Climate Change Impacts on Water Management and Irrigated Agriculture in the Yakima River Basin, Washington, USA

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Abstract

The Yakima River Reservoir system supplies irrigation water to over 180,000 irrigated hectares (450,000 acres). Runoff is derived mostly from winter precipitation in the Cascade Mountains, much of which is stored as snowpack and runs off in the spring and early summer. Five reservoirs within the basin have cumulative reservoir storage of approximately 30% of the river's mean annual flow. Climate change during the 21st century is expected to result in earlier snowmelt runoff, and reduced summer flows. The effects of these changes on irrigated agriculture in the basin were simulated using a hydrological model driven by downscaled climate scenarios from 20 climate models, output of which was archived by the 2007 IPCC Fourth Assessment Report. In general, we find that the basin transitions to earlier and reduced spring snowmelt as the century progresses, which results in increased curtailment of water deliveries, especially to junior water rights holders. Historically, the Yakima basin has experienced water shortages (years in which substantial prorating of deliveries to junior water users was required) in 14% of years. Without adaptations, for the A1B emission scenarios, water shortages that occur in 14% of years historically increase to 32% (15% to 54% range) in the 2020s, to 36% in the 2040s, and to 77% of years in the 2080s. For the B1 emissions scenario, water shortages occur in 27% of years (14% to 54% range), in the 2020s, 33% for the 2040s and 50% for the 2080s. Furthermore, the historically unprecedented condition in which the senior water rights holders suffer shortfalls occurs with increasing frequency in both the A1B and B1 climate change scenarios. Economic losses include lost value of expected annual production in the range of 5% to 16%, with significantly greater probabilities of annual net operating losses for junior water rights holders.

1. Introduction

The Yakima River basin is an agriculture-rich region in central Washington State (Figure 1) that contains the largest agricultural economy in the state (US Bureau of Reclamation , 2002). Most crops in the basin are irrigated. Thirty-four percent of the irrigated land in the three counties included within the basin is planted in tree crops and vineyards. The remainder is mostly planted in forage, pasture, and annual vegetable and field crops, but also includes specialty crops such as mint and hops (USDA, 2004). The U.S. Bureau of Reclamation (USBR) operates a system of five reservoirs (Figure 1; Table 1) that supply water to the basin. Much of the basin's runoff is derived from mountain snowpack and the reservoirs are small enough that they generally fill in the springtime of most years (USBR, 2002).

Climate change is expected to cause continued decline in snowpack and earlier snowmelt resulting in reduced water supplies. Analysis of past observations suggests that this process is already underway (Mote et al, 2005). Previous studies have shown that the Washington Cascade Mountains, from which the Yakima River drains, are likely to lose about 20% of their April 1st snowpack with 1°C (1.8°F) of warming (Casola et al, 2008), and an accompanying study (Elsner et al, 2009, this report) suggests that for the Yakima basin, a similar temperature-snowpack sensitivity can be expected. Using +1ºC and +2ºC warming scenarios, Mastin (2008) showed a 12 and 27% decrease, respectively, in snowmelt within the basin over a base period 1981-2005. Because the reservoir system is relatively small (total reservoir storage is about 30% of the mean annual flow of the river), and because the snowpack is highly sensitive to even modest warming, water deliveries from the reservoir system have been sensitive to even small departures from

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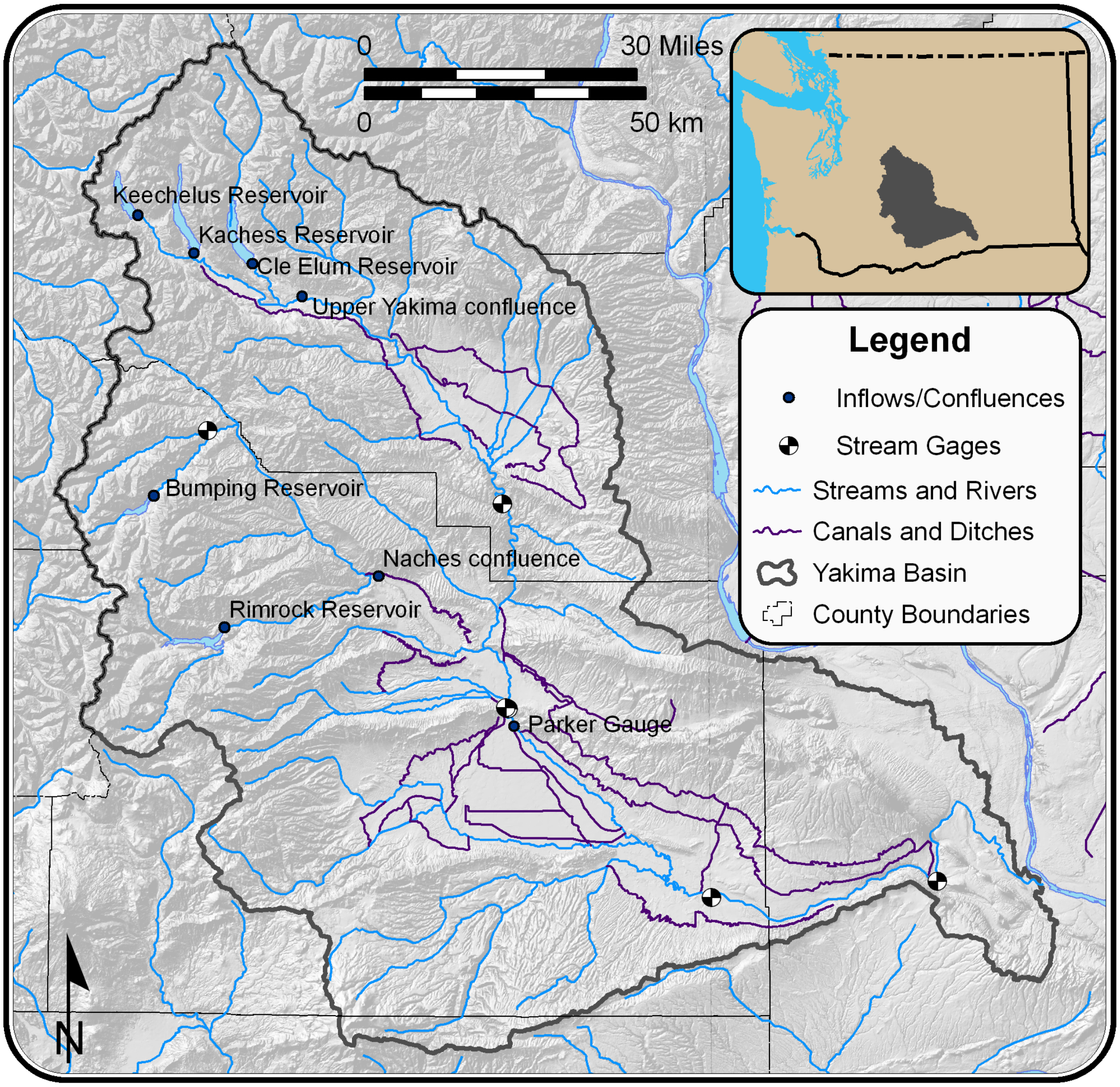


Figure 1. Yakima watershed. Reservoir inflow locations used in the water management model are specified, including five reservoirs, two confluences, and the gage near Parker.

Table 1. Physical properties of the Yakima River reservoir system

	Elevation of Reservoir Sill (ft)	Drainage Area (miles^2)	Reservoir Capacity (AF)	Percent of Total Water Supply (%)	Ratio of average runoff to reservoir capacity
Bumping	3426	70.7	33700	13	6.2:1
Cle Elum	2223	203	436900	42	1.5:1
Kachess	2254	63.6	239000	12	0.9:1
Keechelus	2427	54.7	157800	13	1.5:1
Rimrock	2766	187	198000	20	1.8:1

*Values provided by Reclamation (USBR, 2002) average historic conditions.

Most assessments of climate change impacts on agriculture have focused on annual crops, although some studies have addressed impacts on perennial crops as well, and are relevant to the high-valued tree crops and vineyards of the Yakima basin. Using a statistical model, Lobell et al. (2006) found that climate change would reduce yields of four California perennials (almond, walnut, avocado, and table grape) by 2050, even without consideration of climate change impacts on irrigation water availability. Projected losses ranged from 0 to more than 40% depending on the crop and the particular climate change scenario.[1] Scott et al. (2004a, b) analyzed effects of periodic droughts in the Yakima basin, and found substantial reductions in crop yields and increases in economic risk both in dry years with current climate, and in a future climate with 2°C warming and no change in annual precipitation.

Since the 1970s, water managers in the Yakima Basin have managed water supply using regression-based forecasts of Total Water Supply Available (TWSA). TWSA is defined by the USBR as “the total water available for the Yakima River basin above Parker for the period April through September” (USBR, 2002). It accounts for a combination of measures including forecasted runoff, reservoir storage contents, and projected return flow. These forecasts are issued by the USBR Yakima regional field office starting in the beginning of March and are updated every month (USBR, 2002). This management strategy implicitly assumes that the historic conditions - on which regression parameters for their water supply forecasts are based - will persist in the future. As indicated by Milly et al. (2008), assumptions based on a stationary climate may no longer be tenable.

To provide a better understanding of how the Yakima River reservoir system may respond to climate change, we used future climate scenarios that were archived as part of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007). The methodology of selecting general circulation models (GCMs) is described in detail by Mote and Salathé (2009, this report). The scenarios are based on two global emissions scenarios A1B and B1. B1 has lower CO_2 emissions than A1B and therefore results in less projected warming for the region. The emissions scenarios are quite similar until about mid-century, with differences evolving mostly thereafter (SRES, 2007; Mote and Salathé, 2009, this report). Climate change projection departures from the 1970-1999 climatology were averaged over the 2020s (average of 2010-2039), 2040s (average of 2030-2059), and 2080s (average of 2070-2099). A delta method approach incremented historical precipitation and temperature on a monthly basis to produce scenarios of future climate that were used as input to a hydrology model, which produced scenarios of future Yakima River streamflow at selected reservoir inflow points for the climate of the 2020s, 2040s, and 2080s. Elsner et al. (2009, this report) describe the approach in more detail. We specifically focus here on how the projected hydrologic changes in the Yakima River basin affect reservoir operations and alter water availability for junior and senior water rights users (Section 4). We then investigate how these shifts in reservoir system performance impact economic crop value by application of crop

[1]They did not model CO_2 fertilization effects or any adaptation measures on the part of farmers. Note that the uptake of adaptive actions like adopting heat-tolerant varieties is likely to proceed more slowly in long-lived crops than in annual crops.

models to projected irrigation water releases for future climate scenarios (Section 5).

2. Site Description

The Yakima River basin drains the east side slope of the central Washington Cascade Mountains (Figure 1). Climate varies strongly within the basin. Mean-annual precipitation averaged over 1970-2000 ranged from 203 to 356 cm (80 to 140 inches) along the Cascade Crest headwaters to less than 25 cm (10 inches) at the basin outlet. Most of the annual precipitation (61-81% depending on the particular year) falls in the cool season between October and March (USBR, 2002; WRCC, 2007).

The five major USBR reservoirs in the system are Bumping Lake [established 1910], Cle Elum [1933], Kachess [1912], Keechelus [1917], and Rimrock/Tieton Dam [1925] (USBR, 2002). They have a combined total capacity of 1.2 billion cubic meters (bcm) (1.07 million acre-feet, maf), which is approximately one-third of the average annual unregulated flow of the Yakima River basin at its mouth at the Columbia River. Annual discharge is estimated to be 4.2 bcm (3.4 maf) per year, as averaged from 1961-1990. The reservoirs vary in their upstream drainage area, capacity, and contributions to total basin water supply as shown in Figure 1 and Table 1; however, the capacity of the system is such that the reservoirs generally refill every year. In managing the refill cycle, USBR must carefully balance reservoir outflow to avoid potential flooding while still capturing water for use throughout the dry summer months. The irrigation season begins in April (some water use starts in March), therefore in the early spring and summer, the snowpack effectively acts as a sixth reservoir, which augments the reservoir storage so that reservoirs do not need to be drawn down until June (USBR, 2002). However, in some low snowpack years, such as 1992-1994, 2001, and 2005, reservoir storage has been insufficient to meet demands, and in these years, water was allocated to junior users based on prorating according to the seniority of their water rights and the TWSA, a process described in more detail below.

Notwithstanding consideration of possible spring flooding and maintenance of instream flows in the operating policies that dictate reservoir releases, the system's primary operating purpose is to supply irrigation water. Maintenance of in-stream flows for protection and enhancement of native and anadromous fish, however, has changed reservoir operating policies somewhat in recent years. In 1994, legislation was enacted for a river basin water enhancement project with approximately $200 million allocated for fishery and irrigation system efficiency improvements including fish ladders and other infrastructure projects. Since then, various other management actions have been proposed and/or implemented to enhance storage, recreation, and fish and wildlife habitat. The final planning report for the Yakima River Basin Water Storage Feasibility Study (2008) provides an overview of these water management policies and projects.

Water withdrawals typically begin in March, but reservoirs generally do not reach their maximum storage volumes until June. Reservoir storage at Cle Elum and Keechelus is usually lowest in September when outflows are reduced to the instream flow maintenance levels. Kachess and Rimrock usually continue to draft into October in order to maintain specific flow levels throughout the winter months on reaches of the Cle Elum and Teanaway Rivers to increase the likelihood of successful spawning of several endangered species of salmon (USBR, 2006). This management strategy, implemented as a component of the 1980 Quackenbush Decision, is intended to encourage spring Chinook salmon to spawn at relatively low flows, so that lower flows are required to keep redds (egg nests) covered in winter (USBR, 2002). This is primarily accomplished by limiting irrigation releases from the Cle Elum Reservoir and increasing flows from Rimrock Reservoir to compensate. This switch in reservoir releases in early September is commonly known within the basin as "flip-flop."

Water allocations within the basin are based on seniority according to the 1945 Consent Decree by the District Court of Eastern Washington (as referenced in USBR, 2002). In low runoff years, not all water demands can be met; therefore water is first allocated to the senior (non-proratable, indicating they receive their total entitlement every year) water right holders and then to junior (proratable)water users. Therefore, water availability for irrigators with junior water rights is a measure of how well the system meets its nominal water demands. The system's total reservoir capacity is 1.25 bcm (1.07 maf), whereas the annual diversions allocated by the Consent Decree is approximately 2.57 bcm (2.2 maf), of which about half is allocated to senior, non-proratable water users. Because the reservoirs historically capture only about 30% of the annual unregulated flow of the Yakima River near Parker, this discontinuity is typically compensated by unregulated flow, much of which is derived from snowpack.

Between 1970 and 2005, water allocations have been restricted for junior water users in 13 years. The lowest prorating levels for junior water users, defined as the portion of their water right they can expect to receive in the upcoming irrigation season, was in 1977 with prorating of 6-26% in May and 13-50% in June; these ranges proved controversial and increased later in the season when reservoir inflow forecasts were revised (Glantz, 1982; USBR, 2002). This drought resulted in a court ruling (Acquavella Adjudication, Case No. 77-2-0148-5 in the Superior Court of Yakima County) that continues to impact water management in the basin (Glantz, 1982; Kent, 2004). In general, when prorating levels are greater than 75%, shifting the start and end of the irrigation season can compensate for water limitation impacts. When prorating levels drop below 75%, however, decisions become more challenging at the farm level in terms of how to apportion limited water to specific crops.

The Yakima basin currently has a water-trading program that began in 2001 and is activated in drought emergencies as declared by the state of Washington. It is intended to relieve the impact of drought on junior water rights holders by providing a mechanism for voluntary transfers of water from interruptible or low-valued to higher-valued uses. The water-trading program is supervised by the Washington State Department of Ecology and was active in both the 2001 and 2005 drought years (Scott et al. 2004, Anderson et al. 2006). The program generally has the effect of creating an economic market that diverts water in low runoff years from low-valued annual crops (which are fallowed), to high-valued perennial crops. There are nonetheless numerous institutional and "plumbing" complications in the application of this program. These include the inability to move water to junior water rights holders in some parts of the basin. Furthermore, legally, water trades must not adversely affect outflow from the basin (as measured near Parker), and must not have adverse third-party impacts such as reduced flows for fish (Yakima River Basin Conservation Advisory Group 2002, Isley 2001). Finally, only irrigation districts can purchase water on behalf of irrigators. Nonetheless, the Sunnyside Valley Irrigation District, which has a mix of senior and junior water rights holders, and the Roza Irrigation District, which has primarily junior water rights holders, have been able to make good use of the water trading program. The Washington Department of Ecology Yakima Basin website (2009) provides background and discussion of current water-trading and water-banking activities in the basin.

3. Approach

We use a multi-model ensemble approach similar to that described in the accompanying papers by Elsner et al. (2009, this report) and Vano et al. (2009a, this report) to explore climate impacts on the Yakima River reservoir system (Figure 2). Spatially and temporally complete daily records of historic and future streamflows were simulated using the Variable Infiltration Capacity (VIC) macroscale hydrology model, forced with both gridded historical observation data, and downscaled future climate scenarios. Both historical data and future climate scenarios are described in accompanying papers by Mote and Salathé (2009, this report) and Elsner et al. (2009, this report). Note that each downscaled scenario in fact consists of the historical (daily) precipitation and temperature for 1916-2006, but adjusted on a monthly basis to reflect predicted changes for the 2020s, 2040s or 2080s (delta method); these adjusted precipitation and temperature sequences were then used as forcings to a hydrology model to produce daily streamflow sequences as described in Elsner et al (2009, this report). Summary statistics and information about the climate scenarios are included in Table 2. The streamflows simulated by the hydrological model for both historical and future climate were used as input to the water management model described in Section 3.2. The water management model computes the amount of prorating (if any) that is required at each model time step (daily). These prorating values are then used in the subsequent agricultural and economic analysis (Section 5).

3.1. Climate and Hydrologic Information

Inflow sequences for the historical period from 1916 to 2006 as well as selected future climate periods were simulated using the VIC hydrology model as described in Elsner et al (2009, this report). Streamflows were produced at locations shown in Figure 1, which are required by the water management model. In general, these points represent inflows to the five reservoirs, as well as inflows below the reservoirs. Future streamflow were provided as quasi-stationary sequences as projected by climate models for the 2020s, 2040s, and 2080s, with more focus on the near-term 2020s simulations. For the 2020s, we ran the water management model with each of 20 streamflow sequences downscaled from individual GCMs for IPCC emissions scenario A1B, and 19 for B1. We also use composites that effectively represent the best estimate of 2020s, 2040s, and 2080s climate

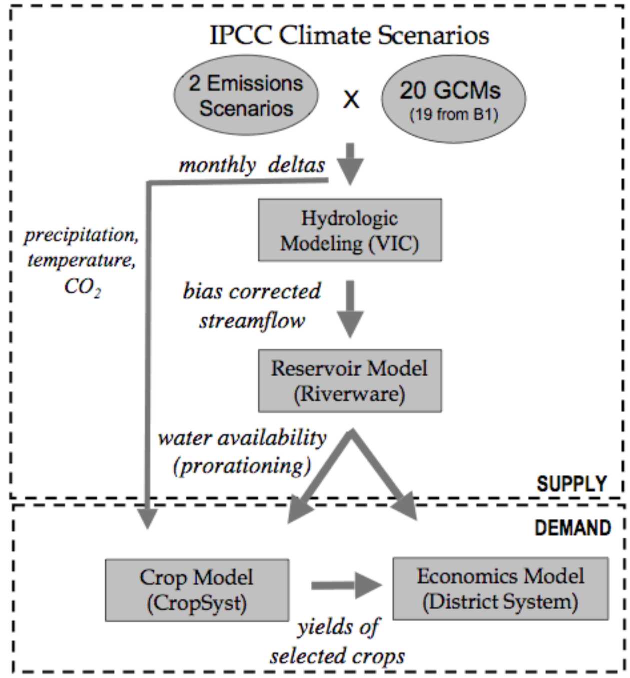


Figure 2. Multi-model process. Schematic of how climate model projections, hydrologic model, and water management models are connected.

Table 2. Annual temperature and precipitation for climate change scenarios.

	2020s (2010-2039)		2040s (2030-2059)		2080s (2070-2099)	
	A1B	**B1**	**A1B**	**B1**	**A1B**	**B1**
% Change in Annual Precipitation	+0.22%	+1.9%	+2.1%	+2.2%	+4.9%	+3.4%
% Change in Cool Season Precipitation	+2.3%	+3.3%	+5.4%	+3.9%	+9.6%	+6.4%
% Change in Warm Season Precipitation	-4.2%	-0.9%	-5.0%	-1.3%	-4.7%	-2.2%

Notes: Cool season defined as October through March, while warm season is defined as April through September.

	2020s (2010-2039)		2040s (2030-2059)		2080s (2070-2099)	
	A1B	**B1**	**A1B**	**B1**	**A1B**	**B1**
Change in Annual Temperature (°C)	+1.18	+1.08	+2.05	+1.57	+3.52	+2.49
Change in Cool Season Temperature (°C)	+1.05	+1.01	+1.83	+1.42	+3.24	+2.33
Change in Warm Season Temperature (°C)	+1.31	+1.16	+2.26	+1.71	+3.79	+2.66

averaged for the GCMs for each of the two emissions scenarios.

We removed remaining systematic biases in the calibrated streamflow simulations by applying a bias correction procedure trained on historical observations (e.g. the historical period VIC simulation was corrected to match, on a probabilistic basis, reservoir inflows reconstructed from observations by the USBR, referred to in the Hydromet dataset as ‘Computed Natural Flowí). The same bias correction procedure was then applied to future flows. The bias correction method is a quantile mapping technique discussed by Wood et al (2002) and Snover et al (2003). In brief, the technique involves a mapping procedure that matches the statistics of the unregulated flow record with observations at monthly time scales. Simulated daily flows are subsequently rescaled to match the bias-corrected monthly values.

For this study, simulated VIC streamflows were bias corrected to correspond with inflows used by the USBR in their water planning. In this comparison, we use only unregulated (or ‘naturalized’) streamflow, meaning that these flows represent ‘natural’ conditions prior to management alterations. The USBR provided 24-year records of unregulated streamflow for water years 1982-2005. The data included reservoir inflows and local inflows downstream of reservoirs that are required by their water management model. To extend data records beyond 24-years, we used a closely related set of daily unregulated flows (http://www.usbr.gov/pn/hydromet/yakima) for the period 1930-2006. These two sets of unregulated flows differ primarily in the accounting of routing time lags and irrigation return flows. We adjusted the 77-year records to be comparable to the 24 year records using a quantile-mapping bias correction procedure similar to the one outlined above. The longer record was used as the basis for bias correcting VIC output.

The monthly-daily adjustment procedure discussed above does not by construct preserve annual totals. Therefore, as a second step, we bias adjusted the annual total flows at each site, and then made second stage adjustments to monthly flows to add to the annual total, and of daily flows to sum to monthly. We also adjusted to assure that mass balance was preserved over sites by moving from the lowest site (Yakima near Parker), upstream to higher locations. In general, the adjusted 1930-2006 record was similar to the original record, matching both the shape of the hydrograph and its magnitude. During the Autumn and Winter months this process adjusted the VIC’s higher streamflow to match the historic mean by minimizing the late Autumn rain dominated runoff. In the Spring, flows shifted from peak flow in June to peak flows in May, which corresponds to the historical record. Elsner et al. (2009, this report) provides more details on how well historical runs represent the hydrology prior to bias correction. The process followed for adjustment of future climate flows generally paralleled the one outlined above for historical flows. Procedures similar to those outlined above were also implemented to assure mass balance of monthly and annual flows, and across sites.

3.2. Water Management Model

We used a modified version of the reservoir operations model used by USBR in their operational planning, referred to as the ‘water management model' throughout this paper. The model is written in RiverWare™ software (see Zagona et al (2001) for a RiverWare overview) and is one component of the Watershed and Rivers System Management Program (WARSMP), a collaborative effort to simulate water management in the Yakima basin between the U.S. Geological Survey and USBR (Mastin and Vaccaro, 2002). Within the model, simulated system operations are primarily focused on agriculture, however constraints provided by minimum instream flow and other operating requirements are also represented. Because we are focused on capturing the average response of the management system to climate change, reservoirs are operated with the same rules each year regardless of year-to-year maintenance concerns.

To allow the water management model to run with VIC simulated flows (1915-2006 for the historical run, and adjusted 1915-2006 following the delta method for future streamflow projections), we made several modifications to the original model. The version of RiverWare we used was originally constrained to an operations period 1981 to 2003. Because RiverWare saves all variables internally, simulations longer than 25 years are computationally cumbersome. To improve performance, we effectively concatenated simulations of 20-year segments with 5 years of overlap (spin-up). These runs covered periods 1915-1940, 1935-1960, 1955-1980, 1975-2000 and 1981-2006, where the first five years of each sequential run was discarded as spin-up and the 1981 run had more spin up to keep runs a consistent length for batch processing. Because the reservoirs typically refill each year, the spin up period proved more than adequate, and test comparisons using explicit model initialization showed little difference from simulations performed using the spin-up procedure.

Another modification of the water management model was that we used eight inflow locations as shown in Figure 1, including five reservoir inflows (Bumping, Cle Elum, Kachess, Keechelus, Rimrock), and two confluences (Upper Yakima, Naches) and the Yakima River gage at Parker. The operational USBR model has 15 inflow locations, eight of which are intervening flows that include smaller inflow locations such as the American River. We aggregated the intervening flows to three, by subtracting upstream from downstream flows, with negative values set to zero. Intervening flows were inferred from those estimated for the historical period of record. In locations where VIC did not directly produce intervening inflow values, we used the proportion of 1981-2003 long-term averages of these flows to distribute between multiple intervening locations. We compared simulations produced using our simplified setup (5 upstream flow locations and 3 intervening flows) with the USBR setup for the historical period 1981-2003 and found no significant differences in model predictions of water apportionment to the irrigation districts, primarily because the key water allocation decisions in the model are keyed to predicted flows near Parker, which are constrained in our approach to be the same as in the more detailed USBR version of the model. One additional consideration is that the USBR operational model requires forecasts of reservoir inflows through the end of the water year. In our simulations, we assumed perfect knowledge of future streamflows, which allowed prorating values to align with water availability exactly. In the operational setting, managers must make forecasts of how much water will be available based on external streamflow forecast measures.

Prior to this study, the water management model had been run primarily for conditions in 1981 to 2003, and we found several instances in the longer historical record where flow conditions were outside the bounds of the model, a problem that was exacerbated for some of the future climate simulations. To allow the model to run with these new flow conditions, we made several alterations including allowing allocations to junior water users to go to zero, extending the interpolation of anticipated September flow at the Keechelus Reservoir (by linear extrapolation), and disabling computations for the Chandler Canal which is below the Parker gage and therefore was not a factor in this study. With these revisions, all simulations were completed except for one GCM run, the BCCR B1 scenario, which failed in the 1915-1940 period because of an inability of the model to account properly for operations of the Cle Elum Reservoir in these particular sequences of inflows (second warmer and wetter scenario for B1).

The prorating of water is calculated in the water management model for junior and senior water rights according to their monthly prorating entitlements as determined by the Consent Decree of 1945. The water supply available within their allocation is divided by the total amount remaining to obtain a prorating ratio. In the management model, water demands are taken as constant across all projections according to water rights, e.g. the simulations do not allow for the possibility that water demands might change in a future climate.

Results of the historic water management simulation, specifically regulated flow near Parker, reservoir storage and outflow at the Cle Elum Reservoir (the largest reservoir which contributes 42% of the total basin storage), and prorating are shown in Figure 3 and discussed in Section 4. In our presentation of results, years indicate water years (October-September). Most analyses are aggregated to a weekly time step for ease of presentation, where week 1 starts on October 1 (see also Table 3).

Table 3. Week number designations.

week number	date
1	1-Oct
5	29-Oct
10	3-Dec
15	7-Jan
20	11-Feb
25	18-Mar
30	22-Apr
35	27-May
40	1-Jul
45	5-Aug
50	9-Sep

4. Results: Water Supply

In reservoir systems that depend on snowpack to enhance reservoir storage, the more delayed the snowmelt, the greater the effective storage capacity of the reservoir system. As warming progresses, the seasonal peak of simulated reservoir inflows in the Yakima system shift progressively earlier in the year, as more winter precipitation occurs as rain and less as snow (Elsner et al., 2009, this report). To assess how these altered hydrologic conditions impact water supplies, we first evaluate how well water-management-model simulations represent historical operations (Section 4.1). Then in Section 4.2 we show how water deliveries are projected to respond to climate-change scenarios. We subsequently discuss variability of inflows, storage, and outflows in future years and between various locations in the basin (Section 4.3).

4.1. Reservoir System Historical Operations

Figure 3 compares reservoir system historical operations between (1) water management model simulations run using 1917-2006 VIC historical

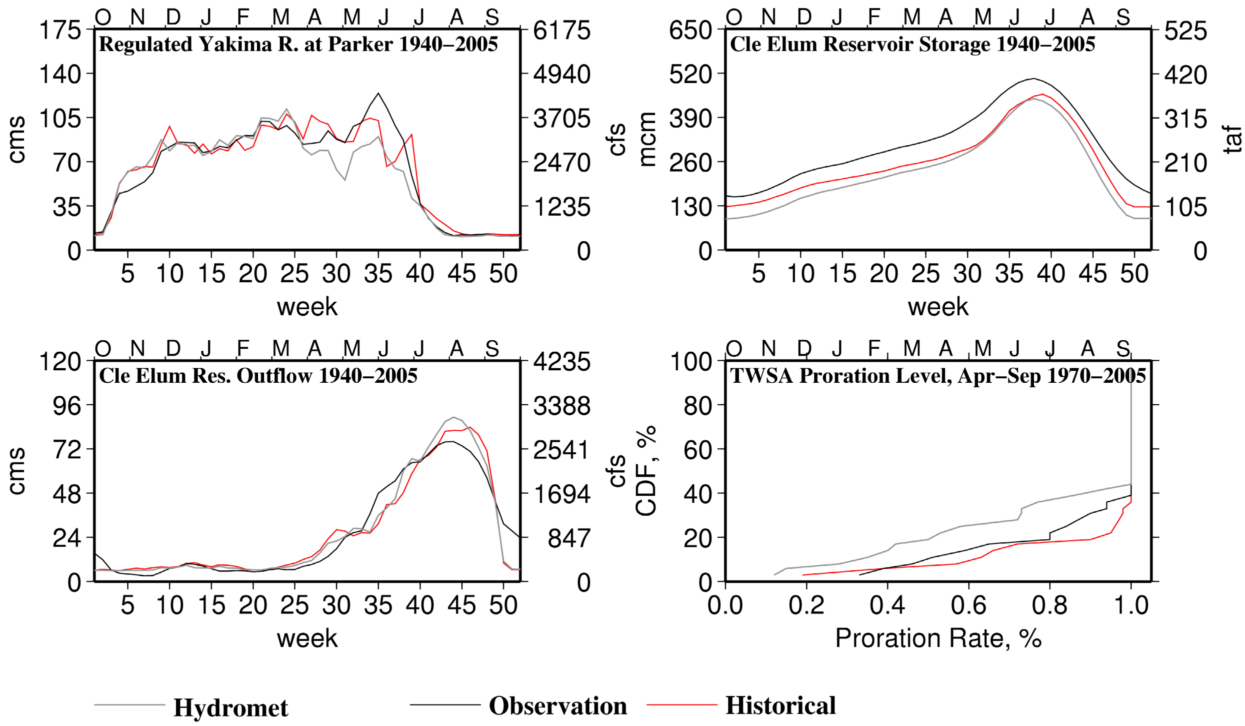


Figure 3. Historic comparisons. Historical regulated flows near Parker, reservoir storage and outflow for Cle Elum reservoir (largest reservoir in the basin) and prorating levels. Years begin on October 1st and end on September 30th.

bias-corrected streamflow (termed '*Historical*') (2) water management model simulations run using the adjusted reconstructed USBR 'Computed Natural Flowí for the period 1930-2006 as discussed in Section 3.2. (termed '*Hydromet*'), and (3) USBR observations of streamflows, reservoir storage, and prorationing values (termed '*Observation*'). *Historical* and *Hydromet* simulated values assume current irrigation demands and operating policies. *Observation* values alternatively reflect actual year-to-year management operations from 1940 to 2005, which differ from the consistent model representation of current operating policies (USBR, 2002; USBR, 2008).

The upper left panel on Figure 3 shows Yakima River regulated flows near Parker from 1940 to 2005. The current reservoir system was in place by 1940, therefore comparisons of simulations with observed flows and storage is only appropriate, with caveats mention above, after 1940. Seasonal average flows are lowest between mid-July and mid-October. They increase gradually from October until December and then increase more rapidly from about 85 cubic meters per second (cms) to 115 cms (3000 to 4000 cubic feet per second (cfs)) in May. In May, flows reach their highest weekly averages before declining as the irrigation season progresses. *Observation*, *Hydromet*, and *Historical* regulated flows have similar seasonality, with the largest divergence occurring in mid-April through May. More regulated flow in the irrigation season for the *Observation* flow is realistic given that reservoir operations and irrigation demands have changed since 1940.

The Cle Elum Reservoir is the largest in the basin (representing 42% of the total basin storage), and we therefore focus on simulated and observed storage at this location (Figure 3, upper right panel). Results for other reservoirs (not shown) were qualitatively similar. Seasonal average storage (units in mcm, or million cubic meters, or taf, thousands of acre feet) in Cle Elum Reservoir peaks at about 490 mcm (400 taf) at the end of May and then declines until September to about 0.123 mcm (100 taf). Storage then increases gradually until April-May, when the rate of reservoir refill increases. On average, throughout the year the Cle Elum Reservoir *Observation* storage is greater by about 61.2 mcm (50 taf) than simulated storage. The difference is not unexpected because reservoir operating procedures and water demands have changed considerably over the last 60 years. Simulated *Hydromet* and *Historical* storage are generally closer to each other than to *Observation* storage, because these simulations reflect the same reservoir operating rules. It is worth noting that *Historical* storages tend to be somewhat higher than *Hydromet*, and our interpretation is therefore somewhat conservative for simulated results in terms of the implications of climate effects on reservoir system performance.

With *Historical* simulations, average weekly reservoir outflows from Cle Elum Reservoir begin to increase in March, peak in July at ~80 cms (~2800 cfs), and decline quickly to ~7 cms (~250 cfs) by the beginning of September (Figure 3, lower left panel). They then remain at about this level through the fall and winter until mid-March. These changes in outflows are largely determined by target instream flows for fish, as outlined in Section 2. In particular, during the low flow months the target is to keep flows relatively low so as to encourage spawning at low flows.

Comparisons between *Observation* reservoir releases and the simulated *Hydromet* and *Historical* reservoir outflows show similar seasonality, however *Observation* outflows have a longer, lower peak than simulated reservoir outflows (see Figure 3, lower left panel). Reservoir outflows are heavily constrained at the end of September at the point of transition in the operating policy (sometimes termed “flip-flop” as described in Section 2), when the source of water deliveries changes from Cle Elum to Rimrock.

As discussed in Section 2, in dry years, not all water allocations can be fulfilled and proratable entitlements are the first to be reduced. To compare prorating levels, we evaluated the cumulative probability distribution of water supplied (Figure 3, lower right panel), which is a way to compare the frequency and the severity of simulated proratings between simulations. Our water management model plausibly reproduces monthly total water supply available (TWSA) water prorating rates that have been set in practice by USBR since 1970. *Observation* prorating has occurred in 13 of 35 years (~37% of the years on the ordinate in Figure 3). This compares closely with our *Historical* (VIC-based) simulations in which prorating occurs in 12 of 35 years. Prorating occurs in 15 of 35 years (~42% of the time) in Hydromet simulations. Prorating values, which we have assessed as annual averages from April to September, have similar trends in all three simulations (Figure 3, lower right); *Observation* prorating values are highly correlated with *Historical* (r=0.96) and *Hydromet* simulations (r=0.96). Actual TWSA observations (*Observation*) only drop to ~37% of prorating, whereas *Hydromet* simulations decline to ~17% and *Historical* simulations decline to ~20%. Year-to-year variability in simulated prorating values are similar to the actual *Observation* prorating values designated by the USBR, especially significant dry years including drought years in the early 1990s, 2001, and 2005. Generally, the water management model run with VIC inflows has more conservative prorating values than predicted by model runs using Hydromet values.

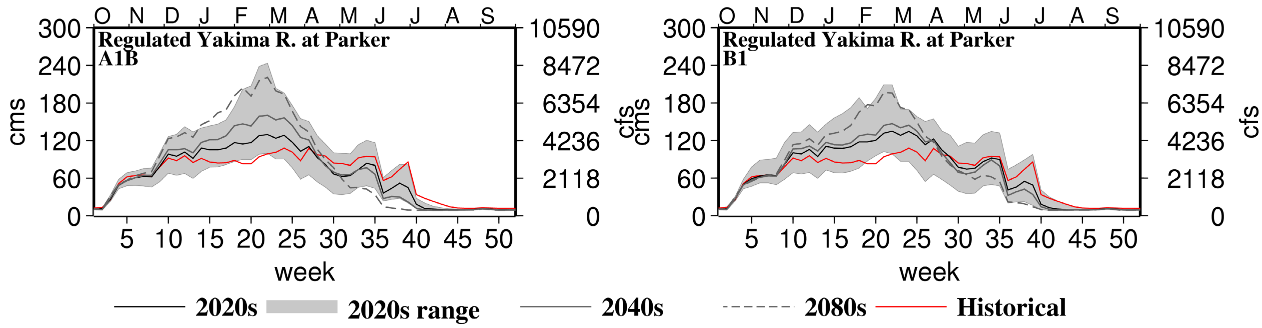


Figure 4. Regulated flow. Simulated regulated flow of the Yakima River near Parker for historical, 2020s, 2040s, and 2080s climate conditions.

Because *Observation* values, which reflect actual operating policies, are not consistent from year to year, we use simulated historical reservoir storages and releases to compare values simulated from the climate change experiments in subsequent sections. Our climate change comparisons are between VIC simulated (rather than actual) historical conditions, and simulated future conditions.

4.2. Water Supply for Agriculture

Figure 4 shows the simulated regulated flow for the Yakima River near Parker for historical, 2020s, 2040s, and 2080s climate conditions. The regulated flows at Parker are key indices of reservoir system performances because they are used in determining TWSA, which in turn determines the proportion of water that is available to junior and senior water right users. Historically, on average regulated flows near Parker are highest in April (115 cms (4000 cfs)) however in simulated historical record they were over 566 cms (20,000 cfs) 40 days in 90 years in December and January and a maximum flow of approximately 50,000 cfs. In the future scenarios, streamflows are higher during the fall and winter seasons and streamflow peaks earlier in the year. For the A1B emission scenarios, in the last week of February flows increase on average to 129.4 cms (4570 cfs) (ensemble range from 103.1 cms (3640 cfs) to 243.2 cms (8590 cfs)) in the 2020s, 160.6 cms (5670 cfs) in the 2040s, and 220.6 cms (7790 cfs) in the 2080s. Then, in June, climate projected flows are less than historical flows until November when reservoirs begin to refill. For B1 scenarios, these trends and timing of changes are similar, although the differences from historical values are smaller. The February average flow is 135.1 cms (4770 cfs) (ensemble range from 103.6 cms (3660 cfs) to 209.2 cms (7390 cfs)) for the 2020s, 147.2 cms (5200 cfs) for the 2040s, and 196.8 cms (6950 cfs) for the 2080s.

In the water management model, when there is insufficient supply for all water users, once junior water rights supply reaches zero, senior water rights are prorated. Subsequent to implementation of TWSA prorating in the 1970s, senior water rights users have always received 100% of their allocation. In our historical simulations with current water demands, infrastructure, and operating rules, junior water rights would have been prorated (less than 100% allocation) in 30% of years, and in just 1% of years (one year, 1941) for senior water rights (top of Table 4a or 4b).

Figure 5 and Tables 4a and 4b show how water rights for junior water

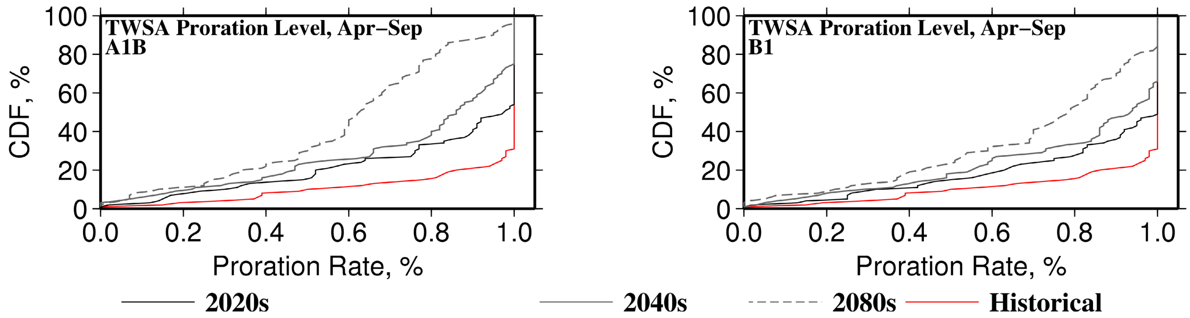


Figure 5. Total Water Supply Available Proration Levels. Cumulative distribution function (CDF) of water supply prorating for junior water users for historical, 2020s, 2040s, and 2080s conditions ranks the likelihood of water supply availability for Junior water users from 0 to 100% of the time (horizontal axis) for April to September average annual values. For example, historically, Junior water users receive 80% or less of their water supply (horizontal axis), 20% of the time (vertical axis). Whereas, they receive 40% or less of their allocated water supply about 8% of the time.

users are simulated to be impacted by climate change. Junior water users experience prorating considerably more frequently. Historically, prorating declines to values below 75% (a approximate threshold beyond which water shortages can no longer be handled without significant impacts to agricultural production and costs) in 14% of years. For the A1B emission scenarios, the fraction of years with prorating values less than 75% increases in the 2020 to 32% for the composite simulation (ensemble range 15% to 54%). These fractions increase to 36% in the 2040s, and 77% in the 2080s. The B1 emission scenario is projected to have a slightly smaller impact on water shortages than A1B. In the 2020s, the fraction of years with prorating values of 75% or less is 27% for the composite simulation, with ensemble range from 14% to 54%. The equivalent fractions for B1 composite case increase to 33% in the 2040s and 50% in the 2080s.

Water deliveries to senior water users drop below 100% for a few climate scenarios and below 75% in the driest scenarios of the 2020s ensembles (1 of 20 for A1B and 2 of 20 for B1). The increased likelihood of senior water user shortfalls indicates that the system will be impacted in ways not previously encountered in the past. Failure to meet senior water rights occurs in 2% of years in the 2020s composite (ensemble range from 0 to 8%) and increases to 3% in the 2040s and 2080s for A1B emission scenarios. For B1 emissions scenarios, the frequencies are slightly less.

4.3. Future System Inflows, Storage, and Outflow

The April 1 snow water equivalent analysis in Elsner et al. (2009, this report) indicates that 78% of the Yakima basin is in what is commonly termed the transition zone, where precipitation transitions many times each winter between rain and snow. Because much of the basin is in the transition zone, it is highly sensitive to temperature changes as discussed further in Elsner et al (2009, this report).

Although natural flow varies throughout the basin, we assess unregulated simulated flow near Parker, which is representative of the basin as a whole (Figure 6). Changes in unregulated flow near Parker and upstream flows have similar trends. It is important to note that these are bias-adjusted flows taken directly from the hydrologic model and represent unregulated conditions. The water management model incorporates these flows at the specific locations indicated in Figure 1 using differences between downstream and upstream locations to generate intervening flows. Unregulated flows in the Yakima basin historically peak in the end of May

Table 4a. Summary of reservoir simulation results for A1B emissions scenario: prorating

AIB	Junior water right prorating: likelihood of having September value drop below					Senior water right prorating: likelihood of having September value drop below		
	100%	**75%**	**50%**	**25%**	**10%**	**100%**	**95%**	**75%**
historical simulation	30%	14%	10%	3%	1%	1%	1%	0%
warmest and wetter:								
hadcm	56%	33%	17%	9%	4%	3%	2%	0%
miroc_3.2	70%	35%	21%	8%	5%	2%	1%	0%
miroc3_2_hi	62%	30%	15%	6%	4%	1%	0%	0%
ipsl_cm4	53%	20%	10%	2%	1%	0%	0%	0%
inmcm3_0	52%	21%	11%	4%	1%	1%	0%	0%
cgcm3.1_t47	50%	24%	13%	3%	2%	0%	0%	0%
warmest and drier:								
ccsm3	80%	54%	33%	14%	10%	6%	6%	0%
hadgem1	69%	39%	25%	14%	6%	4%	4%	0%
gfdl_cm2_1	58%	37%	25%	10%	8%	4%	4%	0%
warmer and drier :								
echo_g	67%	54%	40%	19%	9%	8%	8%	1%
fgoals1_0_g	68%	44%	30%	14%	8%	6%	6%	0%
pcm1	59%	44%	28%	12%	7%	3%	3%	0%
gfdl_cm2_0	58%	35%	20%	9%	2%	1%	0%	0%
giss_er	48%	29%	14%	8%	2%	2%	1%	0%
warmer and wetter:								
csiro_3_5	51%	26%	14%	8%	2%	1%	0%	0%
cgcm3.1_t63	50%	18%	10%	4%	1%	0%	0%	0%
giss_aom	50%	28%	14%	6%	2%	1%	0%	0%
cnrm_cm3	41%	22%	13%	7%	2%	1%	1%	0%
echam5	45%	24%	13%	3%	2%	1%	0%	0%
bccr	33%	15%	11%	4%	2%	0%	0%	0%
Composites								
2020	52%	32%	17%	9%	2%	2%	1%	0%
2040	74%	36%	24%	11%	6%	3%	3%	0%
2080	95%	77%	33%	13%	9%	3%	2%	0%

* Delta categories of warming and dry/wet are based on annual deltas.
* More information on GCM properties and selection can be found in Mote and Salathˇ (2009, this report).

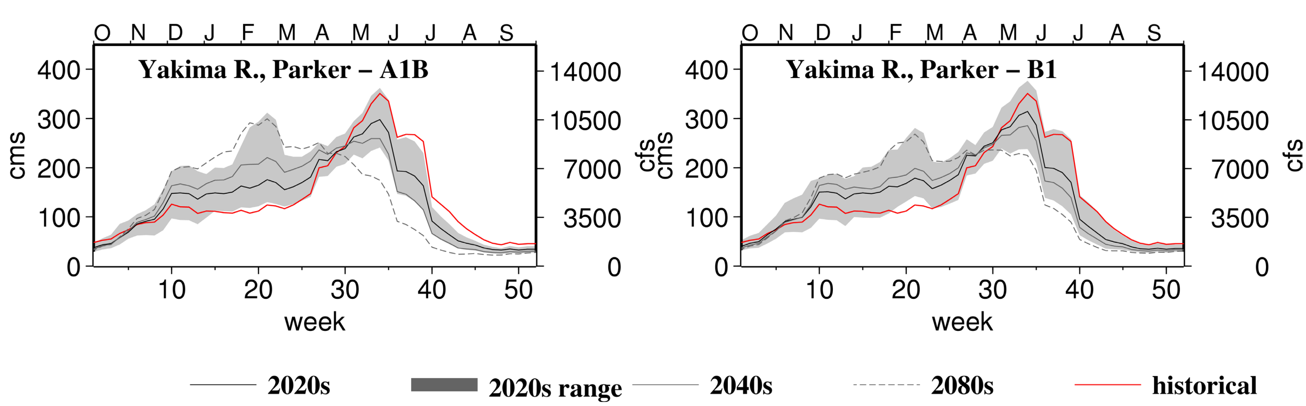
Figure 6 (right). Basin-average reservoir inflow. Simulated unregulated flow (flow that would occur in the absence of reservoirs and irrigation withdrawals) near Parker for historical, 2020s, 2040s, and 2080s conditions.

Table 4b. Summary of reservoir simulation results for B1 emissions scenario: prorating

B1	Junior water right prorating: likelihood of having September value drop below					Senior water right prorating: likelihood of having September value drop below		
	100%	**75%**	**50%**	**25%**	**10%**	**100%**	**95%**	**75%**
historical simulation	30%	14%	10%	3%	1%	1%	1%	0%
warmest and wetter:								
miroc_3.2	57%	29%	13%	7%	3%	1%	0%	0%
miroc3_2_hi	74%	34%	18%	8%	5%	2%	0%	0%
ipsl_cm4	52%	22%	11%	3%	2%	0%	0%	0%
cgcm3.1_t47	58%	28%	14%	8%	2%	1%	0%	0%
cgcm3.1_t63	64%	32%	17%	8%	5%	2%	0%	0%
warmest and drier, or less wet:								
ccsm3	77%	54%	37%	15%	12%	8%	7%	1%
echo_g	74%	58%	39%	21%	12%	10%	9%	1%
hadcm	48%	28%	15%	7%	2%	2%	1%	0%
warmer and drier, or less wet :								
fgoals1_0_g	54%	33%	17%	9%	3%	1%	0%	0%
pcm1	39%	25%	14%	4%	2%	0%	0%	0%
echam5	47%	25%	14%	7%	2%	1%	1%	0%
gfdl_cm2_0	50%	32%	17%	9%	2%	0%	0%	0%
gfdl_cm2_1	50%	32%	15%	8%	2%	1%	1%	0%
warmer and wetter:								
csiro_3_5	30%	15%	7%	4%	1%	0%	0%	0%
giss_aom	50%	25%	13%	7%	2%	1%	0%	0%
giss_er	46%	25%	13%	3%	2%	1%	0%	0%
cnrm_cm3	39%	14%	10%	3%	1%	0%	0%	0%
bccr	NA	NA	NA	NA	NA	NA	NA	NA
inmcm3_0	40%	19%	11%	4%	2%	1%	0%	0%
Composites								
2020	48%	27%	15%	6%	2%	2%	1%	0%
2040	65%	33%	18%	9%	6%	2%	1%	0%
2080	82%	50%	26%	11%	7%	3%	1%	0%

* Delta categories of warming and dry/wet are based on annual deltas.

* More information on GCM properties and selection can be found in Mote and Salathˇ (2009, this report).



at an average of 340 cms (~12,000 cfs) and they are at their lowest in September at ~55 cms (~2000 cfs).

In the A1B emission scenarios, the May peak flow declines in the 2020s composite run to ~280 cms (~10000 cfs) (ensemble range from ~225 cms (~8000 cfs) to 370 cms (~13000 cfs)), then declines further to 255 cms (~9000 cfs) in the 2040s composite and further declines and shifts earlier to mid-February at 225 cms (~8000 cfs) in the 2080s composite (Figure 6). In the B1 emissions scenarios, the peak streamflow declines in the 2020s composite to ~310 cms (~11000 cfs) (ensemble range from ~225 cms (~8000 cfs) to 370 cms (~13000 cfs)), ~280 cms (~10000 cfs) in the 2040s composite, and 255 cms (~9000 cfs) in the 2080s composite with the 2080s peak shifting to February (Figure 6). Low flows in both A1B and B1 emissions scenarios decrease slightly, but not dramatically.

Figure 7 shows how reservoir storage varies throughout the basin as the climate changes. Total system storage (Figure 7, top panel) is, on average, highest historically at the end of June at 1,140 mcm (~ 923 taf). In A1B emission scenarios, the peak in storage occurs 2 weeks earlier for the 2020s composite at 1.098 mcm (890 taf) (ensemble range from 941 to 1,114 mcm, or 763 to 968 taf), 4 weeks earlier in the 2040s at 1.122 mcm (910 taf), and 5 weeks earlier in the 2080s at 1.131 mcm (917 taf). In all future projections, storage is less than historical storage levels from mid-June through January. Between January and June future storage values increase. With the B1 emission scenarios, changes in basin-wide storage are less substantial, especially in the 2080s. The peak in storage occurs 2 weeks earlier in 2020s composite run at 1,118 mcm (906 thousands af) (ensemble range 940 to 1,176 mcm, or 762 to 953 taf,) and 3 weeks earlier in the 2040s at 1.120 mcm (908 taf), and 4 weeks earlier in the 2080s at 1.130 mcm (916 taf).

In addition to the combined reservoir flows, storage in each of the five reservoirs changes, more or less in concert with total system storage (Figure 7), although reservoir storage varies between reservoirs according to specific management goals as well as the capacity and inflows of each reservoir. In general, summer reservoir storage declines and winter storage increases, although the magnitude and extent of these differences are most notable in winter storage in Bumping Reservoir and through much of the year in Kachess. Bumping has the smallest reservoir capacity to annual runoff ratio (0.2), whereas Kachess has the largest (1.1), effectively, this means that Kachess does not fill even in years of "normal" flow, whereas Bumping can refill multiple times throughout a year.

Tables 5a and 5b summarize projected storage changes for the five major reservoirs in October, the month when the entire system capacity is at its lowest. Under historical conditions, reservoirs drop below 10% of their capacities on average, ranging from 53% of the time for Keechelus to 7% of the time for Bumping. In the 2020s A1B ensembles, for the warmest and driest ensemble members, storage is likely to drop below current levels. The warmer and wetter scenarios are closest to historical values, but are still substantially more likely to drop below 10% of capacity. Considering all of the 2020s ensemble members, there is a substantial incidence of lower early fall reservoir storage. For example, historically Cle Elum Reservoir drops below 10% of capacity 1 out of every 3 years, whereas in

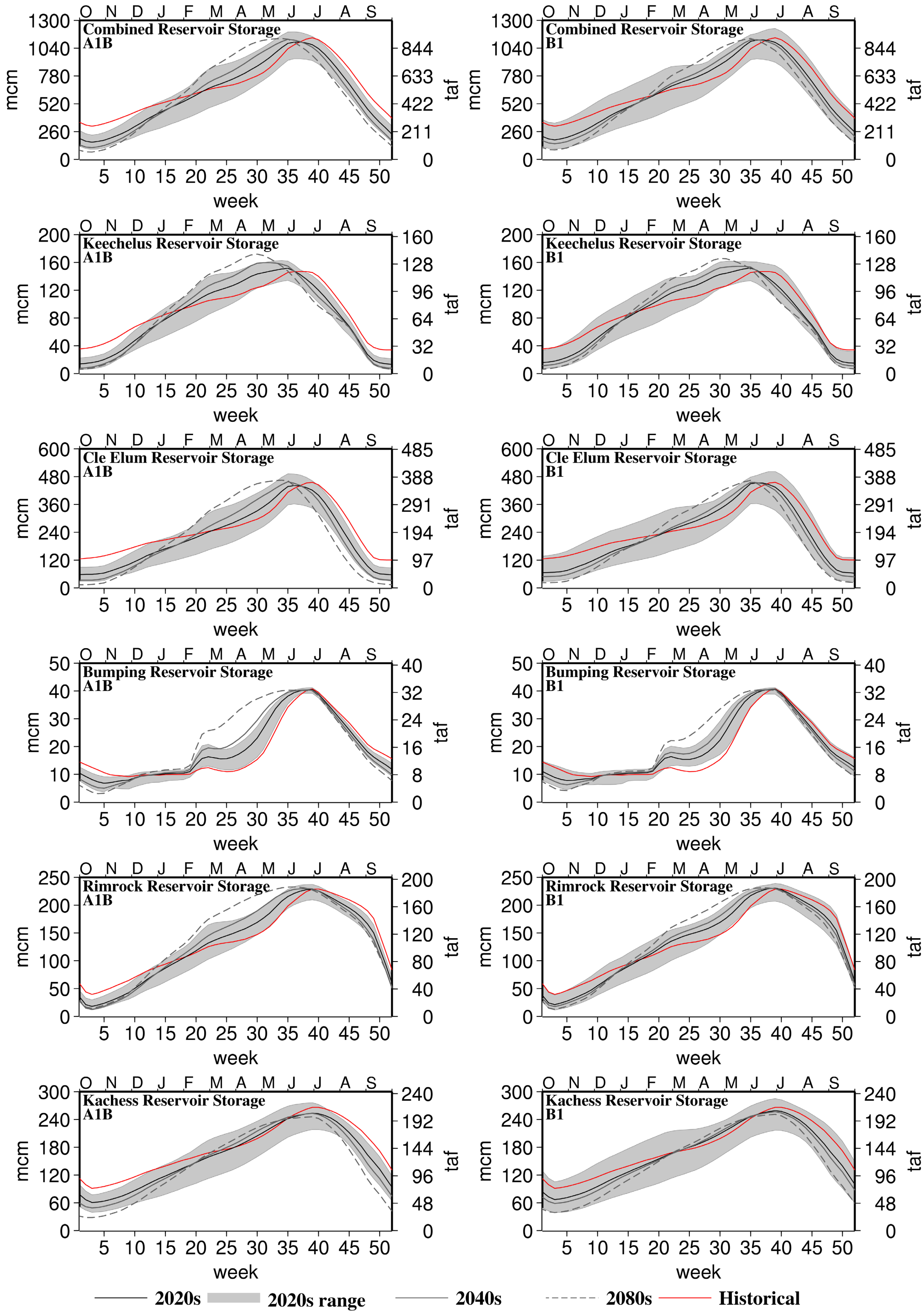


Figure 7. Reservoir storage. Simulated reservoir storage for the combined system (top panel) and for each of the five major reservoirs (lower five panels) for historical, 2020s, 2040s, and 2080s conditions.

Table 5a. Summary of reservoir simulation results for A1B emissions scenario: reservoir storage

AIB	Likelihood of October Reservoir Storage dropping below 10%				
	Cle Elum	**Keechelus**	**Bumping**	**Rimrock**	**Kaches**
historical simulation	33%	53%	7%	34%	19%
warmest and wetter:					
hadcm	60%	80%	27%	63%	37%
miroc_3.2	69%	84%	28%	64%	40%
miroc3_2_hi	68%	81%	25%	59%	38%
ipsl_cm4	59%	80%	20%	60%	26%
inmcm3_0	59%	82%	23%	61%	28%
cgcm3.1_t47	54%	73%	16%	48%	31%
warmest and drier:					
ccsm3	78%	94%	42%	71%	52%
hadgem1	62%	78%	25%	59%	39%
gfdl_cm2_1	67%	81%	27%	60%	43%
warmer and drier :					
echo_g	73%	85%	35%	69%	57%
fgoals1_0_g	72%	84%	31%	65%	50%
pcm1	66%	79%	26%	58%	48%
gfdl_cm2_0	63%	76%	22%	52%	37%
giss_er	49%	71%	19%	50%	33%
warmer and wetter:					
csiro_3_5	54%	77%	21%	56%	34%
cgcm3.1_t63	59%	72%	16%	51%	26%
giss_aom	57%	76%	18%	54%	38%
cnrm_cm3	46%	72%	19%	55%	28%
echam5	47%	69%	12%	40%	26%
bccr	44%	68%	12%	49%	25%
Composites					
2020	63%	79%	23%	60%	37%
2040	76%	88%	34%	70%	41%
2080	91%	93%	53%	65%	67%

* Delta categories of warming and dry/wet are based on annual deltas.
* More information on GCM properties and selection can be found in Mote and Salathé (2009, this report).

Table 5b. Summary of reservoir simulation results for B1 emissions scenario: Reservoir storage

B1	Likelihood of October Reservoir Storage dropping below 10%				
	Cle Elum	**Keechelus**	**Bumping**	**Rimrock**	**Kaches**
historical simulation	33%	53%	7%	34%	19%
warmest and wetter:					
miroc_3.2	62%	81%	25%	60%	36%
miroc3_2_hi	73%	84%	32%	63%	40%
ipsl_cm4	59%	73%	19%	50%	29%
cgcm3.1_t47	59%	74%	22%	51%	36%
cgcm3.1_t63	62%	80%	26%	58%	39%
warmest and drier, or less wet:					
ccsm3	77%	90%	35%	65%	51%
echo_g	77%	90%	40%	70%	58%
hadcm	52%	72%	19%	53%	35%
warmer and drier, or less wet :					
fgoals1_0_g	62%	74%	20%	58%	37%
pcm1	43%	65%	13%	50%	31%
echam5	53%	72%	17%	56%	33%
gfdl_cm2_0	56%	73%	20%	60%	38%
gfdl_cm2_1	59%	77%	21%	57%	37%
warmer and wetter:					
csiro_3_5	42%	69%	10%	46%	21%
giss_aom	56%	75%	19%	54%	31%
giss_er	49%	70%	16%	47%	27%
cnrm_cm3	43%	71%	13%	52%	19%
bccr	NA	NA	NA	NA	NA
inmcm3_0	44%	71%	15%	52%	27%
Composites					
2020	55%	76%	20%	55%	34%
2040	63%	81%	26%	58%	39%
2080	86%	91%	41%	70%	47%

* Delta categories of warming and dry/wet are based on annual deltas.
* More information on GCM properties and selection can be found in Mote and Salathé (2009, this report).

the 2020s composite (A1B emissions), it drops below this level in 63% of years (ensemble range 44% to 78%) of the time. This percentage increases to 76% in the 2040s and to 91% in the 2080s. B1 emission scenarios have similar trends, although the frequency of low storage is somewhat less than for A1B.

Unlike the municipal systems in the Puget Sound basin (Vano et al, 2009a, this report), in the Yakima system demands are reduced substantially until the beginning of the irrigation season the following spring. However, low carry-over at the end of the irrigation season can impact the system's ability to meet instream flows due to hydraulic capacity limitations or insufficient volumes to supplement natural flows. [2] Therefore the increase in the frequency of this condition shows that the system may be under increased water stress with progressing climate change. Furthermore, USBR attempts to maintain some reservoir storage carry-over, especially in the Kachess Reservoir, which has a relatively high storage to inflow ratio. Carry-over storage is especially important when the upcoming fall and winter are dry. Reservoir outflows (Figure 8) reflect similar variations in the total system and in particular storage components within the system.

5. Economic Impacts on Irrigated Agriculture

An economic analysis of the impacts of climate change on Yakima basin perennial crops was conducted using two models: the CropSyst model (Stöckle and Nelson, 1996; Stöckle, et al., 2003) (which simulates irrigated crop response to climate change) and the Irrigation District System Model (which projects economic impacts), briefly described in this paper. The perennial crops analyzed include apples and sweet cherries, which represent 48 percent of the region's crop value. For this analysis, we used the A1B and B1 emissions scenarios and the composite model runs for the 2020s, 2040s and 2080s. Comparisons over time were performed with composite model runs. For each time period, potential fertilization effects CO_2 were simulated for the average CO_2 levels expected in both the A1B and B1 scenarios for each time step. Higher future average CO_2 levels are believed likely by many researchers to increase the future effectiveness of photosynthesis in many crops as well as reduce the plants' loss of water in transpiration. The strength and longevity these effects are still a matter of both some controversy and active field research. (The likely effects of CO_2 on plants are described in Stöckle et al. (2009, this report) and methods for incorporating CO_2 effects in Cropsyst in Stöckle et al. 2003). The Cropsyst analysis for this paper was done both with and without CO_2 fertilization effects for both the A1B and B1 scenarios. The Cropsyst yield estimates include the effects of changed growing weather and the impacts of prorationing resulting from projected climate change for the composite scenario for the 2020s, 2040s, and 2080s. (See Table 6.) They are discussed in Section 5.2.

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[2] Future considerations such as additional mandated fish flows or additional endangered species designations could make winter flows a larger consideration.

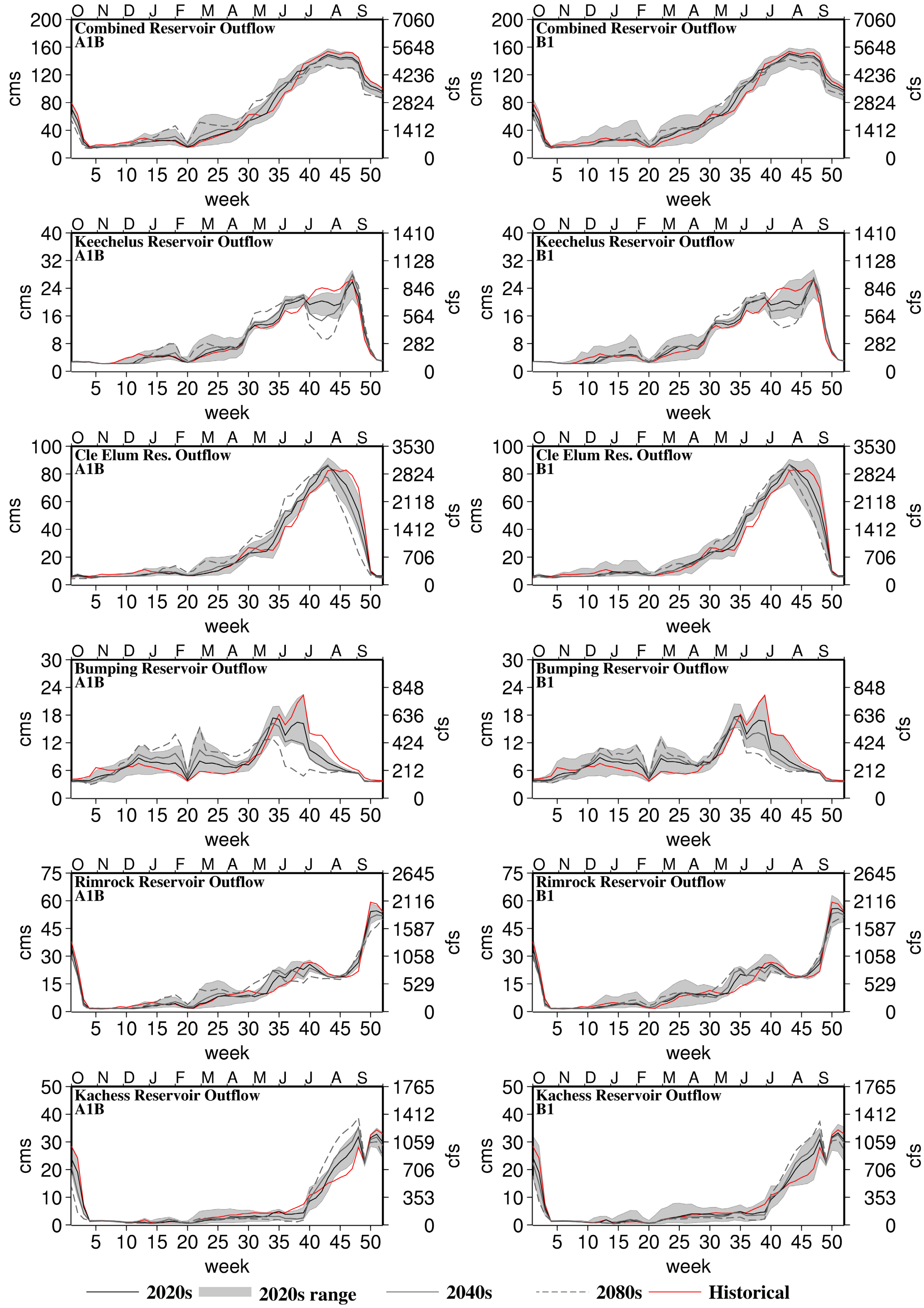

Figure 8. Reservoir outflow. Projected reservoir outflow for the combined system (top panel) and for each of the five major reservoirs (lower five panels) for historical, 2020s, 2040s, and 2080s conditions.

Table 6. Agricultural economics assumptions and data for apples and sweet cherries

		Apples				Sweet Cherries			
Statewide Yields 1995-2007, Tons/Acre (Junior and Senior Lands Combined)									
	Mean	17.2				4.61			
	Standard Deviation	1.74				0.72			
Cropsyst Model Scenario Composite Case Yields, by Time Period and Scenario, with and without CO2 Fertilization									
		Mean (senior)	Mean (junior)	Std Dev (senior)	Std Dev (junior)	Mean (senior)	Mean (junior)	Std Dev (senior)	Std Dev (junior)
	Historical	22.2	20	1.2	5.3	8.9	8.1	0.9	1.9
2020 A1B	No CO2	19.7	15.8	0.9	6.1	7.4	6	0.8	2.2
	CO2	21	17	1	6.6	8	6.4	0.9	2.3
B1	No CO2	19.7	16.4	0.9	5.8	7.4	6.2	0.8	1.9
	CO2	20.8	17.4	0.9	6.1	7.8	6.5	0.9	2.2
2040 A1B	No CO2	19.1	15.7	1	5.1	7	5.5	0.7	2.1
	CO2	21.6	17.8	1	5.6	8	6.2	0.9	2.5
B1	No CO2	19.3	15.9	0.9	5.4	7.2	5.8	0.8	2.2
	CO2	21.2	17.5	0.9	5.8	8	6.5	0.9	2.4
2080 A1B	No CO2	17.9	12.4	1.2	4.6	6.3	4	0.8	2.1
	CO2	22.2	15.7	1.4	5.5	7.9	5	1	2.5
B1	No CO2	18.6	14.6	1.1	5	6.8	4.9	0.8	2.1
	CO2	21.5	16.9	1.1	5.6	7.9	5.8	0.9	2.5
Statewide Prices (Dollars/Ton)									
	Historical Average Price per Ton (2000-2007)	$401				$1,741			
	Standard Deviation in Price (1995-2007)	$109				$309			
	Price Sensitivity to Yield	= Random Normal(0, $109)+$795-$25.008 x Yield				Random Normal ($1,741, $309)			
Production Cost Data (2007 Dollars per Acre)									
	Total Variable Production Cost per Acre	$6,543				$5,188			
	Picking Labor and Transportation per Acre	$1,526				$2,176			
Estimated Acreages of Crops (Yakima Irrigation Project)									
	Senior	22,842				3,138			
	Junior	39,267				6,370			
	Total	62,109				9,508			

5.1. Economic Analysis Approach

The economic simulations calculate the impact of climate change on value of farm output and net profit for apple and cherry growing operations in Yakima basin that are similar to those prevailing in 2007. Therefore, the simulations reflect the potential impacts of climate change on Yakima basin farm operations for today's economic conditions, not those that might evolve over the next 20, 40, or 80 years.

Economic risks associated with changes in yield were evaluated with a spreadsheet-based model of Yakima River Basin irrigated agriculture called the Irrigation District System Model (IDSM). The IDSM takes as input statistical distributions of per- acre yields of apples and cherries shown in Table 6 for the historical simulation from 1975-2004, with delta method climate change projections applied to this 30 year period as described earlier for the 2020s (2010-2039), 2040s (2030-2059), and 2080s (2070-2099). The model sampled values from these distribution of crop yields from Cropsyst using Crystal Ball® (Oracle 2009) and multiplied the per-acre yields times the estimated acreage of apples and cherries operated by junior and senior irrigators in the Yakima basin irrigation districts to obtain statistical distributions of total production for each time period for junior and senior irrigators. It also multiplied sampled per-acre yields times sampled values of 2000-2007 crop prices from Table 6 to obtain statistical distributions of per acre value of output, and subtracted estimated year 2007 operating costs per acre to obtain statistical distributions of net operating profit per acre. Both these values are multiplied times the affected acreages to obtain estimates of the total impact on value of production and net operating profit. Acreages are shown in Table 6.

Crop price can be either statistically associated with local yields or may be somewhat independent, depending on market circumstances. For example, there is a statistically significant negative correlation in Washington between statewide average yields and prices, with prices declining about $25 per ton of increase in yield during the period 1995-2007[3]. That relationship has been included in the economic projections. Analysis of prices for cherries showed highly variable prices, but did not show a similar statistically significant historical relationship to yields[4], so cherry prices were allowed to vary independently. Operating costs came from Washington State University crop budget information for apples and sweet cherries.[5] They vary with yield. In water-short years, a smaller or non-existent harvest would result in savings of costs closely related to harvest such as picking labor and transportation (Table 6).

Most water charges in Yakima Valley irrigation districts are fixed charges (since these charges are primarily levied by irrigation districts for retirement of capital debt and maintenance of distribution systems), so those costs would not be saved in water-short years. Many farmers that have proratable water supplies also have emergency wells that they use during droughts. Because wells take more energy to operate than gravity-fed irrigation district water, water costs can actually increase (this would have added to the production costs, but also would have reduced crop losses in water-short years).

5.2. Economic Impacts

Table 6 shows the Cropsyst-estimated impact of climate change on yields for A1B and B1 emissions scenarios for apples and for sweet cherries grown

[3]Statewide apple yields varied from 14.6 tons per acre to 19.9 tons per acre during the period, and prices ranged from $230 to $580 per ton. Also, see Table 6.

[4]Statewide sweet cherry yields varied from 3.35 to 5.48 tons per acre, and prices varied from $1310 to $2440 per ton, but there was no relationship noted between price and yield based on historical statewide data. Also see Table 6.

[5]Crop budgets were supplied by Suzette Galinato, IMPACT Center, Washington State University, on September 22, 2008.

by senior and junior water users, compared with the corresponding yields for historical conditions (1975-2004). While there are other important crops in the Yakima River basin (for example, timothy hay in the upper part of the basin in Kittitas County, wine grapes in Yakima and Benton Counties, and mint and hops in Yakima County), apples and cherries have among the highest dollar yields (regionally and statewide in 2007), and have among the highest values per acre. Both are also perennial crops, which are rarely modeled in climate impacts work, both are sensitive to growing weather and water shortages, and they span the growing season (cherries are an early crop, harvested in June, and apples are a late crop, harvested in September or October). The means and standard deviations shown in Table 6 are for individual crop years for the 30-year periods indicated and do not account for potential carryover losses associated with potential loss of entire trees, or for any additional effects of persistent drought. The analysis also ignores effects of climate on fruit size, quality, and marketability.

The adverse effect of climate change on yield is apparent in these Cropsyst runs. While the impacts differ substantially by year, it is apparent that, notwithstanding a positive CO_2 fertilization effect, warmer future climate generally results in lower yields than in the historical period, mostly due to water stress. This is apparent for both crops, both scenarios, and with and without CO_2 fertilization effects. Junior water users (whose irrigation water is sometimes prorated and prorated more frequently as the century progresses) experience more steeply declining yields than do senior water users. CO_2 fertilization effects potentially offset many of the effects of higher temperatures and reduced water availability. An example of this occurs in Table 6 for apples between 2020 and 2040 for junior water users in the A1B scenario. In 2020 no-CO_2 case the average yield for junior water users is 15.8 tons per acre, whereas in the CO_2 case it is 17.0 tons per acre. In addition, between 2020 and 2040 in the no-CO_2 case the average yield falls from 15.8 tons to 15.7 tons, whereas in the CO_2 case, higher average CO_2 in 2040 leads to an increase in yields from 17.0 tons to 17.8 tons. This effect does not persist, however. In the 2080 period the lack of water dominates, with average yields falling back to the 15.7 ton level, even with CO_2 fertilization.

A secondary effect of warming is an earlier and reduced growing season and a reduction in the need for irrigation. Table 7 shows the effect of warming with and without the CO_2 fertilization effect on reducing season length and net requirement for irrigation, By the end of the century, the growing season begins 10 to 20 days earlier and ends up to 30 days earlier for apples, shortening the growing season by between 3 days and two weeks. With climate change and earlier and shorter season irrigation requirements, water demands are reduced by as much as 37% for apples and 47% for cherries in the 2080s in the A1B case without a CO_2 fertilization effect. The additional amount of water saved with CO_2 fertilization is about 4% for apples and 2% for cherries. However, in the absence of adaptation, the increasing frequency and severity of water shortages as the century progresses increases the number and severity of water stress days, and yields decline on average, as shown in Table 6.

The negative impact on yields adversely affects growers' incomes. Figure 9 shows the impact of the warming scenarios on the cumulative probability

Table 7. Season length in days and net requirements for irrigation for apples and cherries in the A1B and B1 emissions scenarios for the 2020s, 2040s, and 2060s (mm/season)

			Average Season Length			Net Required Irrigation	
			Bud Break (day)	Maturity (day)	Season Length (day)	Average (mm/season)	Std Dev (mm/season)
Apples							
		Historical	89	243	151	656	166
2020	**A1B**	**No CO2**	81	228	146	529	182
		CO2	81	227	146	524	182
	B1	**No CO2**	81	227	147	537	170
		CO2	81	228	147	530	167
2040	**A1B**	**No CO2**	79	222	143	515	159
		CO2	79	222	143	501	155
	B1	**No CO2**	80	225	145	524	167
		CO2	80	225	145	512	161
2080	**A1B**	**No CO2**	76	213	138	415	143
		CO2	76	213	138	384	130
	B1	**No CO2**	78	219	141	478	155
		CO2	78	219	141	462	149
Sweet Cherries							
		Historical	88	209	121	448	118
2020	**A1B**	**No CO2**	74	197	124	333	136
		CO2	74	197	124	333	134
	B1	**No CO2**	73	198	125	344	124
		CO2	73	198	125	343	128
2040	**A1B**	**No CO2**	70	192	122	311	127
		CO2	70	192	122	312	131
	B1	**No CO2**	71	195	124	323	134
		CO2	71	195	124	325	134
2080	**A1B**	**No CO2**	65	175	118	239	124
		CO2	65	183	118	226	110
	B1	**No CO2**	68	189	121	285	129
		CO2	68	189	121	287	132

distributions of per-acre value of crop yields for apples and cherries in the period of the 2020s, 2040s, and 2080s (in the absence of adaptation) at 2000-2007 prices and 2007 costs . The figure indicates a substantial shift toward lower yields and therefore, lower values per acre. For apples it also shows the effect of CO_2 fertilization and the inverse effect of lower yields causing higher prices. Cherries do not have a price effect in this analysis, and are an early seasonal crop that may not be able to take advantage as apples do of higher CO_2 in the 2040s. As a consequence, in Table 6 yields and values of cherry production in Figure 9 fall between the 2020s and the 2040s for those with junior water rights. For senior irrigators, CO_2 fertilization appears to increase yields and warmer weather appears to produce less negative effects on yields, as shown in Table 6.

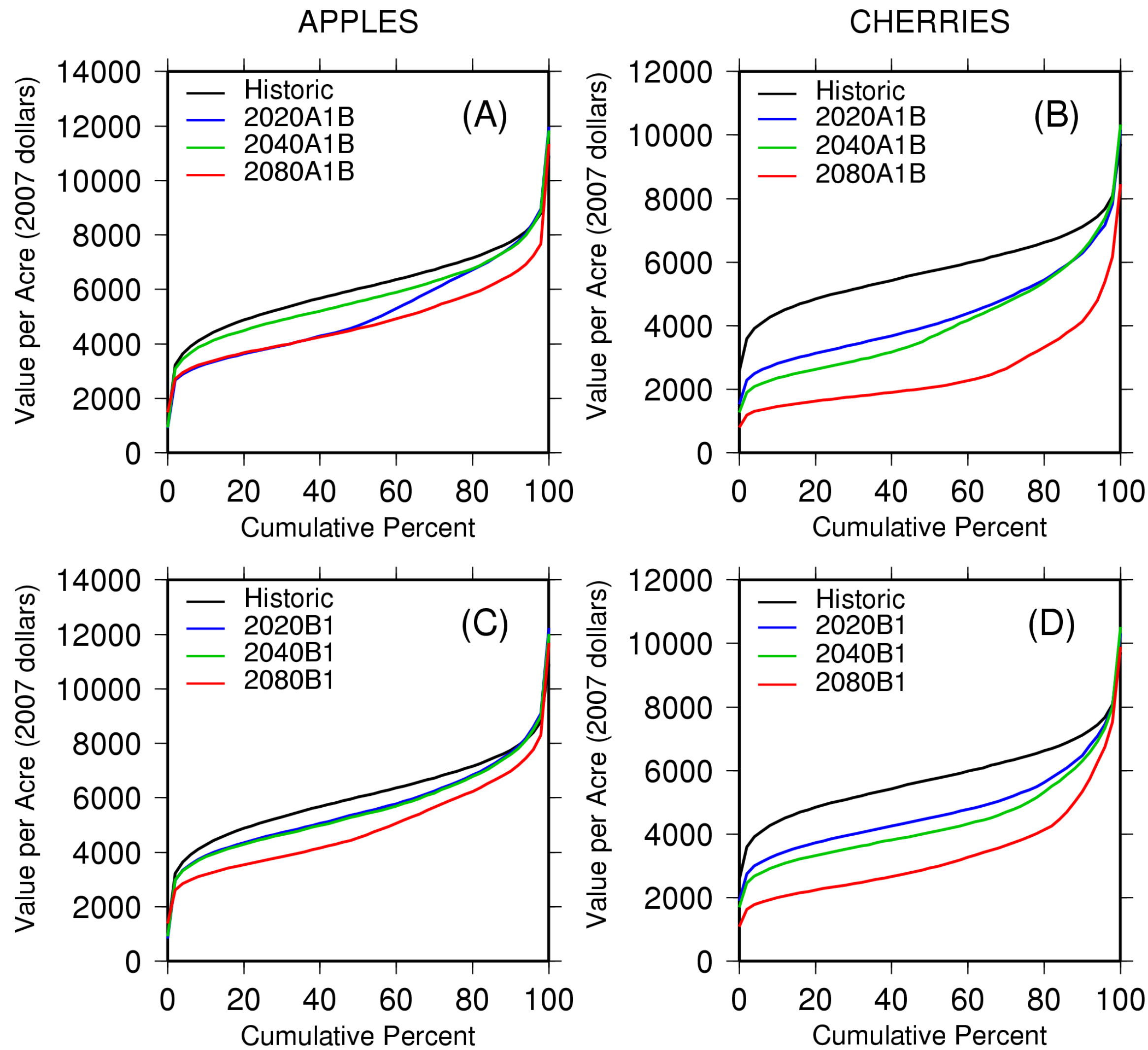

Figure 9. Impact of climate change for junior irrigators of apples A1B (A), cherries A1B (B), apples B1 (C), and cherries B1 (D) on value of production per acre in the 2020s, 204s, and 2080s.

Table 8 shows the impact of climate change on average physical yields and on the mean and standard deviations of per-acre value of production, per-acre operating profit, and overall value of production for apples and cherries in the Yakima River basin. The table shows that in all three future time periods (2020s, 2040s, and 2080s) and for both crops, lower water availability substantially reduces the per-acre average value of production as well as net operating profit. In addition, there is an increasing probability of poor harvest years, leading to greater and more frequent operating losses. Table 8 shows that the expected annual operating profit on junior land raising cherries goes from a net profit to a net loss in both the A1B and B1 scenarios and that apples become increasingly unprofitable. These losses can be attributed to lack of water. With full water availability, as Table 6 shows, the projected climate change would not be harmful. These negative results for water-limited apple production indicate why there is the difference from the generally positive results for fully irrigated apples reported by Stöckle et al. (2009, this report).

The estimated expected average loss of annual value of production for these two crops from climate change ranges between \$23 million (2020s, B1 scenario) and \$70 million (2080s, A1B scenario) per year, even with CO_2

Table 8. Impact of climate change (A1B and B1 scenarios) on value of production, operating profit, and aggregate value of production for irrigated apples and cherries in the Yakima River basin, 2020s, 2040s, and 2080s

		Historical Conditions (1975-2004)	A1B 2020s	B1 2020s	A1B 2040s	B1 2040s	A1B 2080s	B1 2080s
Average and Standard Deviation of Value Per Acre, Junior Water Rights Growers (2007 Dollars)								
Apples	Expected Value	$6,017	$5,118	$5,599	$5,659	$5,531	$4,763	$4,867
	Standard Deviation	$1,357	$1,694	$1,501	$1,399	$1,486	$1,277	$1,504
Cherries	Expected Value	$5,733	$4,311	$4,729	$4,028	$4,364	$2,492	$3,325
	Standard Deviation	$1,073	$1,394	$1,266	$1,601	$1,342	$1,204	$1,420
Average and Standard Deviation of Annual Operating Profit/Acre, Junior Water Rights Growers (2007 Dollars)								
Apples	Expected Value	($14)	($729)	($367)	($291)	($403)	($914)	($867)
	Standard Deviation	$1,357	$1,470	$1,394	$1,332	$1,371	$1,148	$1,317
Cherries	Expected Value	$1,163	$128	$432	($79)	$166	($1,197)	($590)
	Standard Deviation	$1,046	$1,151	$1,091	$1,275	$1,118	$936	$1,119
Average and Standard Deviation of Total Annual Value of Production (Million 2007 Dollars)								
Apples	Expected Value	$379,392	$344,102	$362,963	$365,343	$360,297	$330,148	$334,228
	Standard Deviation	$96,157	$100,173	$97,931	$95,280	$96,906	$86,114	$92,834
Cherries	Expected Value	$61,663	$52,616	$55,272	$50,813	$52,953	$41,038	$46,343
	Standard Deviation	$11,127	$11,911	$11,493	$12,810	$11,680	$10,166	$11,593
Total	Expected Value	$441,055	$396,718	$418,235	$416,156	$413,250	$371,187	$380,571

fertilization. This decline is between 5% and 16% of historical averages for these crops and between 2% and 5% of the total value of the $1.3 billion of crops and animal products produced in the three counties (Yakima, Benton, and Kittitas) that correspond to the Yakima basin (USDA 2004). It does not account for additional economic losses that may arise from loss of or permanent damage to trees, from carryover effects on yields, or from effects on fruit size, quality, or marketability. It also does not account for the impacts on other crops. An average 5% to 16% decline in the $913 million in (mostly irrigated) crops produced annually in the three counties would range from $46 million to $146 million per year.

6. Conclusions

Climate change is projected to impact water supply within the Yakima River basin, especially for water users with junior water rights and - in the most extreme years – users with senior water rights. Due to changes in seasonal patterns of runoff, the system is projected to become increasingly unable to meet deliveries to junior water rights, and these increased occurrences of curtailments for junior water users may be substantial even in the 2020s. In the recent historical record, the Yakima basin has been significantly water short (as defined by 75% or less of prorating for junior water users) 14% of the years. Without adaptations, projections of the A1B emission scenarios indicate that this value may increase to 32% (with a range of 15% to 54%

over ensemble members) in the 2020s, and may increase further to 36% in the 2040s, and 77% in the 2080s. The B1 emissions scenario would likely have a slightly smaller impact on water shortages than A1B. In the 2020s, our projections show chances of prorating may occur in 27% of years for the composite runs (with an ensemble range from 14% to 54%), 33% for the 2040s and 50% for the 2080s.

Assuming current water rights and operating policies, these changes in system performance may result in decreases in economic value of crop production. Even with earlier crop development, which may somewhat reduce the impacts of summer water shortages, the expected value of production on junior lands may decline substantially as early as the 2020s. Without adaptation, the expected annual profits of perennials on junior land are much more likely to be negative, putting the success of many farm operations in doubt. In addition, the total annual value of farm production for the two crops discussed may decline anywhere from about $23 million to $70 million, depending on the time period and scenario, about 2% to 5% of total current farm production in the three counties that correspond to the Yakima River basin. Because many junior acres in the Yakima are devoted to other crops that would also be harmed by water shortages, the reductions in economic value could be larger. Additionally, shortages to senior water rights, although small, remove elasticity in the system and therefore impact the ability to transfer water in those years. Economic costs in those years may be more extreme because of lasting damage to perennial crops. Future planning within the basin must consider this, in addition to other changes as water rights are further adjudicated and because of legal mandates for instream flows.

Additional research should explore adaptations to future changes. By changing reservoir operation rules and allowing water to move between water users, as discussed further in Whitely Binder et al. (2009, this report), impacts may be reduced. How to adapt to future change requires careful consideration, especially because winter reservoir storage is projected to increase, therefore narrowing the time period between when managers decide to release water to prevent floods and to store water for summertime irrigation.

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