a lesser proportion falling as snow. It is projected that this trend will increase during the 21st century, likely causing reduced snowfall in most areas, more runoff during the winter, earlier peak streamflows during the spring, and diminished runoff during the summer, when water is most needed for salmon and other competing uses. The ceded areas of the member tribes of The Columbia River Inter-Tribal Fish Commission may be highly vulnerable to these changes.

We performed a Geographic Information Systems (GIS)-based analysis to better anticipate changes to snowpack on these tribal ceded areas. This analysis included the use of contemporary climate data and projections of 21st century climate change. Contemporary data were examined to determine the extent of areas near or just above the current mean winter freezing level, which may transition from snow-dominated to rain-dominated regimes with moderate warming. A snowpack model was constructed and implemented at monthly time steps to simulate precipitation, snowpack, and snowmelt over a distributed area during future climate scenarios.

The results of this analysis demonstrate that large portions of the tribal ceded areas are vulnerable to near-term climate change, especially in those subbasins that have a large amount of area at moderate elevations, and those that are further west and experience relatively mild temperature ranges. The results also identify higher elevation areas and areas in more eastern continental climates, which may be buffered from near-term temperature increases and could offer thermal habitat reserves for salmon as temperatures increase. An examination of modeled results showing monthly water balances from precipitation and snowmelt during future scenarios suggests how the timing of runoff may be affected in each subbasin, and generates data that can be used as an input to detailed hydrologic simulations.

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Introduction

The Pacific Northwest is dependent on seasonal snowmelt for water resources that are critical for the migration, spawning, and rearing habitat of salmon, as well as other significant components of the region's ecology and economy. Heavy winter precipitation falls as snow in the mountains, and water is slowly released when this snow melts during the spring and summer, supporting downstream uses. Despite a large network of dams, the total reservoir capacity of the Columbia Basin is only 30% of the annual flow and the winter snowpack is its most effective storage medium (Miles et al. 2000). Hydropower facilities designed according to seasonal snowmelt cycles generate the majority of the electricity used in the burgeoning urban economies located west of the Cascades; prolific salmon runs throughout the Columbia Basin are adapted to migrate and spawn during spring and summer runoff; and agricultural hubs east of the Cascades rely primarily on snowmelt to irrigate their crops through dry summer months, presenting competing demands on spring and summer water supplies.

Since the industrial revolution, anthropogenic emissions and land use practices have increased the atmospheric concentrations of heat-trapping greenhouse gases, primarily carbon dioxide and methane, but also including ozone, nitrogen oxides, sulfur oxides, chlorofluorocarbons, hydrocarbons, and other constituents. This increase in greenhouse gases is correlated to a warming trend that has occurred globally, including in the Pacific Northwest (IPPC 2007). Global General Circulation Models (GCMs) forecast with strong confidence that this warming trend will continue during the 21st century, although the magnitude of this change depends on several complex variables and interactions within and between the oceans and the atmosphere, as well as the societal response to this issue (IPPC 2007).

Increasing air temperatures in the Columbia River Basin will likely cause decreases to seasonal snowpack and disruptions to the timing of snowmelt and stream flows. Research has found that temperatures are warming in the Pacific Northwest at a greater rate than the global average, and this region has already witnessed a decreasing trend in seasonal snowpack and changes to the timing of runoff in its streams and rivers (Mote et al. 2003, Regonda et al. 2005). These temperature increases are projected to continue during the 21st century, even if greenhouse gas emissions are significantly reduced. The best current scientific estimates project a rise in annual Pacific Northwest air temperatures of two degrees Celsius (3.6 degrees Fahrenheit) or more by the middle of the 21st century (UWCIG 2007). These effects will likely most impact snowpack in areas that are near or just above the current winter snowline, because as temperatures warm, such areas will transition from snow-dominated regimes to ones with rainfall as the dominant form of precipitation (Mote et al. 2003). We can expect that these changes will lead to a smaller seasonal snowpack, more runoff during the winter, earlier peak streamflows, and diminished runoff during the summer months, when it is most needed for salmon and other competing uses (Miles et al. 2000, ISAB 2007, Martin and Glick 2008).

The ceded lands of the Confederate Tribes of the Warm Springs Reservation of Oregon, the Confederated Tribes of the Umatilla Indian Reservation, the Confederated Tribes and Bands of the Yakama Nation, and the Nez Perce Tribe all host culturally precious natural resources, including salmon and steelhead, which benefit from the upland melting of snowpack to provide steady stream flows. In order to better anticipate the changes that may occur on these lands, we performed a Geographic Information Systems (GIS) analysis. Using historic climate data and projections of future changes from global warming, we modeled potential changes to snowpack and available water across tribal ceded lands to determine which areas may be the most vulnerable for loss of snowpack.

We hope that this analysis can assist the CRITFC member tribes in their own considerations and preparations for mitigating the effects of climate change on their lands, and also help inform a unified CRITFC policy on climate change and its potential disruptions to salmon and other cold-water fish species.

Methods

Our analysis consisted of four stages: (1) Assembled data about contemporary climate conditions (1971-2000) for the Columbia Basin and examined temperature and precipitation patterns to anticipate which subbasins in the tribal ceded areas are potentially most vulnerable to loss of snowpack from 21st century climate change; (2) Developed and programmed a fairly simple model that simulates precipitation, snowpack, and snowmelt over a distributed area, using monthly inputs of temperature and precipitation; (3) Calibrated the model performance using contemporary (1971-2000) and corresponding measurements of snowpack from various locations in the Pacific Northwest; (4) Once calibrated, ran the model for four climate scenarios (1971-2000, 2020s, 2050s, and 2080s) using projected changes to temperature and precipitation in the Northwest obtained from an ensemble of GCM Simulations, in order to estimate how snowpack and water availability may vary under future climate conditions. Detailed descriptions of each stage of the analysis follow.

(1) We obtained contemporary (1971-2000) mean monthly temperature and precipitation data for the study area from PRISM, a historical distributed climate data set generated at the Spatial Analysis Climate Service at Oregon State University by regressing empirical climate measurements over the landscape (Daly et al. 1994, Oregon Climate Service 2007). We correlated these climate data to a mapped (GIS) grid of the Columbia River Basin based on 1.44 km^2 grid cells so that processes could be evaluated and modeled in each grid cell and aggregated across larger areas as desired.

We identified areas that are near or just above the current winter snowline as being those grid cells with mean monthly winter season (Nov-Mar) temperatures between +1 and -2 degrees Celsius. These areas are presumably those most susceptible to near-term climate change because with the temperature increases projected for the Northwest by mid-century of around two degrees Celsius, they will shift from having mean winter temperatures near or below freezing to above freezing. These areas would therefore be expected to shift from snow-dominated regimes to rain-dominated regimes. For our analysis, we considered seven subbasins of importance to the CRITFC member tribes because they are within their ceded areas and are important for salmon and steelhead: The Deschutes, John Day, Klickitat, Yakima, Umatilla, Clearwater, and Salmon subbasins.

(2) We constructed and ran a fairly simple precipitation and snowmelt model (see Graves and Chang 2007 for a similar application) to estimate the monthly changes to snowpack and water using recent historic conditions (1971-2000). Using monthly precipitation and mean temperature, the model progressed stepwise through each month to determine the total quantity of precipitation falling as snow and rain for each grid cell of the study area. The proportion of precipitation falling as rainfall or snowfall was calculated with an equation from Legates (1991) that was optimized during calibration as ($\text{Snow} (\%) = 100/(1.35^T + 1)$) where T = mean monthly air temperature. Monthly snowpack was tracked in each cell throughout the simulation as a snow water equivalent. Monthly snowmelt was determined using a

linear degree-day (temperature index) approach from (Semadeni-Davies 1997), where Snowmelt (cm) = MRF × (monthly air temperature – snowmelt temperature) ×days/month. The MRF was calibrated as 1.0 and the snowmelt temperature was set as 0.0 degrees Celsius. The model thus simulated a monthly quantity of rainfall, snowfall, snowpack, and snowmelt in each grid cell of the study area, using monthly air temperature and precipitation as inputs.

(3) We ran the model using the contemporary (1971-2000) mean monthly precipitation and temperature data, distributed over the study area at the grid cell resolution of 1.44 sq km. We then calibrated the model with historic SNOTEL (snow water equivalent) measurements from 26 sites across the Northwest (NRCS 2007) in order to assure that it was simulating mean snowpack accumulation accurately. The sites were chosen to represent a sample of different elevations and geographic zones of the Northwest, and their monthly snow water equivalents were tallied and averaged for the 1971-2000 period in order to match the climate data. During the calibration process, coefficients for the Legates equation to simulate rainfall and snowfall proportions and the degree day melt equation were "tuned" to provide the best possible fit of modeled snowpack and SNOTEL measurements.

(4) Once calibrated, we ran the model for three future climate scenarios (2020s, 2040s, and 2080s). In order to simulate the effects of climate change, we obtained future projections of monthly temperature and precipitation changes in the Pacific Northwest from an ensemble of 20 Global Circulation Model (GCM) simulations. These simulations reflect the most widely used and current projections of future global climate change. They were generated for the recent IPPC report (IPPC 2007) by running ten GCMs for two different scenarios (A2 and B1) that demonstrate a range of high to low expectations for emission releases. High and low expectations are helpful because of the uncertainty about how anthropogenic emissions of heat trapping gases may accelerate, stabilize, or be reduced globally during the 21st century. The University of Washington Climate Impacts Group obtained the outputs from these twenty scenarios and extracted and averaged them for the Pacific Northwest region. We downloaded these summary data from the UW CIG web site (UWCIG 2007). It provides monthly expectations of changes to precipitation and temperature from a baseline period (1971-2000) for three future periods: 2010-2039 (centered around the 2020s), 2040-2069 (centered around the 2050s), and 2070-2099 (centered around the 2080s). These same data were used in the analysis of the Independent Scientific Advisory Board climate change report for the Columbia River Basin (ISAB 2007).

It is important to recognize that these data (i) Represent general conditions for the Pacific Northwest, but do not reflect local features such as mountain ranges; (ii) provide better estimates of temperature changes than precipitation changes; and (iii) are a coarse spatial representation of the landscape (UWCIG 2007). They therefore provide a regional signal of climate change, but their use for local analysis such as this one introduces some uncertainty. For example, high elevation areas may warm more quickly than low ones during the 21st century, and this was not captured with these broad regional expectations of climate change. Nevertheless, they provide a valuable projection of future changes, which may be incorporated into finer analysis.

The model runs for these three future scenarios provided data on mean monthly rainfall, snowfall, snowpack, and snowmelt, which are easily compared to the same parameters for the contemporary (1971-2000) period, to project future changes. Because the data are distributed over a GIS grid, it is possible to aggregate these outputs for basins of various sizes and locations. For this study, we aggregated the results for the seven ceded area subbasins of high interest, and summarized monthly rainfall and snowmelt for each subbasin and period in order to demonstrate changes to input water in each subbasin (see Figures 9-15).

Results and Discussion

Results are shown and discussed below for (a) the evaluation of contemporary winter temperatures to determine areas of likely vulnerability (Figures 1-8); and (b) the results of model simulations for one contemporary and three future climate periods (Figures 9-15).

Figure 1 juxtaposes the location of tribal reservations and ceded areas with contemporary mean winter temperatures. It designates in yellow the areas that are likely to be most vulnerable to a loss of snowfall from near-term climate change. It is striking that the vulnerable areas encompass much of the tribal ceded areas, and likely will have a substantial impact on stream flows through these areas. It is also interesting to note that the areas most susceptible appear to be around the Columbia Plateau and lower Upper Columbia and Snake River basin areas. The Salmon River Mountains appear to be fairly well insulated because of their cold winter temperatures. Several key subbasins are considered individually on the following maps (Figures 2-8).

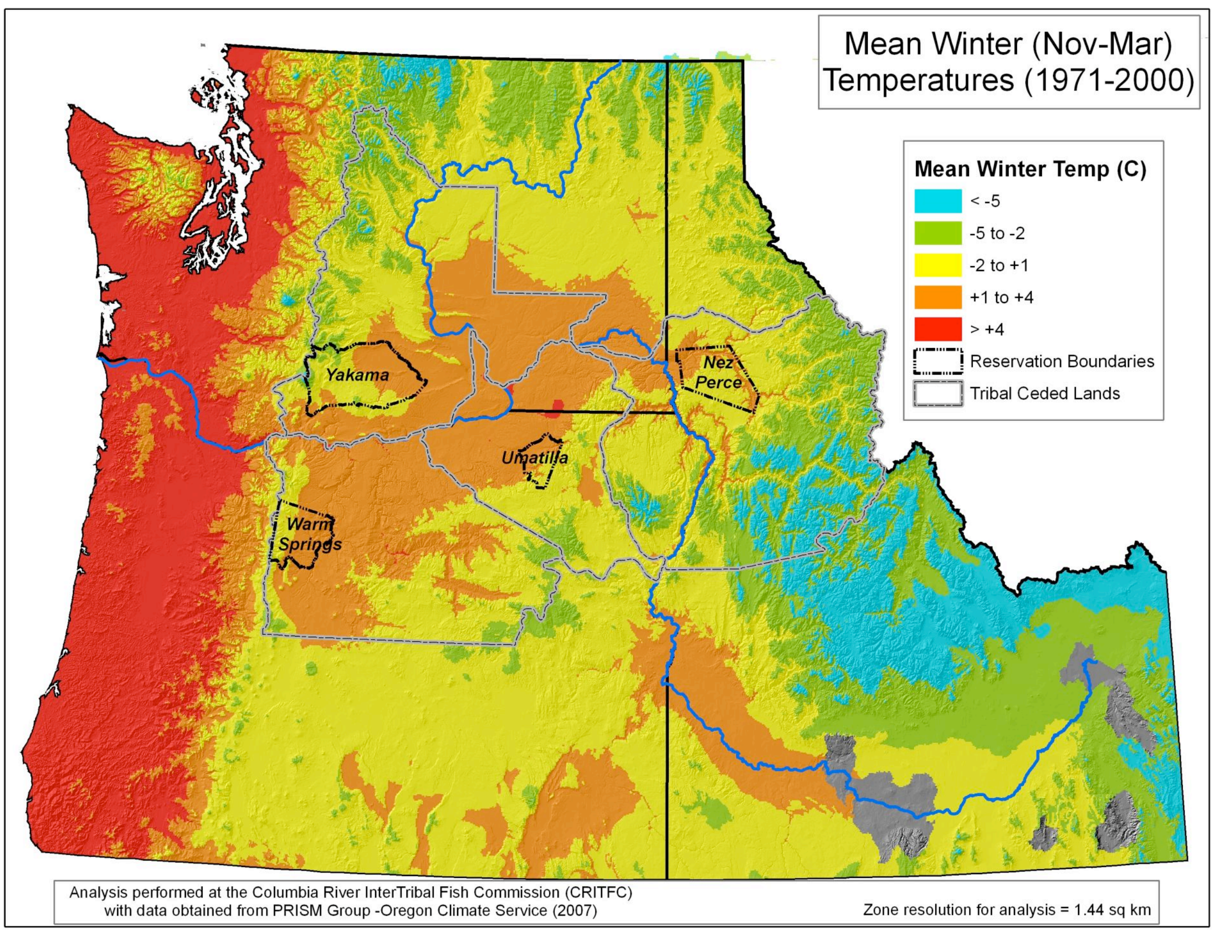

Figure 1: Contemporary mean winter temperatures (1971-2000) in the Pacific Northwest and tribal reservations and ceded Areas

In the Yakima subbasin (Figure 2), much of the area between the Cascade divide and the lower Yakima Basin is at risk for loss of seasonal snowpack from near-term climate change because its winter temperatures are near or just below freezing. 29% of the annual precipitation in the subbasin falls in areas and times when the mean monthly temperatures are between +1 and -2 degrees C. With warming that is expected to occur during the 21st century, it is likely that much of the basin will change from a snow-dominated regime to a rain-dominated regime. Only the areas around the Cascade divide are cool enough to support snow-dominated regimes with near-term climate change, and if projections for increases to temperature occur, then they will also begin to transition late this century. As such, the Yakima Subbasin is at a high risk of losing much of its seasonal snowpack from 21st century climate change.

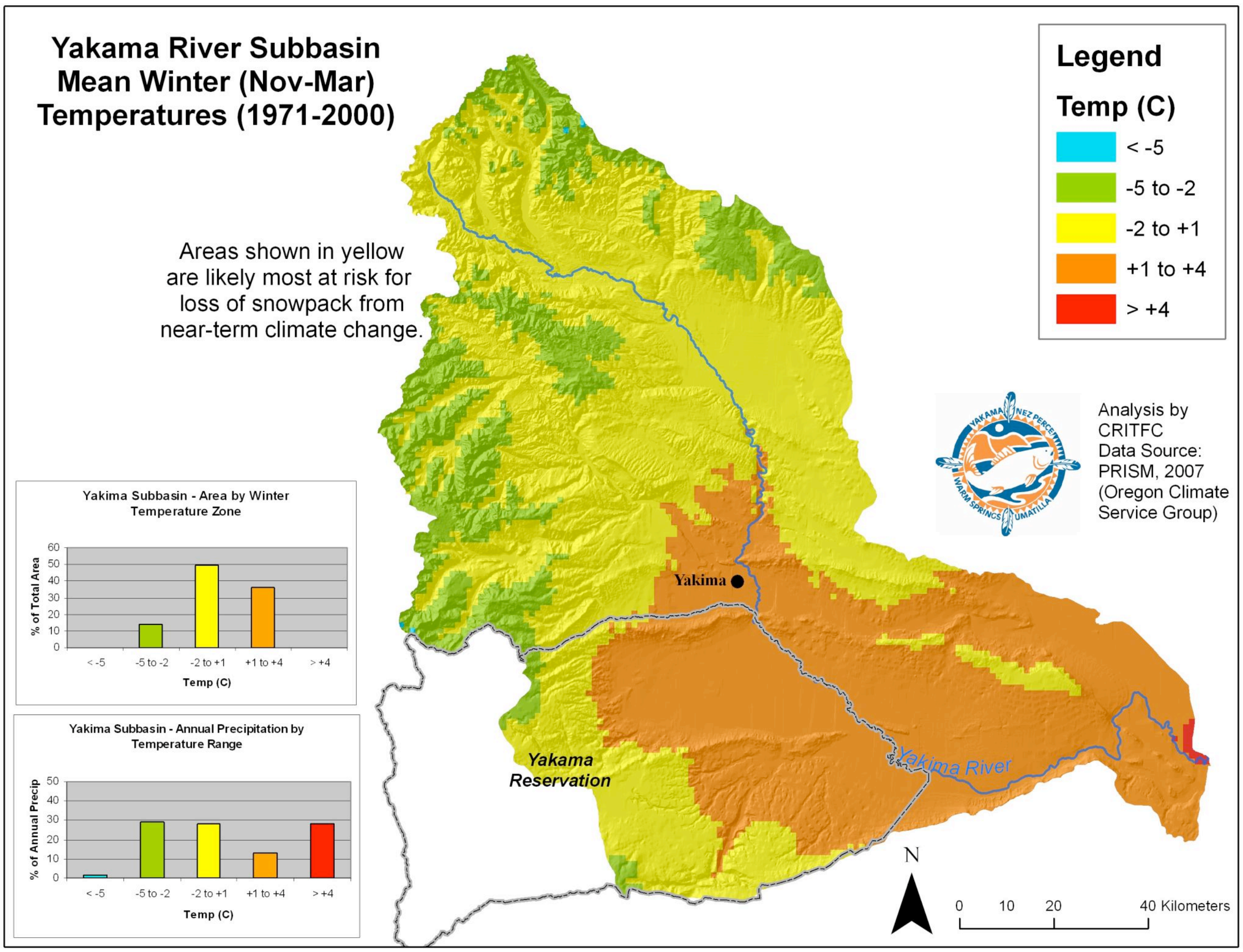

Figure 2: Mean winter temperatures and temperature ranges for annual precipitation in the Yakima River Subbasin (1971-2000)

In the Deschutes subbasin (Figure 3), most of the upper basin (above Bend and the Upper Crooked River) has mean monthly winter (Nov-Mar) temperatures that are near or just below freezing. Only a few areas located around the higher mountains have cooler winter temperatures that should be protected from a near-term increase in temperatures. 31% of the annual precipitation falls when mean monthly temperatures are between +1 and -2 degrees C, meaning that much of the subbasin may shift from a snow-dominated regime to a rain-dominated regime by the middle of this century. However, large portions of the Deschutes subbasin overlay porous volcanic rock, which is an important storage mechanism for water, and a year-round source of cool groundwater inputs into surface streams. We can expect that watersheds with these volcanic rock aquifers, as well as the mainstem Deschutes River, which receives flows from these watersheds, will experience a lower rise in water temperatures because groundwater provides a year-round storage and delivery mechanism for cool water, even when snowpack is lost. More study of this unique area is warranted to better anticipate how climate change may affect stream discharge.

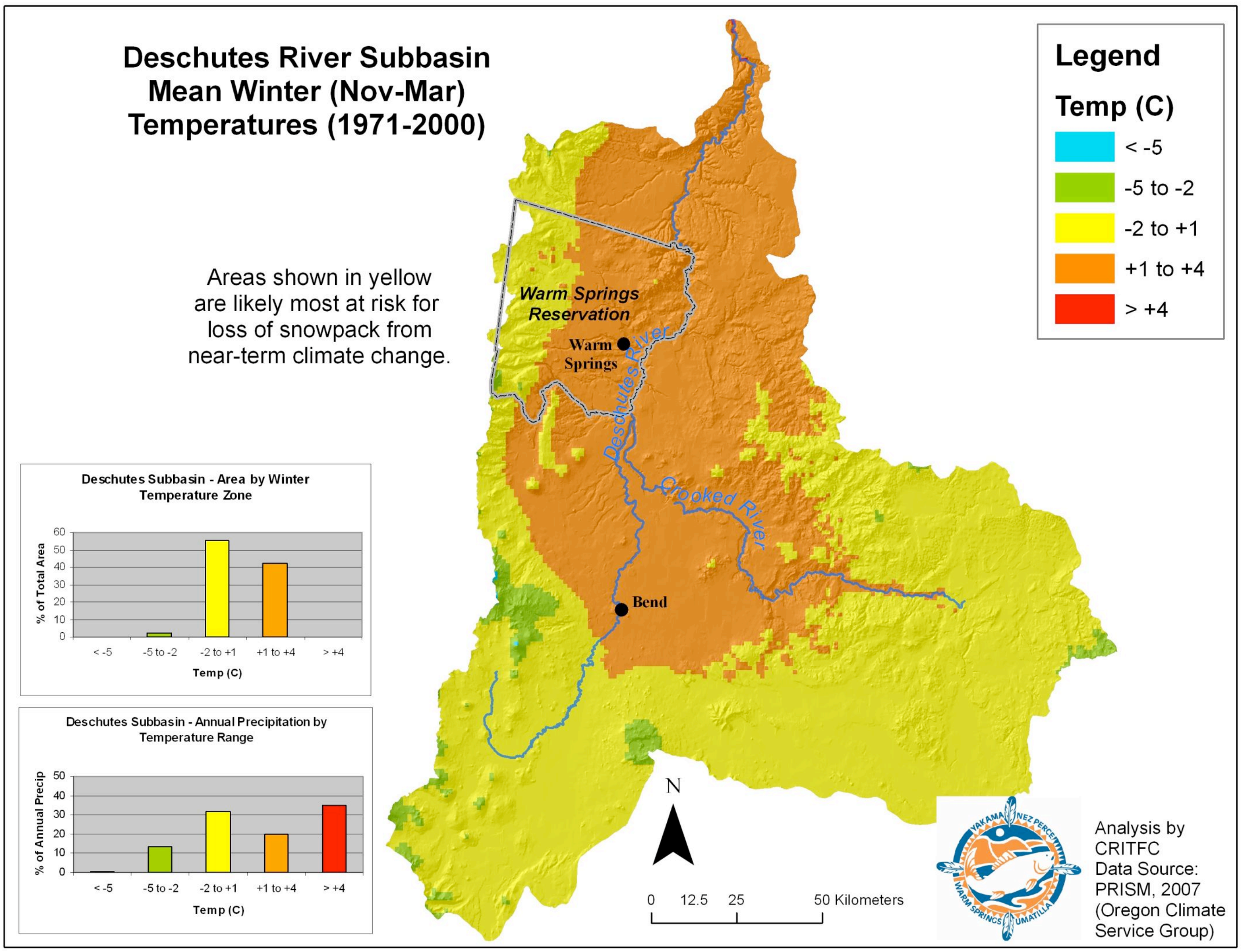

Figure 3: Mean winter temperatures and temperature ranges for annual precipitation in the Deschutes River Subbasin (1971-2000)

In the John Day subbasin (Figure 4), most of the lower river and its forks have mean monthly mid-winter temperatures that are above one degree C, so are not typically snow-dominated regimes, but most of the foothills area above them with the exception of the higher areas of the Blue Mountains, do have moderate mid-winter temperatures that are susceptible to near-term warming. 22% of the annual precipitation falls when mean monthly temperatures are between +1 and -2 degrees C, and precipitation is at risk of changing over to rain rather than snow with a moderate warming of two to three degrees C that is expected by mid-century. Only 14% of precipitation falls during periods of cooler mean monthly temperatures (less than -2 degrees C), meaning that by the mid to late century, the John Day subbasin may receive almost all of its precipitation as rainfall. The mainstem John Day River includes no dams or reservoirs, which places a premium on the benefits of snowpack as a storage mechanism for water withdrawn for irrigation as well as for fish. This subbasin appears to be at a high risk for depleted summer flows and lethal temperatures for salmon if air temperatures increase moderately, as they are expected to do so by mid-century.

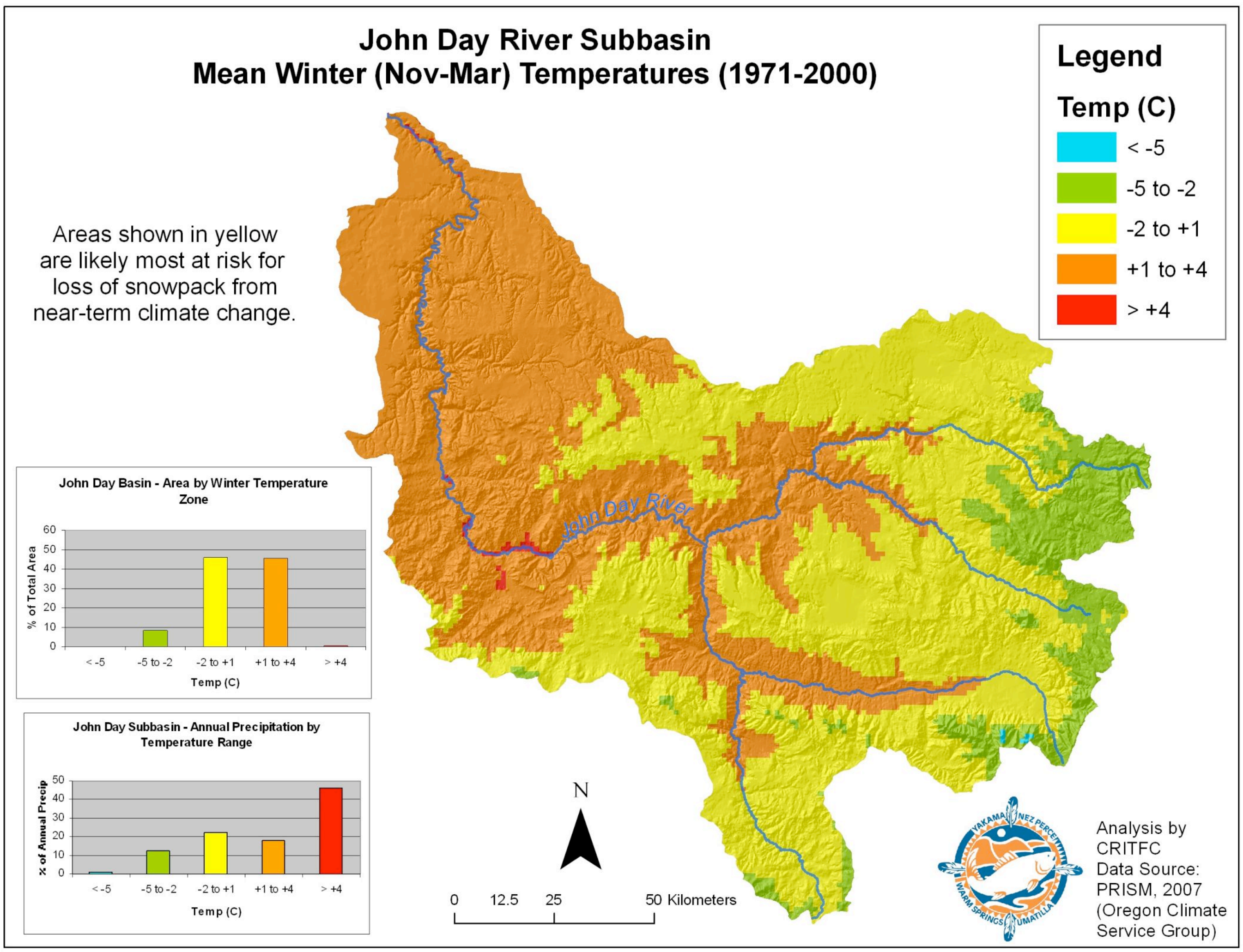

Figure 4: Mean winter temperatures and temperature ranges for annual precipitation in the John Day River Subbasin (1971-2000)

Unlike many other Columbia Plateau subbasins, the Umatilla subbasin (Figure 5) has contemporary temperatures that are warm enough that most of its area already experiences a rain-dominated regime rather than a snow-dominated one. Only the upper portions of the subbasin typically experience mean monthly winter temperatures at or below freezing. Nevertheless, these areas receive a substantial proportion of the annual precipitation of the subbasin, with 20% of subbasin precipitation falling when mean monthly temperatures are between +1 and -2 degrees C, and only 8% falling when mean monthly temperatures are below -2 degrees C. As such, this subbasin is at a high risk of losing most of its seasonal snowpack from near-term climate change. Unlike the other subbasins in this area, it has few high elevation areas that would maintain seasonal snowpack with even moderate warming, and those that exist would be at risk by later this century.

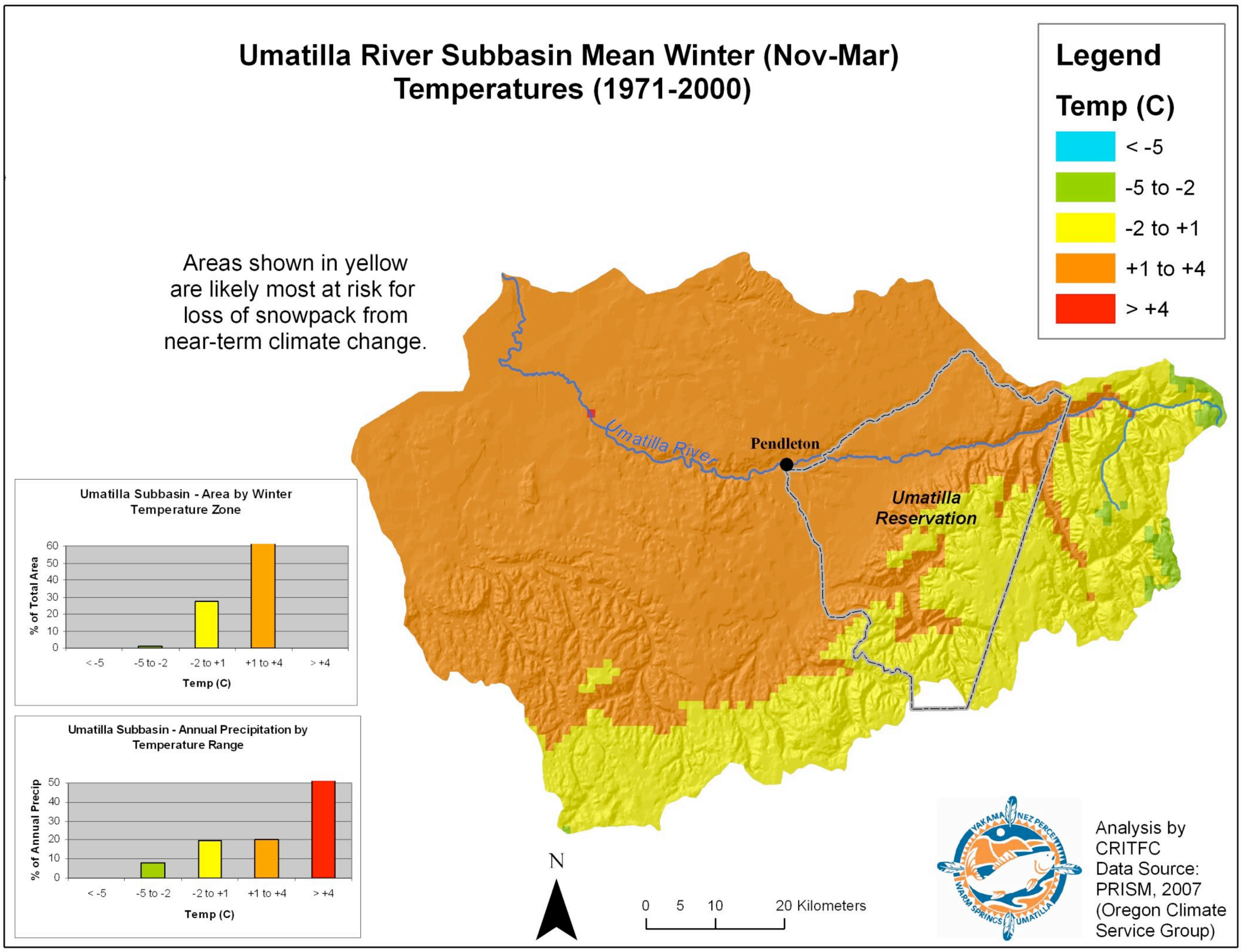

Figure 5: Mean winter temperatures and temperature ranges for annual precipitation in the Umatilla River Subbasin (1971-2000)

The Klickitat subbasin (Figure 6) experiences contemporary winter temperature patterns similar to those of its neighbor, the Yakima subbasin. A large portion of the middle reaches and foothills of the subbasin reflects contemporary mid-winter temperatures near or just below freezing, and are therefore at risk of a transition to a rain-dominated regime from near-term warming. 34% of its annual precipitation falls when winter temperatures are between +1 and -2 degrees Celsius, and aside from the relatively small area around Mt. Adams where winter temperatures are still very cold, the remainder of snowfall mostly occurs in areas where winter temperatures are from -2 to -5 degrees C. Like the Yakima subbasin, the Klickitat subbasin is at high risk of losing much of its seasonal snowpack from 21st century climate change.

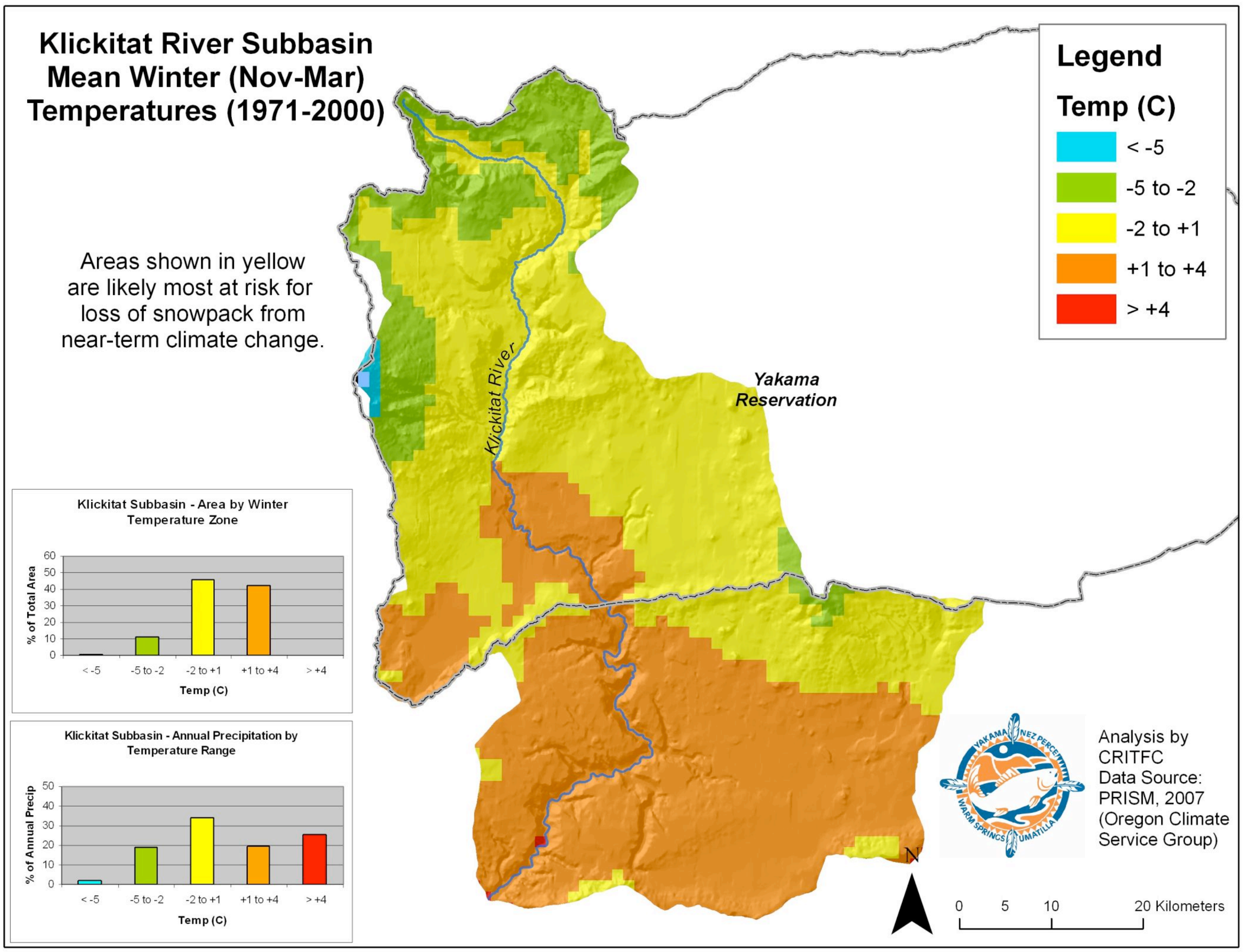

Figure 6: Mean winter temperatures and temperature ranges for annual precipitation in the Klickitat River Subbasin (1971-2000)

The mountains of Idaho generally experience colder winter temperatures than the mountain ranges in Oregon and Washington because of their high mean elevations and continental climates. The map of winter temperatures in the Clearwater subbasin (Figure 7) clearly shows this, with one third of the contemporary annual precipitation falling when mean monthly winter temperatures are less than -2 degrees C, and a substantial portion (10%) falling when these temperatures are less than -5 degrees Celsius. Only 17% of the annual precipitation falls when temperatures are near or just below freezing, meaning that the subbasin is better protected from the effects of near-term climate change than the western subbasins. Nevertheless, air temperatures are projected to increase by three to four degrees C by the end of the century, which could mean that much of this snowfall could transition to rainfall later in the century.

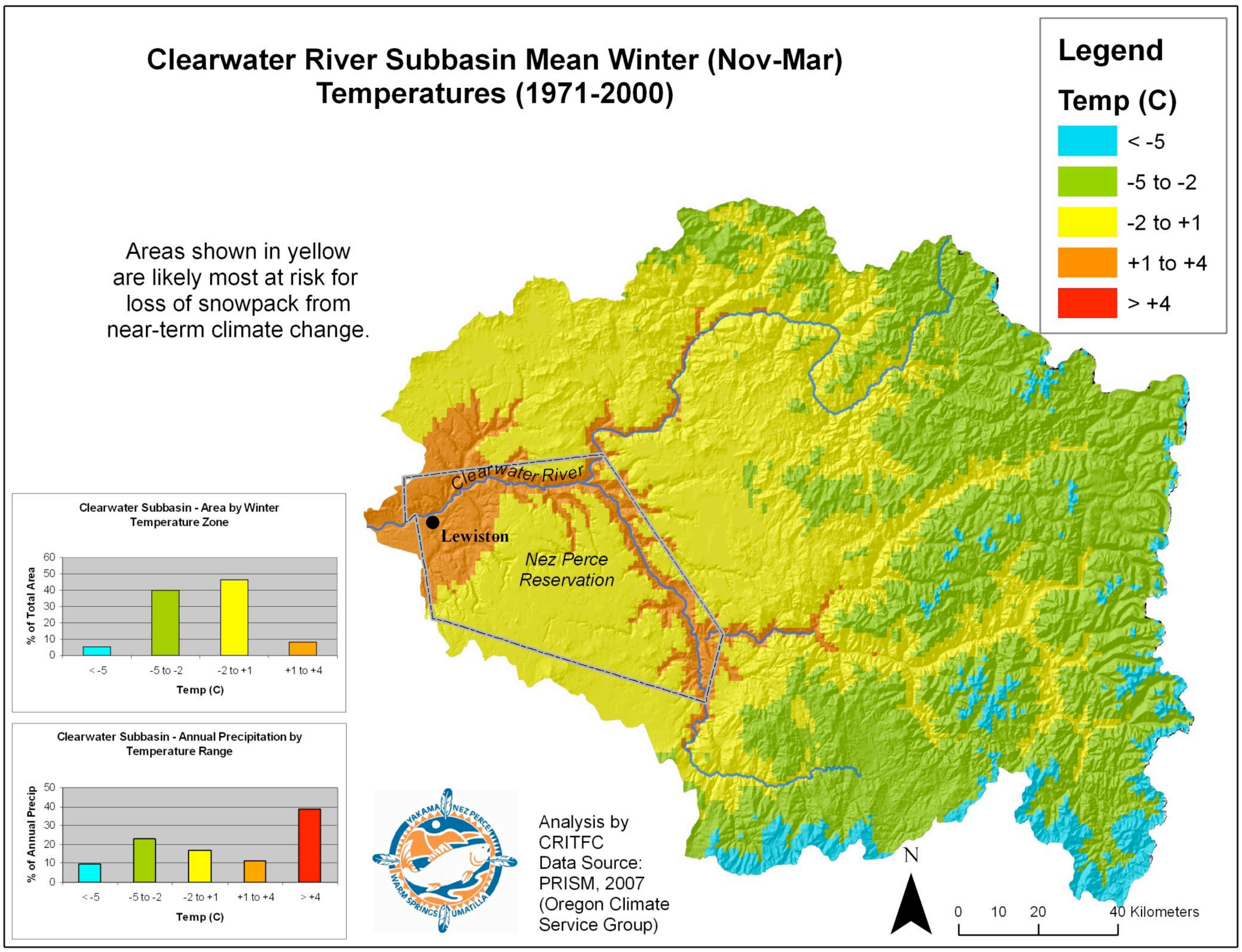

Figure 7: Mean winter temperatures and temperature ranges for annual precipitation in the Clearwater River Subbasin (1971-2000)

Of all of the ceded area subbasins considered in this analysis, the Salmon Subbasin (Figure 8) appears best able to withstand the effects of projected 21st century increases to temperature. The Salmon River Mountains comprise most of the drainage area of the subbasin, and experience very cold winter temperature because of their high elevations and continental climate. Only 9% of contemporary annual precipitation falls when mean monthly temperatures are near or just below freezing (between +1 and -2 degrees Celsius), and 29% falls when these temperatures are less than -5 degrees C. Summer convectional storms appear to be a larger factor in this subbasin, with 35% of the precipitation falling when temperatures are greater than +4 degrees C, a contribution that would presumably not be changed by climate change because it already falls as rain. Because of its cold winter temperature patterns and its large proportion of pristine wilderness habitat, the Salmon subbasin may represent one of the best refuges for salmon to survive under climate change if the passage issues through the Columbia Basin hydrosystem are addressed and these populations are allowed to rebuild themselves.

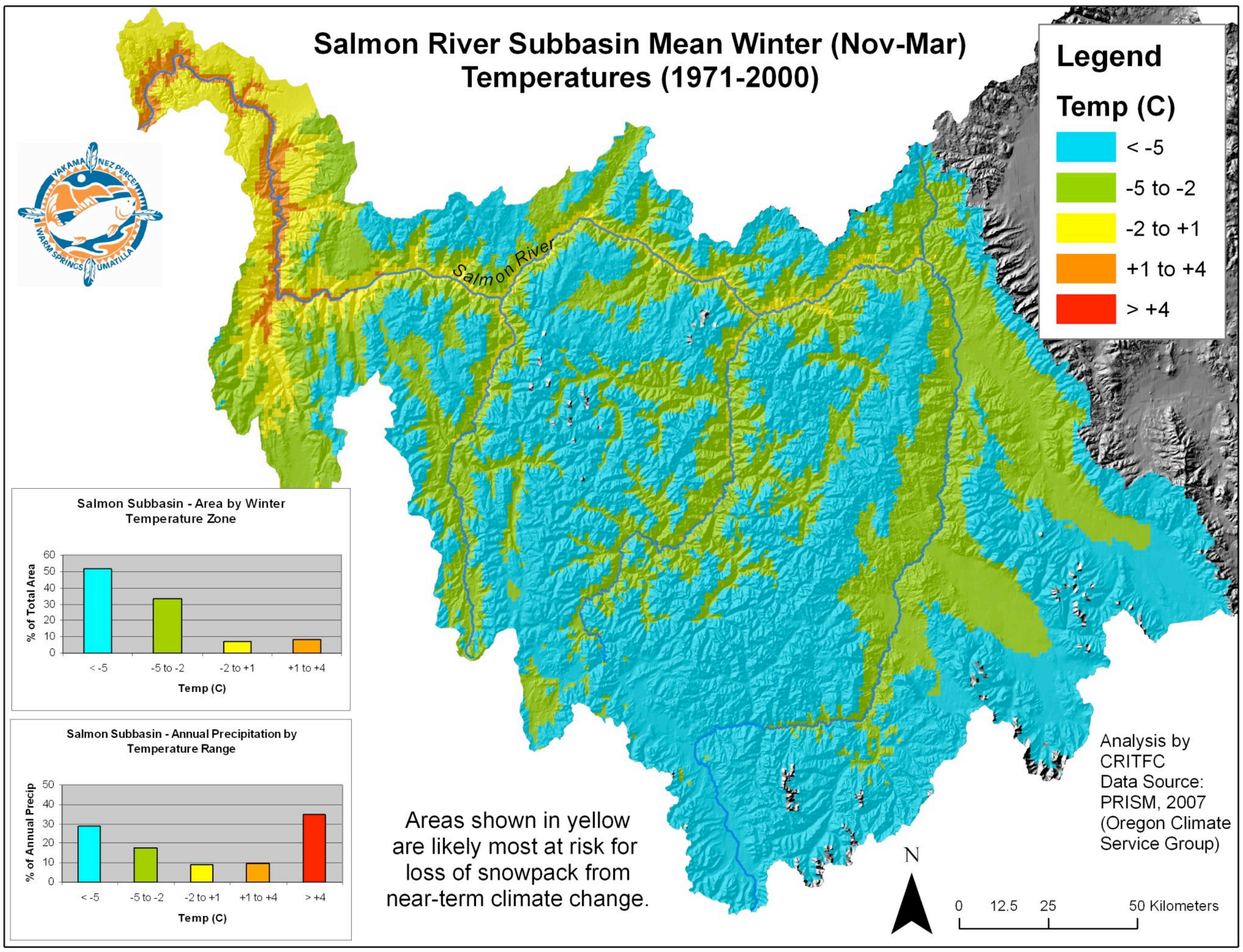

Figure 8: Mean winter temperatures and temperature ranges for annual precipitation in the Salmon River Subbasin (1971-2000)

We produced graphs of monthly input water for select subbasins under four scenarios (1971-2000, 2020s, 2040s, and 2080s) to summarize the results of our monthly precipitation and snowmelt simulations. Input water includes modeled rainfall and snowmelt that occur within a month, and should not be confused with the water surplus from a soil water balance, which wasn't modeled. This input water is the water that is available for soil infiltration and percolation, evaporation, transpiration, and surface water runoff. These data could ideally be used as input into a hydrologic model that incorporates local soil and land cover processes in order to accurately assess changes to surface water runoff. Nevertheless, taken on their own, the subbasin graphs offer general evaluations of how the incoming water into the subbasin may change over future periods with climate change. These water quantities were modeled over a distributed grid across each subbasin area, and are summarized here in acre-feet in Figures 9-15.

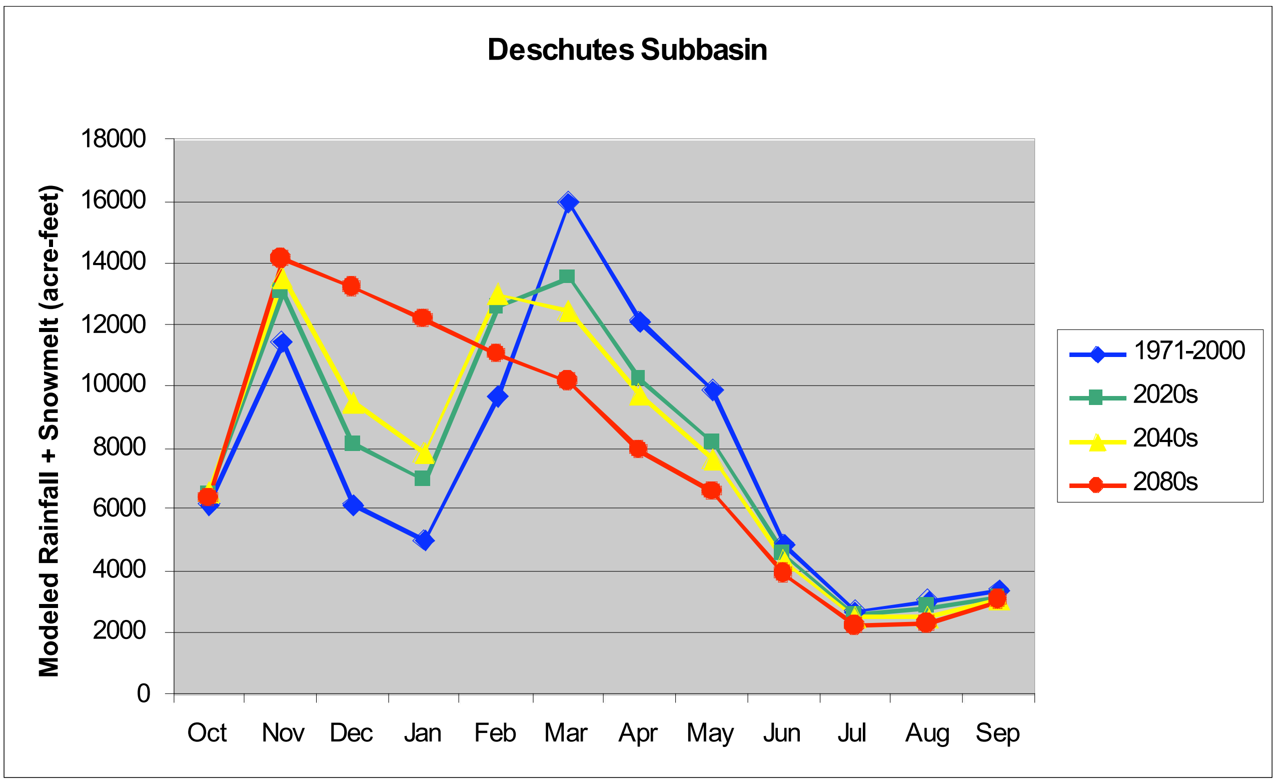

Figure 9: Modeled input water in the Deschutes Subbasin under contemporary and future climate change scenarios

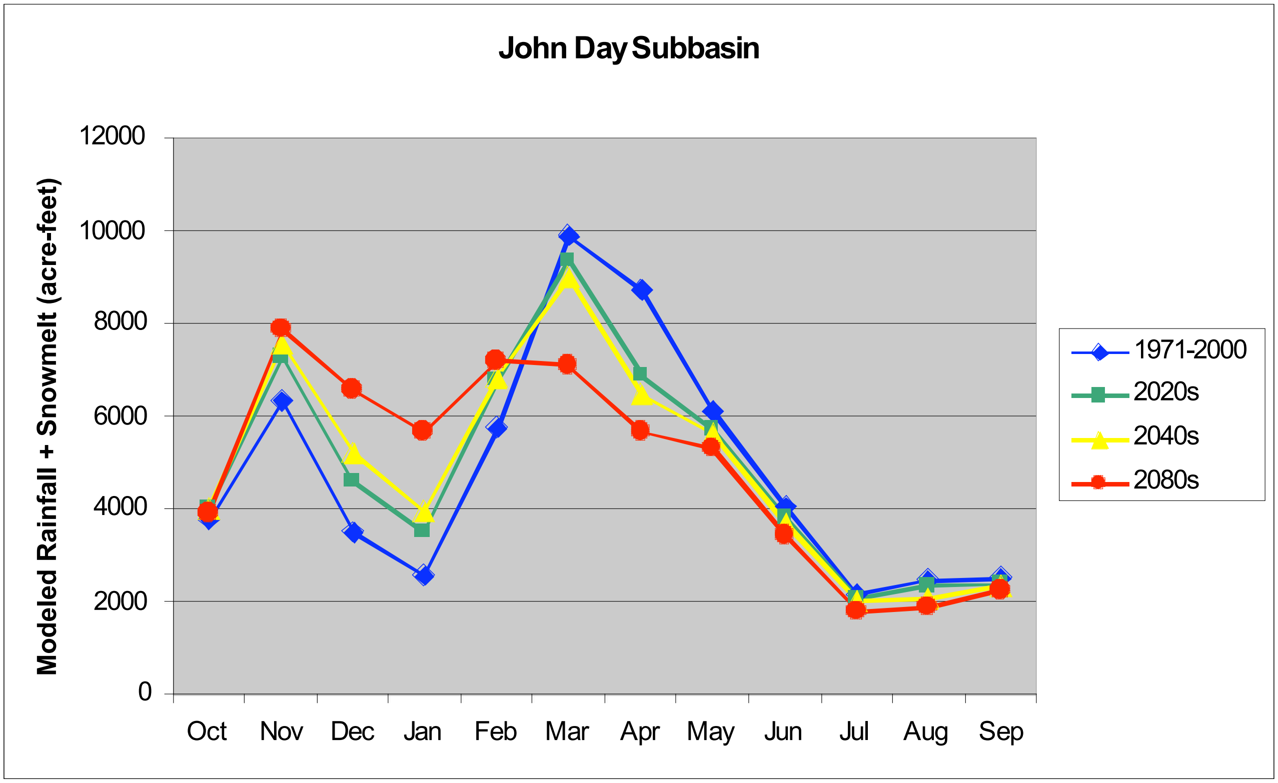

Figure 10: Modeled input water in the John Day Subbasin under contemporary and future climate change scenarios

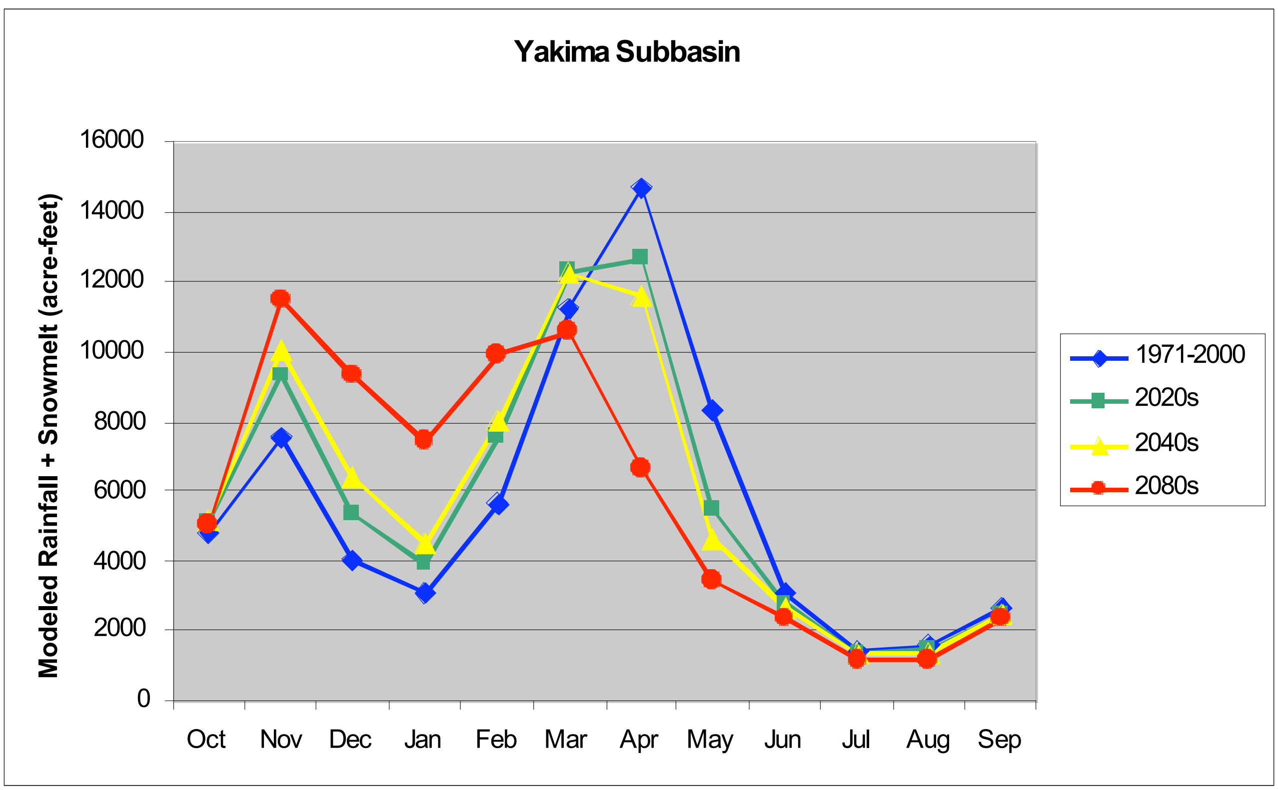

Figure 11: Modeled input water in the Yakima Subbasin under contemporary and future climate change scenarios

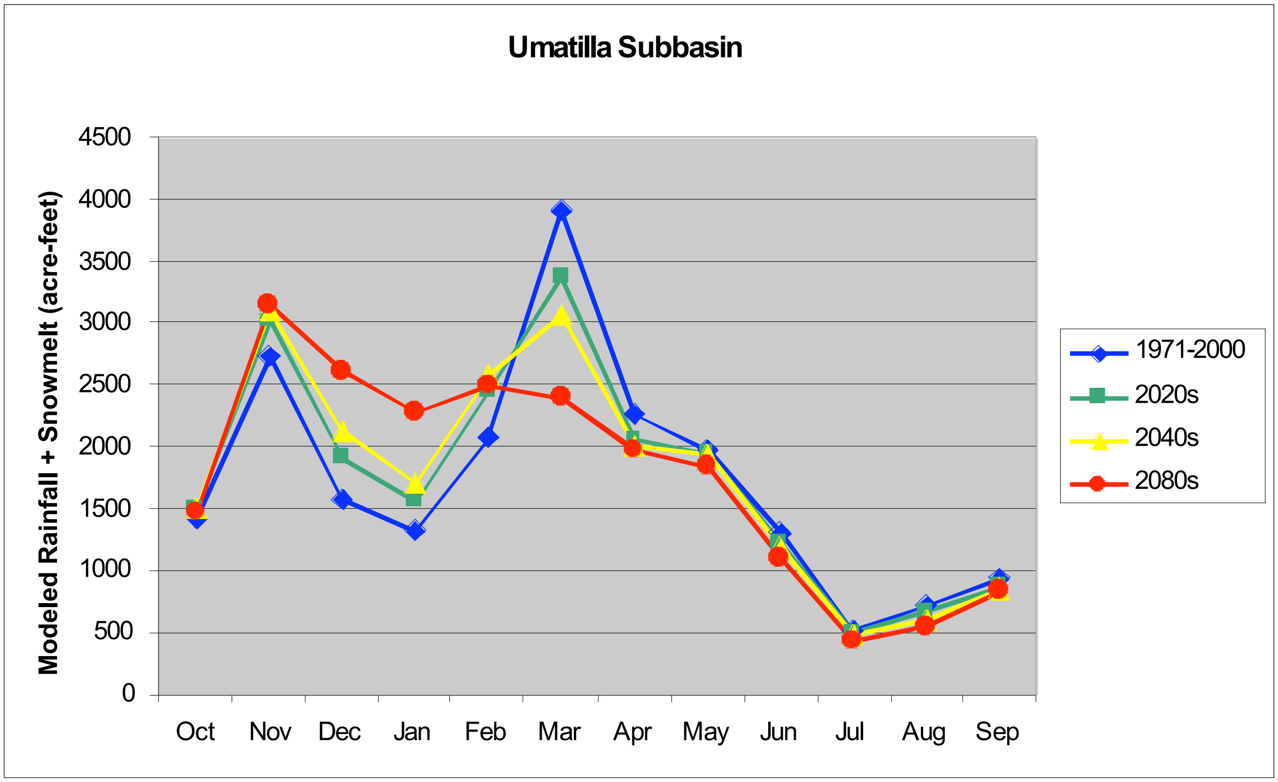

Figure 12: Modeled input water in the Umatilla Subbasin under contemporary and future climate change scenarios

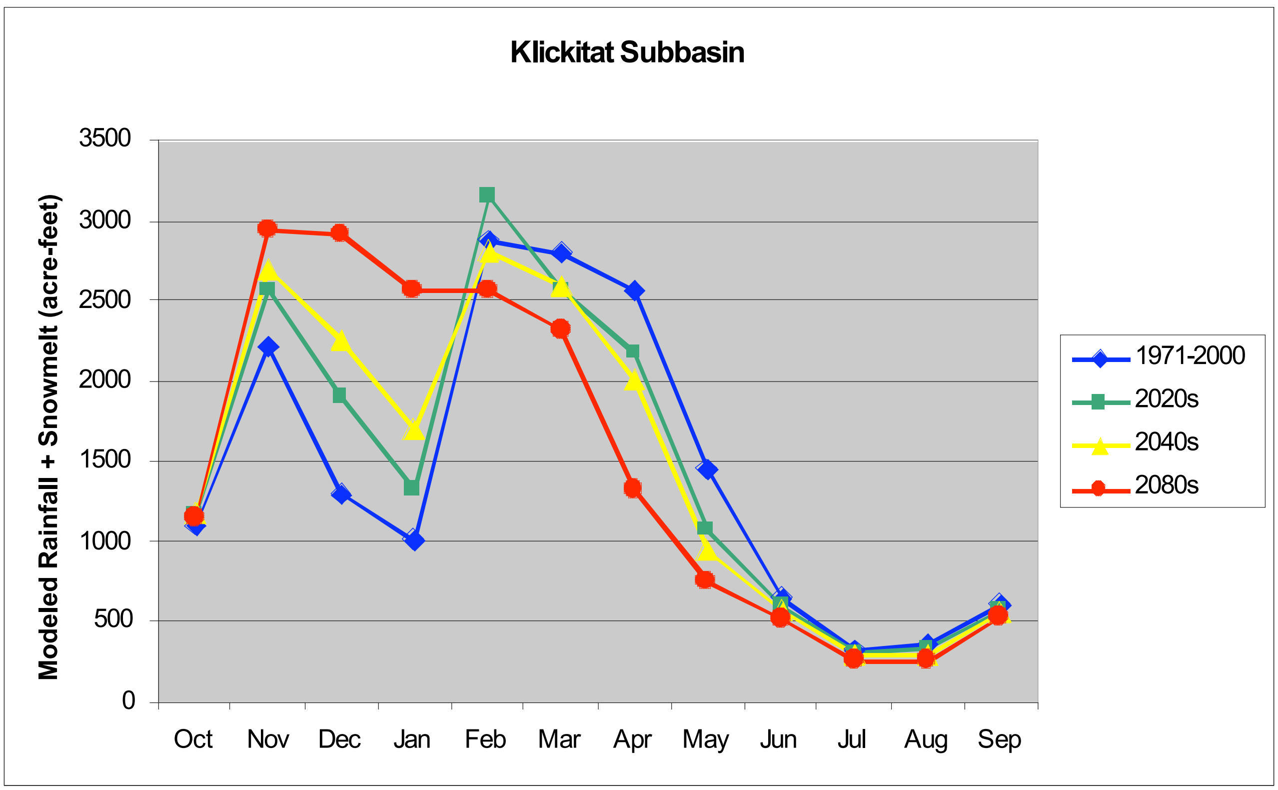

Figure 13: Modeled input water in the Klickitat Subbasin under contemporary and future climate change scenarios

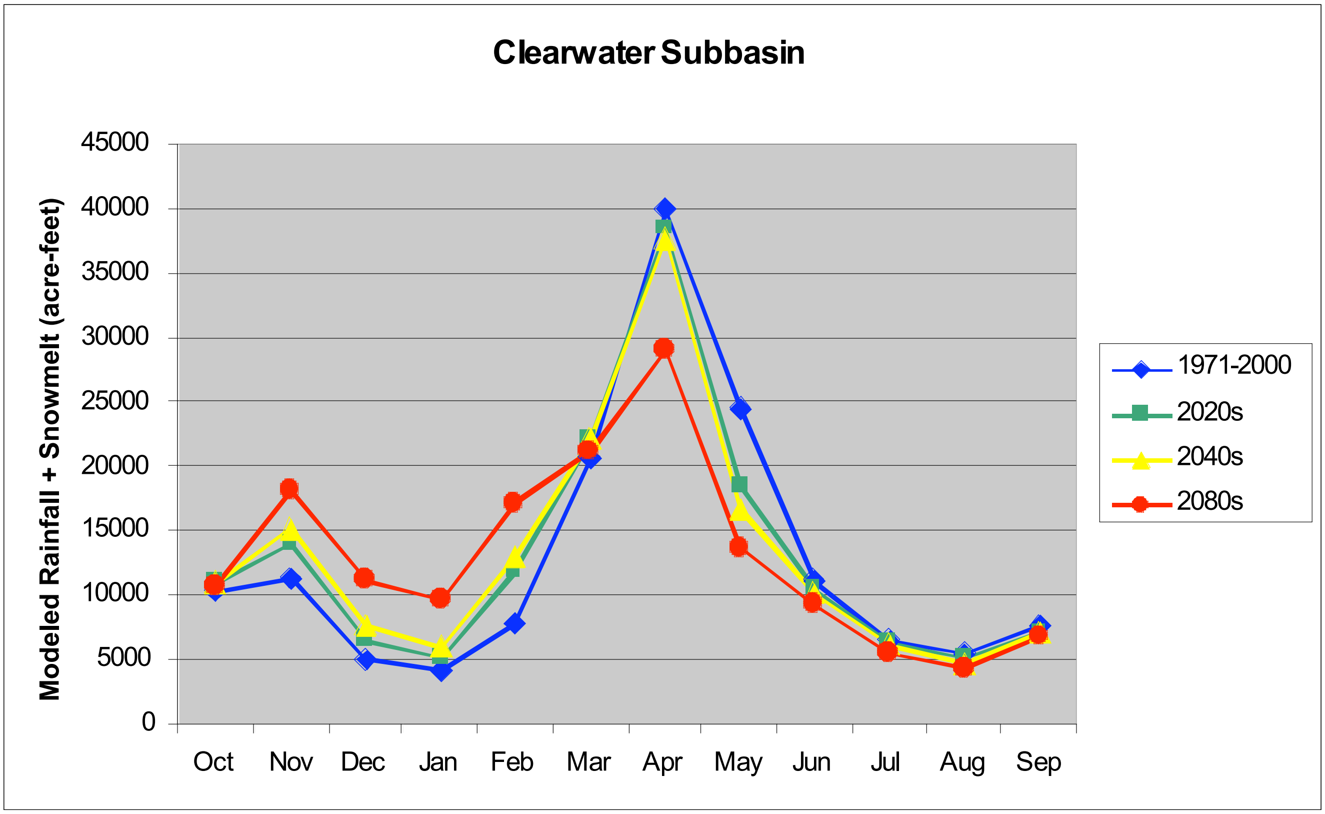

Figure 14: Modeled input water in the Clearwater Subbasin under contemporary and future climate change scenarios

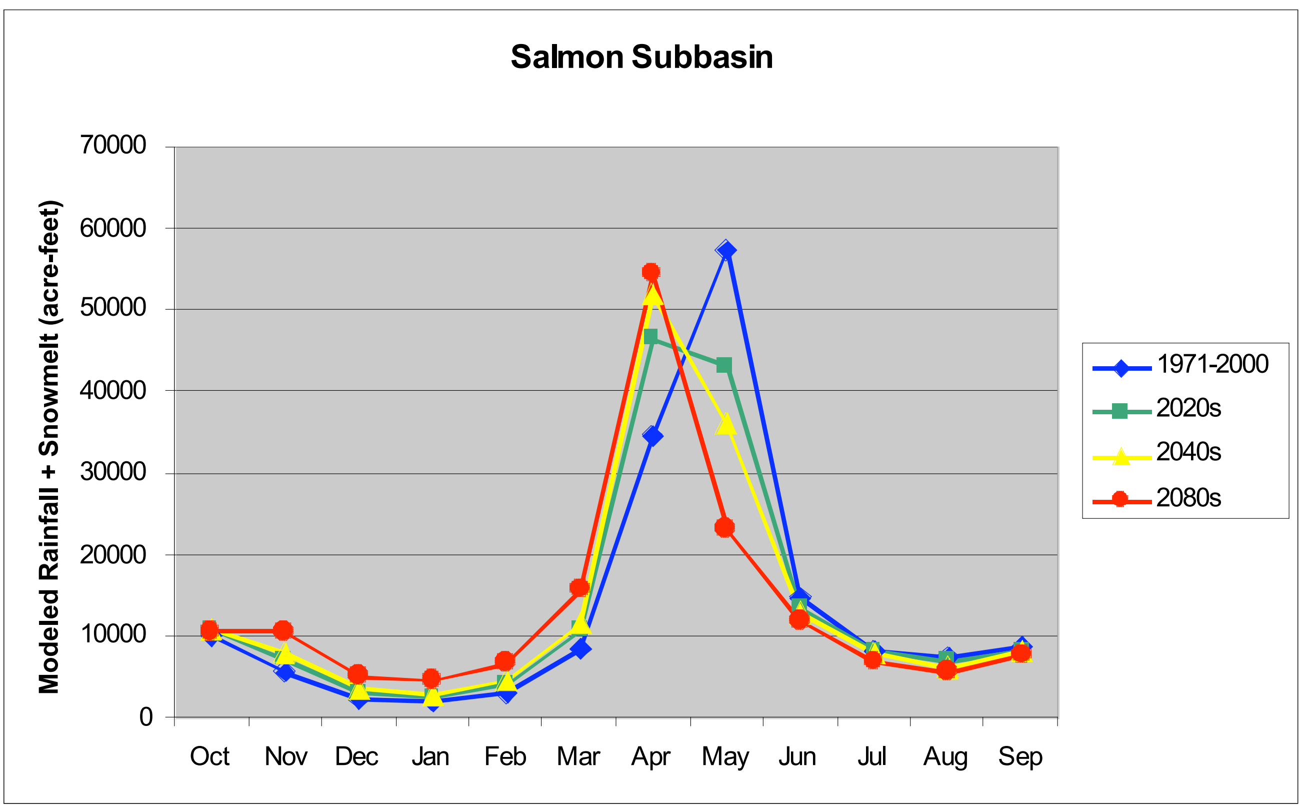

Figure 15: Modeled input water in the Salmon Subbasin under contemporary and future climate change scenarios

The graphs of input water projections show several consistent trends across all subbasins:

First, during the early part of the water years (October-February), combined input water from precipitation and snowmelt is predicted to increase in every subbasin to greater quantities in each successive scenario from contemporary to the 2080s. The data indicate that this is a result of (a) more precipitation falling during these months as rain than snow because of warmer winter air temperatures; and (b) more snowpack melting during these months because of warmer air temperatures; and (c) changes to monthly precipitation quantities projected by the ensemble of global circulation model scenarios. The magnitude of increases to input water vary, though, with western subbasin such as the Klickitat, Deschutes, John Day, and Yakima showing large increases, while the cooler Idaho subbasins (Clearwater and Snake) show small overall increases (although large relative increases).

Second, input water during the summer months (June-September) is projected to decrease in every subbasin to smaller quantities with each successive scenario from contemporary to the 2080s. Rates of decrease are fairly consistent among subbasins, with August input water decreasing in all subbasins by 23% to 27% from the contemporary (1971-2000) to the period of the 2080s. This decrease is from a combined effect of lower 21st century summer precipitation generated by the ensemble GCMs and the virtual disappearance of all late-summer snowpack by the 2080s simulations of this model.

It is during the late winter and spring months, when the greatest river flows from these subbasin currently occur, that results diverge among subbasins. Most subbasins show an overall decrease during this period, except for the Salmon subbasin which registers an increase during March and April greater than its May loss. Indeed the changes to April flows between contemporary and 2080s scenarios vary from a dramatic decrease of around 50% for the Yakima and Klickitat subbasins to a gain of over 58% in the Salmon subbasin.

The most discernible trend is a shift in the month of peak input water in every subbasin, and the notable growth in a preliminary fall-season peak that is projected to occur during the latter part of the 21st centuries. In the western subbasins of the John Day, the Yakima, the Umatilla, and the Klickitat, the month of peak runoff shifts dramatically from late winter or early spring in the contemporary scenario, to a November peak during the 2080s scenario. This November peak is accompanied by a second, smaller peak during late winter or early spring that generally occurs a month earlier in future scenarios then it does in the contemporary scenario. In the Clearwater subbasin, the month of peak input water (April) remains unchanged in all scenarios but diminished in quantity, and a smaller preliminary peak in November still develops. Only in the Salmon subbasin does the shape of the graph remain the same, with a pronounced spring peak, although it shifts one month from May in the contemporary scenario to April by the 2080s. The development of a November peak of runoff during the 21st century is mostly the result of a greater amount of modeled precipitation falling as rain than snow during November. The migration of the late-winter/early spring peak in runoff to earlier in the year is the result of a diminished winter snowpack and earlier snowmelt. If these trends develop, they could both have important consequences for salmon, as well as other water uses.

Finally, it is interesting to look at annual input water. All subbasins showed an increase in annual input water from the contemporary scenario through the 21st century to the 2080s scenario. These increases were generally modest, ranging from a low of 0.3% in the Salmon Subbasin to a high of 5.0% in the Klickitat Subbasin. The source of these increases is solely from the projected increase in precipitation demonstrated in the GCM ensemble simulation. In general, it forecasts precipitation to increase during the winter months and decrease during the summer months. Variations among subbasins occur because these precipitation increases are forecast monthly, and the Idaho subbasins receive a greater proportion of their precipitation from summer convectional storms than the western subbasins. These forecasts are much less predictable, however, than increases to temperature. In addition, this study did not model potential evaporation and transpiration, which will place a greater demand on available water and can be expected to occur more reliably because of higher air temperatures than increases to precipitation, which are less certain.

This analysis suggests that the Columbia River Inter-Tribal Fish Commission should focus on climate change an important issue that may have very disruptive effects in the watersheds of the ceded areas of its member tribes. If temperatures increase as projected during the 21st century, these ceded areas will likely see a sustained and large shift in precipitation from snowfall to rainfall, an earlier seasonal snowmelt, and some changes to the seasonal distribution of precipitation. These effects will almost certainly lead to greater fall and winter water inputs (rainfall and snowmelt) into subbasins, decreasing summer water inputs into subbasins, and shifts in the timing of spring water inputs to earlier in the year, and in many areas, the growth of a preliminary fall peak. The consequent effects will probably be that winter flooding will increase and spring and summer flows will decrease. These shifts will not occur evenly among all areas, and this research suggests that the high-elevation, cool continental climate subbasins of central Idaho may better be able to withstand losses to snowpack than the lower elevation and western subbasins that experience relatively warmer winters. Because this analysis has been produced on a geographic information system, addressing a distributed study area, it is possible to couple these results with specific landscape characteristics in hydrologic models in order to simulate local changes to surface water runoff and the seasonal flows of streams and rivers.

References

Daly, C., R.P. Neilson, and D.L. Phillips. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology* 33: 140-158

Graves, D. and Chang, H. 2007. Hydrologic Impacts of Climate Change in the Upper Clackamas River Basin, Oregon, USA. *Climate Research* 33 (2): 143-158

Independent Scientific Advisory Board (ISAB). 2007. *Climate Change Impacts on Columbia River Fish and Wildlife*. Portland, OR: Northwest Power and Conservation Council

Intergovernmental Panel on Climate Change (IPPC). 2007. *Fourth assessment report – Climate change 2007.* http://www.ipcc.ch/ipccreports/index.htm.

Legates, D. 1991. An evaluation of procedures to estimate monthly precipitation probabilities. *Journal of Hydrology* 122: 129-140

Martin, J., and Glick, P. 2008. *A Great Wave Rising: Solutions for Columbia and Snake River Salmon in the Age of Global Warming*. Seattle, WA: Save Our Wild Salmon – Light in the River Project

Miles, E., A. Snover, A. Hamlet, B. Callahan, and D. Fluharty. 2000. Pacific Northwest regional assessment: The impacts of climate variability and climate change on the water resources of the Columbia River Basin. *Journal of the American Water Resources Association* 36 (2): 399-420

Mote, P.W., E.A. Parson, A.F. Hamlet, W.S. Keeton, D. Lettenmaier, N. Mantua, E.L. Miles, D.W. Peterson, D.L. Peterson, R. Slaughter, and A.K. Snover. 2003. Preparing for climate change: The water, salmon, and forests of the Pacific Northwest. *Climatic Change* 61: 45-88

Natural Resources Conservation Service (NRCS). 2007. Oregon Snow Survey Program. http://www.or.nrcs.usda.gov/snow/.

Oregon Climate Service. 2007. PRISM Climate Data. http://www.ocs.oregonstate.edu/index.html.

Regonda, K.S., Rajagopalan, B., Clark, M., and Pitlick, J. 2005. Seasonal shifts in hydroclimatology over the Western United States. *Journal of Climate* 18: 372-384

Semadeni-Davies, A. 1997. Monthly snowmelt modelling for large-scale climate change studies using the degree day approach. *Ecological Modelling* 101: 303-323

University of Washington Climate Impacts Group (UWCIG). 2007. Projections for 21st Century Climate Change. http://www.cses.washington.edu/cig/