Prepared in cooperation with the Bureau of Reclamation

Effects of Potential Future Warming on Runoff in the Yakima River Basin, Washington

Scientific Investigations Report 2008–5124

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph of U.S. Geological Survey Hydrologist, John Vaccaro, standing in Cabin Creek near Easton, Washington. (Photograph taken by Mark Mastin, U.S. Geological Survey, 1998.)

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Conversion Factors

Multiply	By	To obtain
acre	4,047	square meter (m^2)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32)/1.8.$$

Datums

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929).

Altitude, as used in this report, refers to distance above the vertical datum.

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By Mark C. Mastin

Abstract

The Bureau of Reclamation has implemented a long-term planning study of potential water-storage alternatives in the Yakima River Basin, which includes planning for climate change effects on available water resources in the basin. Previously constructed watershed models for the Yakima River Basin were used to simulate changes in unregulated streamflow under two warmer climate scenarios, one representing a 1ºC increase in the annual air temperature over current conditions (plus one scenario) and one representing a 2ºC increase in the annual air temperature over current conditions (plus two scenario). Simulations were done for water years 1981 through 2005 and the results were compared to simulated unregulated runoff for the same period using recorded daily precipitation, and minimum and maximum air temperatures (base conditions). Precipitation was not altered for the two warmer climate change scenarios.

Simulated annual runoff for the plus one and plus two scenarios decreased modestly from the base conditions, but the seasonal distribution and the general pattern of runoff proved to be highly sensitive to temperature changes throughout the basin. Seasonally increased runoff was simulated during the late autumn and winter months for both the plus one and plus two scenarios compared to base conditions. Comparisons at six principal regulatory locations in the basin showed that the maximum percentage increases in runoff over the base conditions during December to March varied from 24 to 48 percent for the plus one scenario and 59 to 94 percent for the plus two scenario. During late spring and summer months, significantly decreased runoff was simulated at these sites for both scenarios compared to base conditions. Simulated maximum decreases in runoff occurred during June and July, and the changes ranged from -22 to -51 percent for the plus one scenario and -44 to -76 percent for the plus two scenario. Differences in total annual runoff at these sites ranged from -1.4 to -3.9 percent for the plus one scenario and from -2.5 to -8.2 percent for the plus two scenario. The percent change of the monthly mean runoff for both scenarios from the base conditions at many points in the basin will be used in a water-management model developed by the Bureau of Reclamation to assess various storage alternatives.

Introduction

The Bureau of Reclamation (Reclamation) is studying the benefits of additional water storage in the Yakima River Basin (Yakima River Basin Water Storage Feasibility Study or Storage Study) for agriculture, fish, and municipal uses. Long-term planning into the mid-21st century requires consideration of anticipated climate variability and change. Current hydrologic trends and global climate models indicate that the climate of the Pacific Northwest, a region that includes the Yakima River Basin, will be warmer than it is today by the mid-21st century and that streamflow patterns will change (Cayan and others, 2001; Mote, 2003; Stewart and others, 2004).

The U.S. Geological Survey (USGS), in collaboration with Reclamation, developed a detailed set of watershed models (Mastin and Vaccaro, 2002) for non-irrigated areas of the basin under the Watershed and River Systems Management Program (WARSMP; U.S. Geological Survey, 1998). The watershed models have been linked to a Reclamation-developed water management model (RiverWare, Bureau of Reclamation, 2000) currently used for planning and operations in the Yakima River Basin. Reclamation requested that the USGS (L. Brekke, Bureau of Reclamation, written commun., July 2007) use these watershed models to simulate the sensitivities of runoff (streamflow) to potential future warming trends, relative to the current runoff characteristics for water years 1981–2005, referred to as the base period.

Simple climate changes were imposed on the watershed models based on averaged results of global climate models for the Pacific Northwest compiled by the University of Washington Climate Impacts Group (CIG) (Mote and others, 2003). The evaluation of the sensitivities of runoff for these particular climate changes was done by modifying the temperature-related watershed model parameters, running the modified model for the base period, and comparing simulated unregulated runoff to that simulated by the unaltered model.

Purpose and Scope

This report documents the methods used to simulate changes in runoff from current conditions defined as the simulated runoff for the base period (water years 1981–2005) to simulated runoff for two warming-trend scenarios. Simulated runoff was generated using a previously documented watershed model (Mastin and Vaccaro, 2002) for the Yakima River Basin. Two imposed climate scenarios representing warmer climates were simulated by adding 1ºC and then 2ºC to the daily minimum and maximum air temperatures of the model input. The temperature increases varied monthly according to climate change studies modeled for the 2040s. The data will be used by Reclamation as input to its water-management model to simulate regulated runoff under future warming-trend scenarios. The results from RiverWare model simulations will be used in long-term planning of several proposed water-storage alternatives for the basin.

Yakima River Basin Study Area

The Yakima River Basin drainage area is about 6,200 mi^2 and produces a mean annual unregulated runoff of about 5,600 ft^3/s (about 4.1 million acre-ft, or 12.3 in.) and a regulated runoff of about 3,600 ft^3/s (about 2.6 million acre-ft, or 7.9 in.) with reductions accounted for by irrigation diversions and return flows. The headwaters are on the humid east slope of the Cascade Range, where mean annual precipitation is more than 100 in. The basin ends at the confluence of the Yakima and Columbia Rivers in the low-lying, arid part of the basin that receives about 6 in. of precipitation per year. Most precipitation falls during the winter in the form of snow in the mountains. Mean annual precipitation for the entire basin is about 27 in. (about 12,000 ft^3/s, or 8.7 million acre-ft). The spatial pattern of precipitation resembles the pattern of the highly variable topography of the basin, which ranges in altitude from 400 to 8,200 ft.

Agriculture is the primary economic activity in the basin. Average annual surface-water demand is about 2.5 million acre-ft. Most demand is for the irrigation of about 500,000 acres in the low-lying semiarid to arid parts of the basin that, for the most part, is met by surface-water diversions. This demand is partially met by storage in five Reclamation reservoirs (Bumping, Cle Elum, Kachess, Keechelus, and Rimrock Lakes; fig. 1) that can store 1.1 million acre-ft of water.

Snow accumulation usually begins in late October or early November and ends by April. Snowmelt is critical for supplying runoff to fill reservoirs and to meet irrigation demands. The highest monthly runoff follows melting of the snowpack. The runoff volume during the irrigation season (generally April through August) closely relates to the volume of the snowpack on April 1. An example of this relation can be seen in a comparison of runoff for the American River near Nile, Washington, with April 1 snowpack (fig. 2).

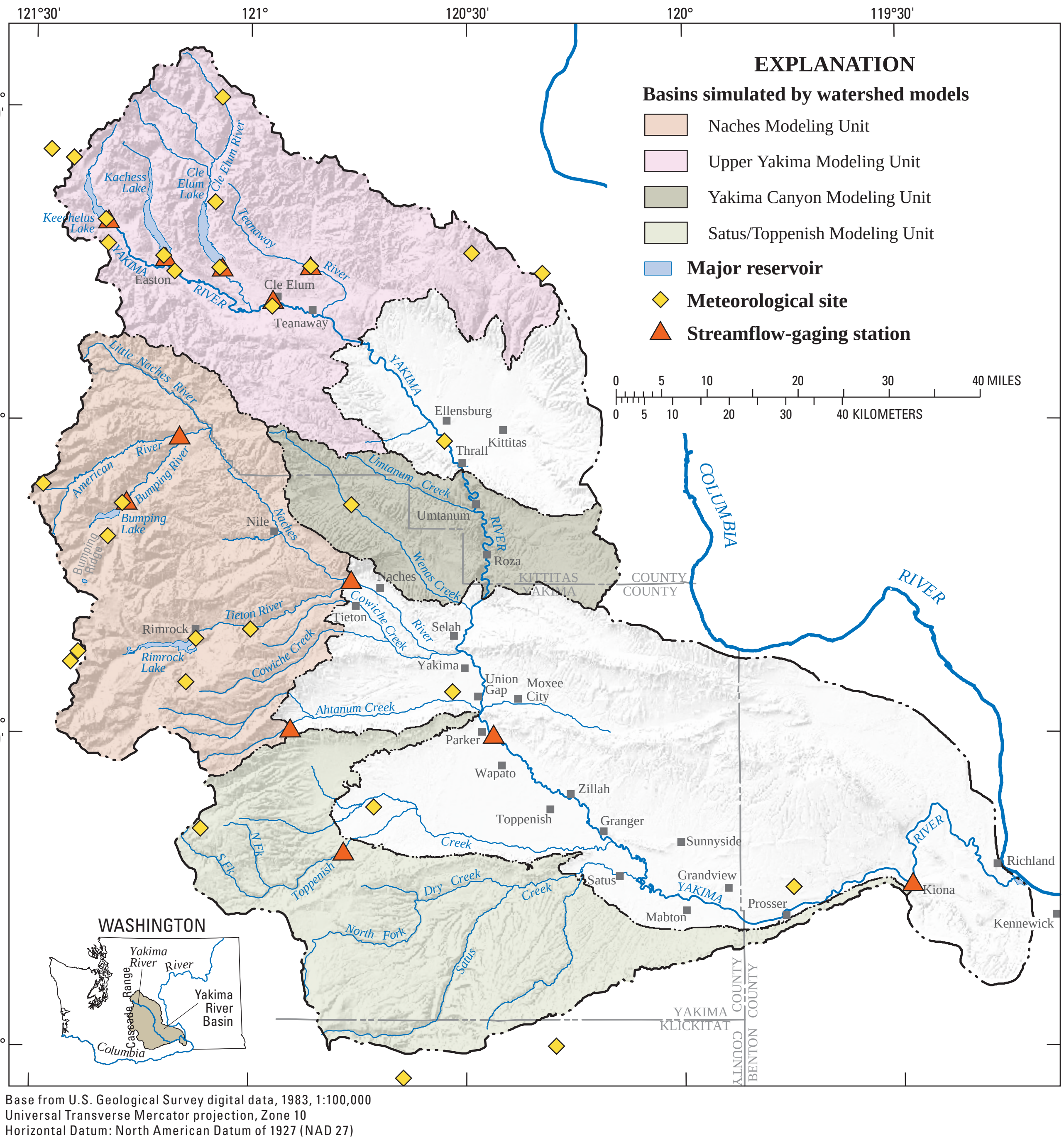

Figure 1. Major reservoirs managed by the Bureau of Reclamation, meteorological and streamflow-gaging stations, and subbasins simulated by the four watershed models, Yakima River Basin, Washington.

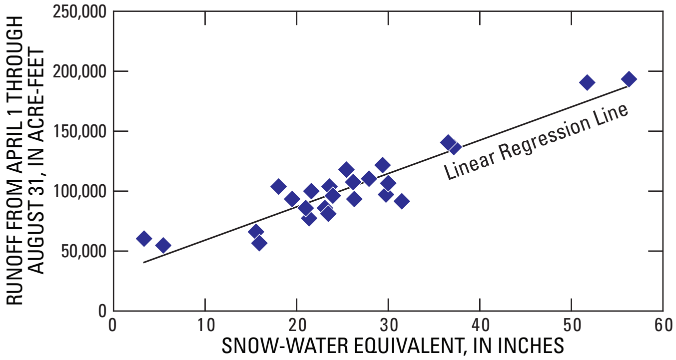

Figure 2. Comparison of irrigation season (April through August) runoff at American River near Nile, and snow-water equivalent at Bumping Ridge on April 1 for water years 1979, 1981, and 1984–2006, Yakima River Basin, Washington.

Imposed Climate Changes

The climate changes considered here include changes in air temperature only, not changes in precipitation. The CIG (Mote and others, 1999, p. 36) determined that, "Projections of temperature changes, both globally and regionally, are made with higher confidence than precipitation changes." Global climate models predict increases and decreases in precipitation for the Pacific Northwest. Due to this lack of consensus on future changes in precipitation, this study used precipitation values for the climate change scenarios that were the same as those measured for the base period.

The CIG reviewed the results of eight global climate models available from the Intergovernmental Panel on Climate Change (IPCC), most were run for 1900–2100, and averaged the results for the Pacific Northwest region (Mote and others, 2003). Average temperature changes (compared to a control run that refers to 1990 measured temperatures) for the Pacific Northwest were 1.5ºC warmer for the 2020s and 2.3ºC warmer for the 2040s. Reclamation determined that two global climate change scenarios would be simulated for the Yakima River Basin analysis: (1) average annual warming of 1ºC relative to the base climate period that represents early 21st century conditions for the region ("plus one" scenario) and (2) average annual warming of 2ºC relative to the base climate period ("plus two" scenario) that represents mid-21st century conditions (L. Brekki, Bureau of Reclamation, written commun., 2007). The Pacific Northwest is described in Mote and others (2003) as regionally coherent where "warm years tend to be warm, and cool years cool, everywere in the region." For this reason, only regionally averaged change is considered and the temperature changes are assumed to be distributed uniformly across the basin.

Annual air temperature changes were divided into monthly changes based on seasonal changes projected for the Columbia River Basin based on IPPC Third Assessment Report models for the 2040s (Alan Hamlet, Climate Impact Group, University of Washington, written commun., 2007). Table 1 provides the monthly air temperature changes used in the watershed models to simulate the two climate-change scenarios. The watershed models operate in units of Fahrenheit, and therefore, both units are shown in table 1.

The evaluation of alternatives in Reclamation's Storage Study are based on the water availability for irrigation and instream flows in the Yakima River Basin for water years 1981–2005 (base period). The unregulated runoff simulated by the watershed models for the same period used the same parameters as those calibrated and tested for the WARSMP study (Mastin and Vaccaro, 2002), and was used as a basis to evaluate sensitivities to the climate change.

Table 1. Monthly changes in air temperature for the plus one and plus two climate change scenarios used in the watershed model simulations, Yakima River Basin, Washington.

[Plus one and plus two scenarios represent an approximate 1 and 2°C, respective annual increase in air temperature from the base climate period. **Abbreviations:** °C, degrees Celsius; °F, degrees Fahrenheit]

Month	Air temperature scenario			
	Plus one (°C)	Plus two (°C)	Plus one (°F)	Plus two (°F)
January	1.05	2.11	1.89	3.80
February	1.15	2.30	2.07	4.14
March	1.17	2.34	2.11	4.21
April	.85	1.69	1.53	3.04
May	.53	1.06	.95	1.91
June	1.01	2.01	1.82	3.62
July	1.19	2.38	2.14	4.28
August	1.34	2.68	2.41	4.82
September	.91	1.83	1.64	3.29
October	.94	1.89	1.69	3.40
November	.72	1.44	1.30	2.59
December	1.14	2.27	2.05	4.09

Watershed Models

Unregulated runoff in the Yakima River Basin was simulated for the warm-climate scenarios by the existing watershed models constructed using the Modular Modeling System (MMS; Leavesley and others, 1996) a component of WARSMP. Using a digital elevation model and a Geographic Information System (GIS) interface called the Weasel (Leavesley and others, 1997), four upland watershed models were delineated for the Yakima River Basin (fig. 1) upstream of the low-lying agricultural basins where streamflow diversions for irrigation and agricultural return flows begin. The modeled area in the basin accounts for more than 95 percent of the total runoff generated within the entire basin. Within the four models, areas of similar hydrologic responses called model response units (MRUs) were delineated based on drainage pattern, precipitation, elevation, and soil characteristics; 1,110 MRUs in total were delineated for the four models. A complete discussion of the construction of the models is available in Mastin and Vaccaro (2002). The climate data input to the models include daily precipitation at 26 sites, and daily minimum and maximum air temperature at 24 sites. A daily water balance was simulated at each MRU and runoff from surface, sub-surface, and ground-water sources was generated and accumulated at flow-routing nodes and used to simulate flow in channels. For the WARSMP, the models were calibrated to measured and estimated streamflow for water years 1950 through 1994 by adjustment of model parameters. The models were tested by holding the parameter values constant, running the model for 1995 through 1998, and comparing the simulated runoff with measured runoff.

Air temperature was used in the watershed models to estimate potential evapotranspiration and solar radiation. The increased air temperature for the two warmer climate scenarios increased the potential evapotranspiration, and therefore, the actual evapotranspiration on each MRU over the base conditions scenario. Solar radiation that reaches the land surface was first estimated from a relation between recorded air temperature and cloudiness for a selected flat location and then adjusted for slope angle and orientation at each MRU. This relation uses the unadjusted recorded air temperatures, and therefore, the estimated solar radiation is the same for all scenarios. Estimated solar radiation was used in the calculations of potential evapotranspiration and the energy budget for snow simulation in the watershed models.

The four WARSMP models were used to simulate runoff at selected flow-routing nodes for the base period (water years 1981–2005) for base conditions. Average runoff was calculated for each month and a mean monthly value was computed for the entire base period. Runoff for the plus one and plus two scenarios was simulated for the base period by changing the monthly adjustment parameters that represent the daily minimum temperature (tmin_adj) and the daily maximum temperature (tmax_adj) to reflect the expected air temperature changes shown in table 1. The model computes maximum air temperature for a particular MRU using all the valid maximum temperature inputs measured at a climate station inversely weighted by distance from the station to the MRU and adjusted using computed lapse rates.

Three model simulations were made with each of the four watershed models and mean monthly runoff at all the flow-routing nodes were saved so they can be used as input of unregulated runoff for the RiverWare model. The mean runoff for each month and the annual runoff for the base period (water years 1981–2005) was then determined. The simulated changes in runoff are provided as percentages of change in monthly runoff; the percentages of change in runoff for the plus one and plus two scenarios from the base conditions simulated were computed from monthly and annual means computed for the base period.

Simulated Runoff Results

This section focuses only on the results for a set of six selected sites because the same general pattern of change to runoff occurs at all model nodes. Results of runoff changes at six regulatory locations in the basin are shown in figure 3 and table 2. The locations include the points of inflow of five Reclamation-operated reservoirs in the basin (Bumping, Cle Elum, Kachess, Keechelus, and Rimrock Lakes) and one streamflow-gaging station that is monitored for regulating discharge on the lower Yakima River (Yakima River near Parker, fig. 1). The percentage of change in runoff for the plus one and plus two scenarios from the base conditions simulation, and the monthly and annual means computed for the period of simulation for 37 subbasins are presented in appendix A. These changes show the sensitivity of runoff to increased air temperature.

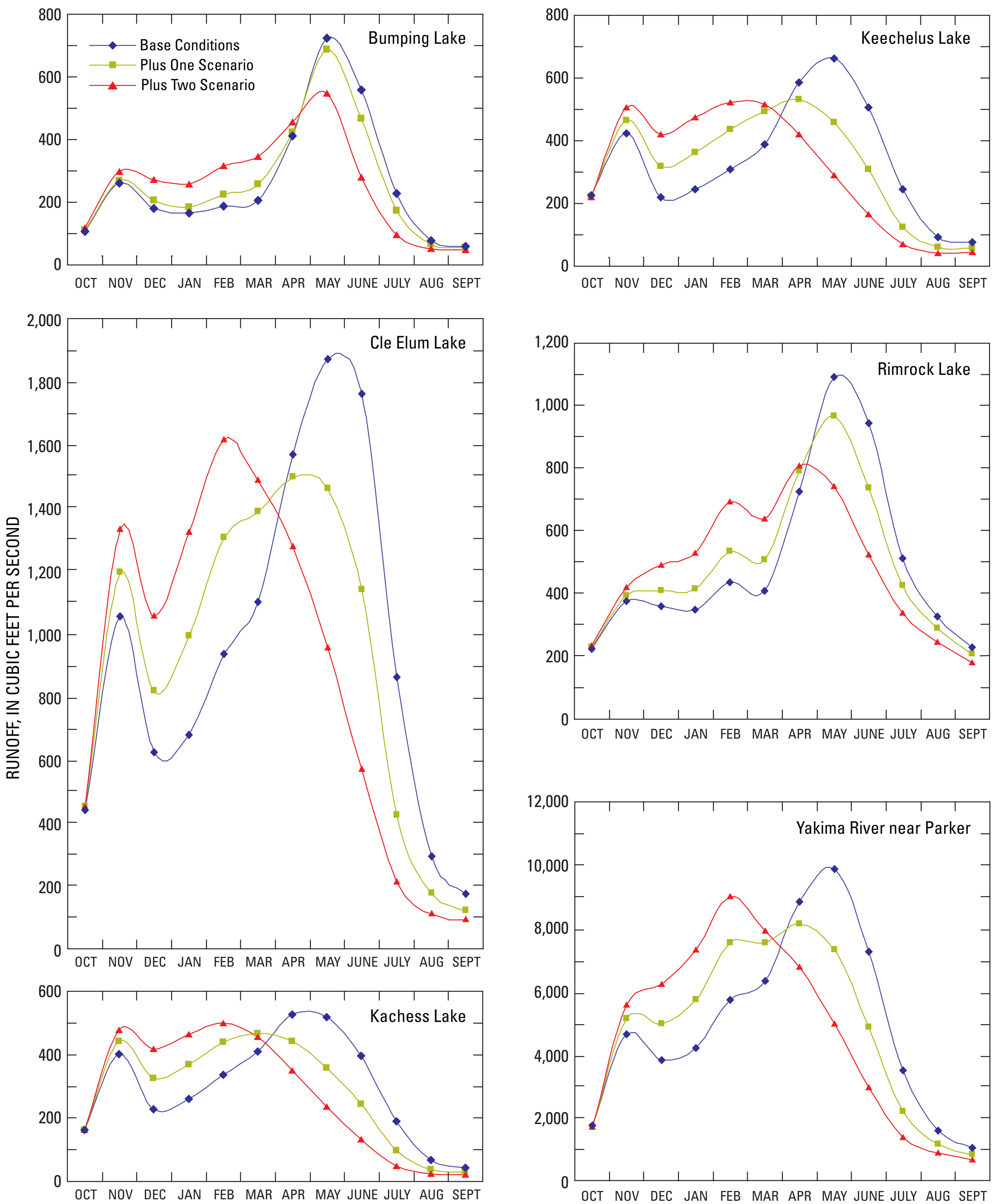

Figure 3. Simulated mean monthly runoff for base conditions and plus one and plus two scenarios at selected sites in the Yakima River Basin, Washington.

Table 2. Simulated changes in mean monthly runoff and mean annual runoff from the base condition for the plus one and plus two scenarios at selected sites in the Yakima River Basin, Washington.

[Plus one and plus two scenarios represent an approximate 1 and 2°C, respective annual increase in air temperature from the base climate period. **Abbreviation:** °C, degrees Celsius]

Site	Simulated change in mean monthly runoff (percent)				Simulated change in mean annual runoff (percent)
	Maximum positive change	Month of maximum change	Maximum negative change	Month of maximum change	
Plus one scenario					
Yakima River near Parker	35.9	January	-37.6	July	-2.8
Bumping Lake	25.2	March	-24.9	July	-1.3
Cle Elum Lake	46.0	January	-50.8	July	-3.8
Kachess Lake	41.8	December	-49.2	July	-3.9
Keechelus Lake	47.6	January	-49.9	July	-3.7
Rimrock Lake	23.5	February	-21.9	June	-1.4
Plus two scenario					
Yakima River near Parker	73.0	January	-60.6	July	-6.1
Bumping Lake	69.7	March	-59.0	July	-2.7
Cle Elum Lake	94.4	January	-75.7	July	-8.2
Kachess Lake	81.9	December	-73.7	July	-7.6
Keechelus Lake	93.1	January	-71.3	July	-7.5
Rimrock Lake	59.1	February	-44.3	June	-2.5

The change in mean monthly values for the plus one and plus two scenarios compared to base conditions ranged from about +48 to -51 percent for the plus one scenario and +94 to -76 percent for the plus two scenario (table 2). The maximum positive percentage deviations from the base conditions occurred during December to March and the maximum negative percentage deviations occurred during June and July. Mean annual changes for the warmer scenarios at the six selected sites were modest and all negative, ranging from -1.3 to -3.9 percent for the plus one scenario and -2.5 to -8.2 percent for the plus two scenario (table 2). A wider range of percent change was found for the entire list of stations in appendix A. Mean annual change ranged from +1.33 to -12.85 percent with two thirds of the sites ranging from 0.00 to -6.75 percent for the plus one scenario and 1.56 to -24.54 percent for the plus two scenario with two thirds of the sites ranging from -1.24 to -14.73 percent.

The general change in the runoff pattern for the two climate change scenarios is shown in hydrographs of monthly means for the three sets of simulations (fig. 3). November through March simulated runoff for the warm-climate scenarios was greater compared to base conditions because more autumn/winter precipitation was simulated as rain rather than snow. Most precipitation that falls as rain will runoff quickly, but precipitation that falls as snow will accumulate in the snowpack and may not become runoff until later in the season when air temperatures increase.

Total simulated snowmelt for the base period was greater for all modeling units than the plus one and plus two climate scenarios (table 3). In a similar analysis for the Yakima River Basin using a 2ºC warming scenario, a -59 percent change in the April 1 snowpack snow-water equivalent (SWE) was simulated relative to base condition (1950–2005) simulations (Mastin and Sharp, 2006). That same analysis simulated the greatest percentage change in the snowpack SWE at lower altitudes (less than 4,000 ft), but the greatest absolute change was in the 4,000–5,000-ft altitude zone. In this study, the smallest percentage of change in annual runoff was in the two highest altitude subbasins, Bumping Lake and Rimrock Lake subbasins (table 2). The small change in simulated runoff from the Rimrock Lake subbasin is partially explained by the fact that the subbasin contains glaciers that were simulated with a simple glacier-melt coefficient related to air temperature that does not change the volume of the glaciers. Spring and summer runoff in the Yakima River Basin depends on the snowpack to sustain flows, so as snowpack accumulation is less in spring due to warming trends, the simulated runoff during spring and summer decreases. Figure 3 shows the plus one and plus two hydrographs crossing the base condition hydrographs in April or May and remaining less than the base-conditions hydrograph through the remainder of the water year.

Table 3. Simulated snowmelt for four watershed models for base conditions and plus one and plus two scenarios, water years 1981–2005, Yakima River Basin, Washington.

[**Base condition:** Simulated snowmelt for the base period (water years 1981-2005) using observed air temperatures. Plus one and plus two scenarios represent an approximate 1 and 2°C, respective annual increase in air temperature from the base climate period. KAF, thousand acre feet]

Modeling unit	Area, in acres	Simulated snowmelt					
		Base condition		Plus one		Plus two	
		Inches	KAF	Inches	KAF	Inches	KAF
Naches	708,543	566.5	33,449	511.7	30,213	435.7	25,726
Upper Yakima	721,638	806.7	48,512	703.8	42,324	575.9	34,633
Yakima Canyon	260,178	66.0	1,431	57.5	1,247	47.5	1,030
Satus/Toppenish	657,858	62.2	3,410	52.5	2,878	40.6	2,226
Total	2,348,217		86,802		76,662		63,615

Summary

Monthly percentage differences in unregulated simulated runoff at points throughout the Yakima River Basin for potential future warming trends compared to base conditions of unregulated simulated runoff for water years 1981 through 2005 were simulated using four previously calibrated watershed models. The watershed models were constructed and calibrated by the U.S. Geological Survey for the Watershed and River Systems Management Program (WARSMP). The simulated runoff for two different warm-climate scenarios will be used by the Bureau of Reclamation to adjust the unregulated runoff input to its water-management model of regulated runoff (RiverWare). The results from RiverWare model simulations will be used in long-term planning of several proposed water-storage alternatives for the basin.

The sensitivity of the runoff in the Yakima River Basin to potential future warming trends was computed with two warm-climate scenarios that were simulated with a set of monthly air temperature increases applied to the time series of minimum and maximum daily recorded air temperature for water years 1981–2005. The monthly distribution of temperature increases were based on seasonal changes projected for the Columbia River Basin for the early and mid-21st century and averaged 1ºC for the plus one scenario and 2ºC for the plus two scenario. Based on work by the Climate Impacts Group at the University of Washington that averaged the results of eight global climate models for the Pacific Northwest, the Bureau of Reclamation determined that the 1 and 2ºC annual temperature increases over the base period (water years 1981–2005) would be used as model scenarios because they represent reasonable estimates of global warming that can be expected by the early and mid-21st century respectively. Precipitation was not altered for the two warmer climate scenarios.

Unregulated runoff was simulated at many of the flow-routing nodes in the watershed models for use as input to the RiverWare model. The same general pattern of increased runoff during late autumn and winter months and decreased runoff during late spring and summer months for the climate change scenarios from the base conditions is seen at all the nodes. Comparisons of the plus one and plus two scenarios to base conditions at six regulatory locations (five reservoirs and one river location) in the basin indicated that the maximum increases over the base conditions during the months of December to March varied from 24 to 48 percent for the plus one scenario and 59 to 94 percent for the plus two scenario. During late spring and summer months, simulations of the regional warming trends at these sites all were less than the base conditions with maximum changes that occurred in June and July, ranging from -22 to -51 percent for the plus one scenario and -44 to -76 percent for the plus two scenario. Annual differences at these sites ranged from -1.4 to -3.9 percent for the plus one scenario and from -2.5 to -8.2 percent for the plus two scenario.

References Cited

Bureau of Reclamation, 2000, RiverWare: U.S. Bureau of Reclamation Fact Sheet, accessed November 2007 at http://www.usbr.gov/pmts/rivers/warsmp/riverware/index.html

Cayan, D.R., Kammerdiener, S.A., Dettinger, M.D., Caprio, J.M., and Peterson, D.H., 2001, Changes in the onset of spring in the western United States: Bulletin of the American Meteorological Society, v. 82, p. 399–415.

Leavesley, G.H., Restrepo, P.J., Markstrom, S.L., Dixon, M., and Stannard, L.G., 1996, The Modular Modeling System (MMS)—User's Manual: U.S. Geological Survey Open-File Report 96-151, 142 p.

Leavesley, G.H., Viger, R.J., Markstrom, S.L., and Brewer, M.S., 1997, A modular approach to integrating environmental modeling and GIS: Proceedings of 15th IMACS World Congress on Scientific Computation, Modelling, and Applied Mathematics, Berlin, Germany, August 24–29, 1997, 7 p.

Mastin, M.C., and Sharp, W., 2006, Comparison of simulated runoff in the Yakima River Basin, Washington, for present and global climate-change conditions: Proceedings of the Third Federal Interagency Hydrologic Modeling Conference, Reno, Nev., April 2–6, 2006.

Mastin, M.C., and Vaccaro, J.J., 2002, Watershed models for decision support in the Yakima River Basin, Washington: U.S. Geological Survey Open-File Report 02-404, 48 p.

Mote, P.W., 2003, Trends in temperature and precipitation in the Pacific Northwest during the twentieth century: Northwest Science, v. 77, no. 4, p. 271–278.

Mote, P.W., Holmberg, M., Mantua, N.J., and Climate Impacts Group, 1999, Impacts of climate variability: National Atmospheric and Oceanic Administration, Office of Global Programs, and JISAO/SMA Climate Impacts Group, Seattle, Washington, 110 p.

Mote, P.W., Parson, E.A., Hamlet, A.F., Keeton, W.S., Lettenmaier, D., Mantua N., Miles, E.L., Peterson, D.W., Peterson, D.L., Slaughter, R., and Snover, A.K., 2003, Preparing for climatic change—The water, salmon, and forests of the Pacific Northwest: Climatic Change, v. 61, no. 1 and 2, p. 45–88.

Stewart, I.T., Cayan, D.R., and Dettinger, M.D., 2004, Changes in snowmelt runoff timing in western North America under a 'Business as Usual' climate change scenario: Climatic Change, v. 62, p. 217–232.

U.S. Geological Survey, 1998, Watershed and River Systems Management Program—Application to the Yakima River Basin, Washington: U.S. Geological Survey Fact Sheet 037-98, 4 p.

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Appendix A. Mean Monthly and Annual Unregulated Runoff Simulated for Base Conditions and Two Climate Change Scenarios, Plus One and Plus Two, for Indicated Subbasins

The percentage of change in runoff for the plus one and plus two scenarios from the base conditions simulation, and the monthly and annual means computed for the period of simulation for 37 subbasins are presented in appendix A in a spreadsheet in Microsoft© Excel. The appendix can be accessed and downloaded at URL http://pubs.usgs.gov/sir/2008/5124/sir20085124_appendix.xls.

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