COMPARISON OF SIMULATED RUNOFF IN THE YAKIMA RIVER BASIN, WASHINGTON, FOR PRESENT AND GLOBAL CLIMATE-CHANGE CONDITIONS

Authors: Mark Mastin, U.S. Geological Survey, Tacoma, WA; Warren Sharp, U.S. Bureau of Reclamation, Yakima, WA

Mark Mastin, U.S. Geological Survey, 1201 Pacific Ave., Suite 600, Tacoma, WA, 98402; phone (253) 428-3600; mcmastin@usgs.gov; Warren Sharp, U.S. Bureau of Reclamation, P.O. Box 1749, Yakima, WA, 98902, phone (509) 575-5848, email wsharp@pn.usbr.gov

Abstract: The U.S. Geological Survey and the U.S. Bureau of Reclamation are collaborating on the Watershed and River Systems Management Program (WARSMP). The goals of WARSMP are (1) to develop and couple watershed and river-management models that simulate runoff and streamflow with river and reservoir simulations that account for water availability and use, and (2) to apply the coupled models as a decision support system to U.S. Bureau of Reclamation projects in the western United States.

The program has been applied to the U.S. Bureau of Reclamation's Yakima Project in central Washington, to aid in the management and allocation of water resources for irrigation and instream flows. The coupling of watershed and river-management models constructed with the U.S. Geological Survey's Modular Modeling System (MMS) and a river and reservoir-management model (Riverware) is achieved through the use of a common hydrologic database (HDB).

The coupled models for the Yakima River Basin were used to simulate water availability for a global climate-change (GCC) scenario that assumed that daily air temperature increased 2 degrees Celsius over present conditions. Precipitation was assumed to remain unchanged. Simulated watershed runoff for the GCC scenario for water years 1950-2005 was compared to simulated runoff for present conditions. On average, the increased temperatures in the GCC scenario cause runoff to be redistributed during different seasons of the year, by generating higher flows in winter, earlier peak runoff, low spring and summer runoff, and less annual runoff overall than the present conditions. Such a pattern would likely pose difficult challenges to water managers in watersheds with limited water storage and high water demand.

Selected subsets of the existing climate record for drought years and warmer-than-average years also were simulated to characterize the challenges that they present. Daily median runoff simulated for the GCC scenario for water years 1950-2005 produced more runoff during the irrigation season (April 1 to August 31 for this analysis) than the two simulated extreme drought years and one extreme warm year, but the 90-percent exceedence simulated by the GCC scenario produced less runoff than any of the extreme years simulated for the present unregulated-flow scenario.

INTRODUCTION

The U.S. Geological Survey (USGS) and the Bureau of Reclamation (Reclamation) are working collaboratively on the Watershed and River Systems Management Program (WARSMP). The goals of WARSMP are (1) to develop and couple watershed and river-management models that simulate the physical hydrology with routing and reservoir-management models that account for water availability and use, and (2) to apply them as a decision support system (DSS) to Reclamation projects in the western United States. The key to coupling these models is linking them through a common database, termed the hydrologic database (HDB) for WARSMP. Output from one model can be written to the HDB for use as input to another model. The HDB also links ancillary tools such as a geographical information system (GIS), statistical analysis, and data query and display capabilities. The coupling, interaction, and other capabilities of the DSS allow for improved assessments of long-term planning and policy decisions, in addition to the major program thrust of improving short-term and mid-term operations of Reclamation projects.

WARSMP has been applied in the Yakima River Basin in eastern Washington (fig. 1), where long-term water-management planning must accommodate future irrigation demand and instream flows for endangered salmonids. Without a sufficient springtime snowpack and reservoir storage, irrigators with junior water rights may not receive their full allotment and juvenile salmonids may not successfully migrate to the ocean due to insufficient streamflows. When evaluating the long-term future hydrology of the basin, it is important to consider how drought years can be managed and what the effects of global climate change may be on the availability of water resources for irrigation and instream needs.

The USGS Modular Modeling System (MMS) is being used for the watershed-modeling component of this study. MMS is an integrated system of computer software developed to provide a framework for the development and application of numerical models (Leavesley, et al., 1996). Four watershed models (fig. 1) for simulating unregulated streamflow were constructed and calibrated for the Yakima River Basin. The watersheds were selected because they account for more than 90 percent of the streamflow in the Yakima River Basin, contain the five major reservoirs managed by Reclamation, and are relatively unaffected by ungaged diversion and irrigation. The models use the precipitation-runoff modeling system (PRMS; Leavesley, et al., 1983), a model component of MMS. PRMS allows for the spatial distribution of hydrologic-model parameters by partitioning, or characterizing a subbasin into modeling response units (MRUs). Partitioning was based on flow-planes, altitude, mean annual precipitation, and soil characteristics, resulting in 1,110 MRU units for the four watershed models (Mastin and Vaccaro, 2002).

The Climate Impacts Group at the University of Washington (UW) averaged the results of three older (1995) and four newer (1998) global climate models for the Pacific Northwest (Mote, et al., 1999). They found that, “Projections of temperature changes, both globally and regionally, are made with higher confidence than precipitation changes.” The climate models simulated increases and decreases in precipitation, and therefore, due to this lack of consensus on precipitation change in the future, it was assumed in this study that precipitation in the GCC scenario would remain the same as that measured for water years 1950-2005. The average simulated air temperature increase in the models compiled by UW was 3.1^{o}F (1.72^{o}C) by 2020 and 5.3°F (2.9°C) by 2050. With the exception of one of the older models, there was little seasonal variation in the air temperature changes. The GCC scenarios examined in this paper used a simple approach of adding 3.6°F (2.0°C) to the daily minimum and maximum air temperatures for the time period of water years 1950 through 2005.

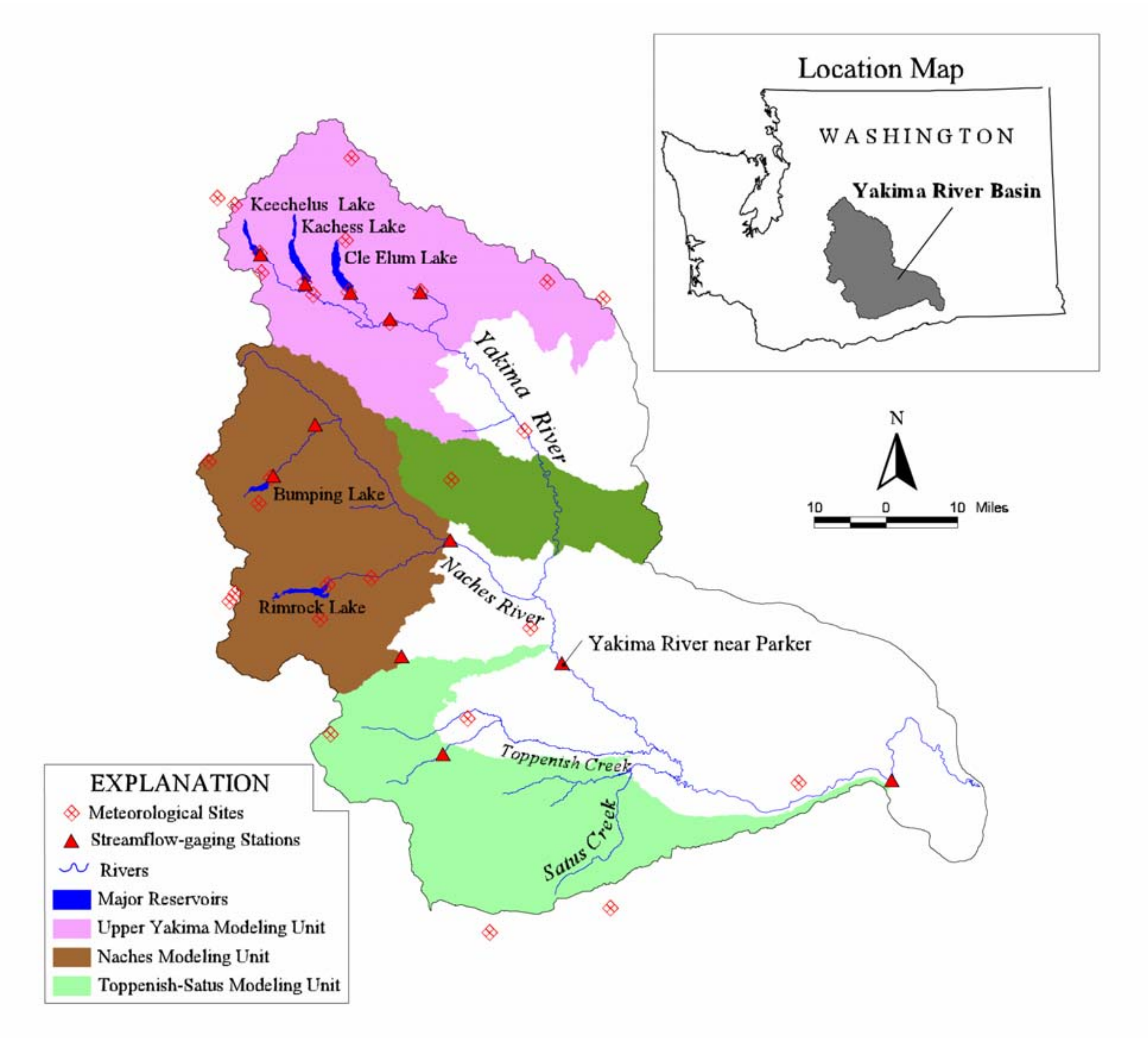

Figure 1. Four watershed modeling units and lakes, streamflow-gaging stations, and meteorological sites in the Yakima River Basin, Washington.

Runoff for the GCC scenario was simulated for water years 1950-2005. Simulated runoff for the GCC scenario was compared with simulated runoff for present climate condition during the same time period—a scenario referred to hearin as the present unregulated-flow (PUF) scenario. Runoff simulations using MMS are compared at six assessment sites: the five major reservoirs operated by Reclamation and at Yakima River near Parker, which is an important streamflow-gaging site used for regulating streamflow in the lower part of the Yakima River. The comparisons focus on the the timing of runoff throughout the year, spring snowpack conditions (April 1), and irrigation runoff volumes (April 1 through August 31). Simulated runoff for the GCC scenario also was compared with two extreme drought years (1977 and 2005) and an exceptionally warm water year 1992.

The agricultural industry was impacted significantly during drought years 1977 and 2005 because irrigators did not receive their full allotment of water. Reclamation makes forecasts of total water supply available (TWSA) each month through the irrigation season generally beginning in February to allow irrigators to plan for the upcoming irrigation season. When the TWSA is estimated to be less than needed to meet instream target flows and irrigation demands, the deficit is met by reducing diversions to irrigators with junior water rights by a specific percentage of their full allotment (proration). Forecasts of proration to irrigators with junior water rights ranged from 6 to 50 percent (February to May) in 1977 (Glantz, 1982) and from 34 to 41 percent (March to July) in 2005 (Bureau of Reclamation, 2005).

YAKIMA RIVER BASIN

The Yakima River Basin has a drainage area of about 6,200 square miles (mi^2) and produces a mean annual unregulated runoff of about 5,600 cubic feet per second (ft^3/s) (about 4.1 million acre-feet, or 12.3 inches) and a regulated runoff of about 3,600 ft^3/s (about 2.6 million acre-feet, or 7.9 inches) that accounts for 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 inches. The basin ends at the confluence of the Yakima and Columbia Rivers in the low-lying, arid part of the basin, which receives about 6 inches of precipitation per year. Most precipitation falls during the winter in the form of snow in the mountains. Mean annual precipitation over the entire basin is about 27 inches (about 12,000 ft^3/s, or 8.7 million acre-feet). The spatial pattern of precipitation resembles the pattern of the basin's highly variable topography, which ranges in altitudes from 400 to nearly 8,000 feet above mean sea level.

Agriculture is the principal economic activity in the basin. Average annual surface-water demand is about 2.5 million acre-feet. Most of the demand is for 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-feet of water. The major management point, where flows are closely monitored for instream flow limits and forecasted to determine the TWSA for the irrigation seasons, is at the streamflow-gaging station at Yakima River near Parker.

Snow accumulation usually begins in late October or November and ends by April. Snowmelt is critical for supplying runoff to fill reservoirs and to meet irrigation demands. The highest monthly runoff follows the melting of the snowpack. The runoff volume during the runoff season (generally April through June) is closely related to the volume of the snowpack on April 1.

COMPARISON OF SIMULATED RUNOFF FOR PRESENT AND GLOBAL CLIMATE CHANGE CONDITIONS

Unregulated runoff was simulated for water years 1950-2005 for two climate scenarios using the set of calibrated watershed models for the Yakima River Basin. The first scenario used the measured weather data as input and represents present unregulated flow (PUF) in the basin and the second scenario added 3.6°F (2.0°C) to all measured daily minimum and maximum air temperature input to represent global climate change (GCC) that is expected to occur sometime between 2020 and 2050. Simulated PUF at the five reservoirs and at Yakima River near Parker are shown in figure 2 and a summary of average spring and summer runoff is shown in table 1. Simulated runoff for the GCC scenario indicates a pattern of higher flows in the late autumn and winter months, peak runoff occurring earlier in the water year, lower spring and summer runoff, and lower annual runoff than for the PUF scenario. This pattern reduces water availability for irrigation and instream-flow needs.

Table 1. Average total runoff from April 1 through August 31 simulated for water years 1950-2005 for the present unregulated flow scenario (PUF) and the global climate change scenario (GCC) and their differences in runoff at five reservoirs and the Yakima River near Parker streamflow-gaging station for three different exceedence percentiles. [Difference, Percent calculated as 100 x (GCC-PUF)/PUF]

	April through August Average Total Runoff for PUF Scenario			**April through August Average Total Runoff for GCC Scenario**		
	Exceedence Percentiles			Exceedence Percentiles		
Reservoir/Streamflow-gaging station	10%	50%	90%	10%	50%	90%
	acre-feet	acre-feet	Acre-feet	acre-feet	acre-feet	acre-feet
Bumping Lake	249,883	124,449	57,783	182,058	89,089	36,611
Rimrock Lake	402,278	203,971	104,177	300,790	163,990	87,889
Cle Elum Lake	778,484	364,746	148,237	468,316	185,328	90,156
Kachess Lake	206,504	102,297	46,860	109,703	47,152	21,043
Keechelus Lake	240,087	121,783	54,844	132,343	57,418	26,002
Yakima River near Parker	3,648,410	1,891,842	922,603	2,279,135	1,118,539	578,980

	Difference, Absolute			**Difference, Percent**		
	Exceedence Percentiles			Exceedence Percentiles		
Reservoir/Streamflow-gaging station	10%	50%	90%	10%	50%	90%
	acre-feet	acre-feet	Acre-feet	acre-feet	acre-feet	acre-feet
Bumping Lake	67,826	35,360	21,172	-27.1	-28.4	-36.6
Rimrock Lake	101,488	39,981	16,289	-25.2	-19.6	-15.6
Cle Elum Lake	310,168	179,417	58,081	-39.8	-49.2	-39.2
Kachess Lake	96,801	55,145	25,817	-46.9	-53.9	-55.1
Keechelus Lake	107,744	64,365	28,842	-44.9	-52.9	-52.6
Yakima River near Parker	1,369,275	773,303	343,623	-37.5	-40.9	-37.2

Much of the change in the patterns of spring and summer runoff between the two different scenarios can be explained by the change in spring snowpack. Percentage of differences of simulated snow-water equivalent (SWE) are high for the altitude zones below 4000 feet (table 2) with differences diminishing in the higher altitude zones. As a result, changes in runoff from high-altitude basins (e.g., Rimrock and Bumping Lakes, table 1) are smaller than those from low-altitude basins. In addition, glacial melt continues to provide low flow to Rimrock Lake. Although most of the runoff is produced by areas above 4,000 feet, lower-altitude areas also are important contributors to runoff. For example, 65 percent of the Yakima River Basin is at altitudes below 4,000 feet, but these areas produces 20 percent of the runoff for the PUF scenario.

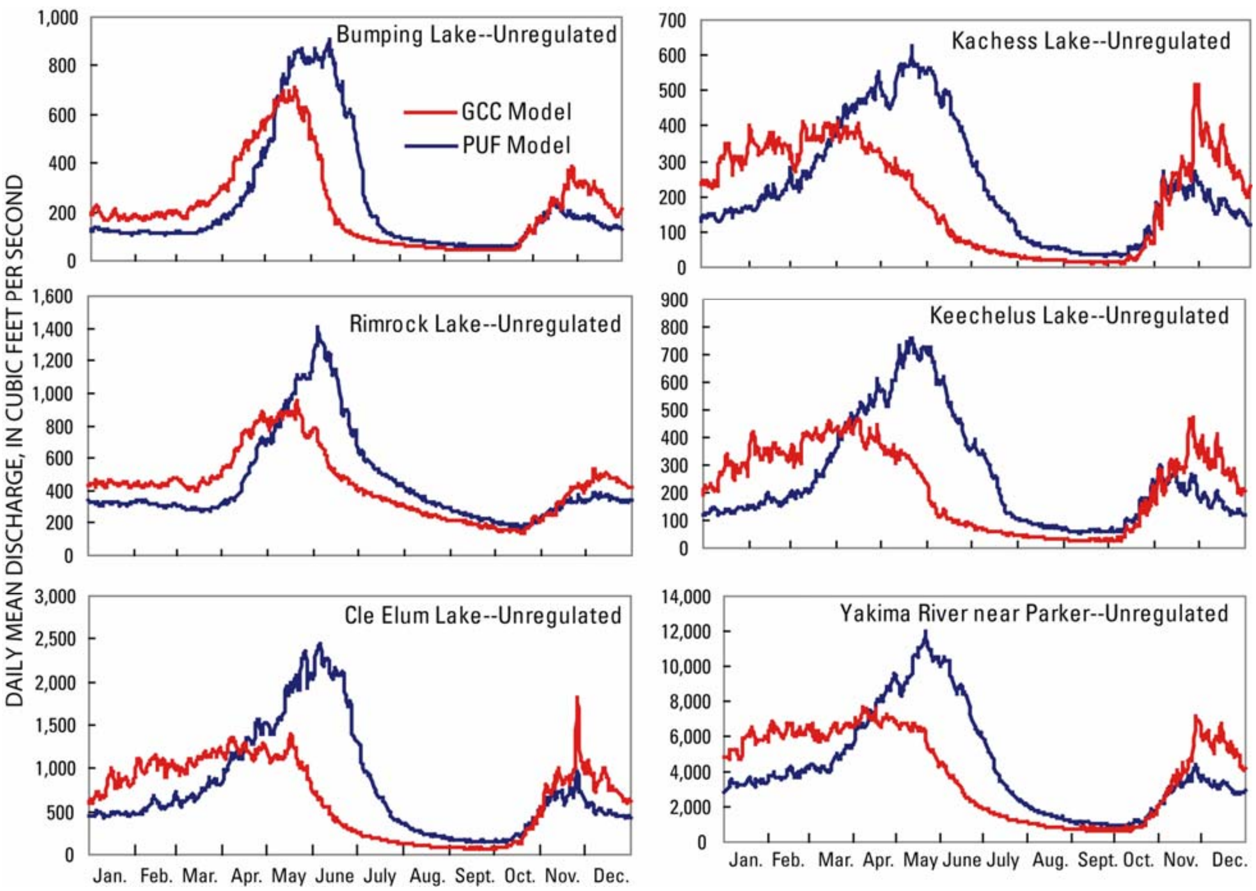

Figure 2. Simulated daily mean discharge for the present unregulated flow (PUF) scenario and the global climate change (GCC) scenario for the five reservoir outflows and the Yakima River near Parker streamflow-gaging station, Yakima River Basin, Washington, water years 1950-2005.

Table 2. Simulated average snow-water equivalent (SWE) on April 1 for the present unregulated flow (PUF) and the global climate change (GCC) scenarios for water years 1950-2005 and differences in SWE by altitude zones in the Yakima River Basin, Washington. [Altitude is above mean sea level, datum NGVD 29]

Altitude Zone in feet	Area of Altitude Zone in acres	Percentage of Total Area	Simulated SWE for PUF Scenario in acre-feet	Simulated SWE for GCC Scenario in acre-feet	Absolute Difference in SWE in acre-feet	Percentage of Difference in SWE
0 to 1,000	24,686	1.0	0	0	–	–
1,000 to 2,000	297,711	12.7	147	5	142	-96.6
2,000 to 3,000	598,615	25.5	59,377	3,762	55,615	-93.7
3,000 to 4,000	608,695	25.9	347,177	60,958	286,219	-82.4
4,000 to 5,000	562,408	24.0	842,120	319,646	522,474	-62.0
5,000 to 6,000	234,171	10.0	609,675	359,194	250,481	-41.1
over 6,000	21,051	0.9	86,234	60,193	26,041	-30.2
All zones	2,347,337	100.0	1,944,730	803,758	1,140,972	-58.7

How does the GCC scenario compare with the extreme drought years or extreme warm years that we have experienced in the recent past? Daily median runoff from the GCC scenario was compared to simulated runoff from the two worst drought years (1977 and 2005) and one extreme warm year (1992) for the PUF scenario (fig. 3 and table 3). Daily runoff from May through August generally was lower for the warmest water year and drought years than the daily median values of the GCC scenario (fig. 3). In addition, runoff volumes were less for all three extreme water years during the irrigation season (table 3). During the extreme water years, several large high-runoff events during the winter were due to warm air temperatures, which caused more precipitation to be rain rather than snow. This rain ran off within a few days rather than becoming snow available for runoff during the spring. These large winter-runoff volumes provide an opportunity for water managers to capture some of winter runoff in reservoirs. The captured water can then be released later in the water year during the irrigation or salmon out-migration seasons, and thus ameliorate some of the natural runoff volume deficiencies that occur during the runoff seasons following warmer-than-average winters.

Table 3. Simulated unregulated runoff volumes at Yakima River near Parker for various scenarios.

Model Simulations	Runoff Volume, in acre-feet (April 1 to August 31)
Present Unregulated Flow —median daily values	1,891,842
Global Climate Change Scenario—median daily values	1,118,539
Present Unregulated Flow Scenario--Water Year 1977	707,066
Present Unregulated Flow Scenario--Water Year 1992	917,180
Present Unregulated Flow Scenario--Water Year 2005	605,474

Median runoff volume simulated at Yakima River near Parker for the GCC scenario during the irrigation season was larger than daily median runoff for the PUF scenario for the extreme drought and warm years (table 3), but the simulated 90-percent exceedence runoff for the GCC scenario was smaller (tables 1 and 3) than the volume simulated for the extreme years. This implies that if demand for water at some point in the future between 2020 and 2050 (when air temperatures are predicted to rise 2 degrees Celsius) is the same as today and our simple assumption for the GCC scenario is reasonably accurate, then the available water during most runoff years should be manageable with all irrigators receiving their full or nearly full supply of water while meeting instream target flows. However, during drought years in the future, the outlook is bleak. At least 10 percent of the water years can be expected to generate runoff volumes during the runoff season that are smaller than the lowest runoff years in the last 56 years.

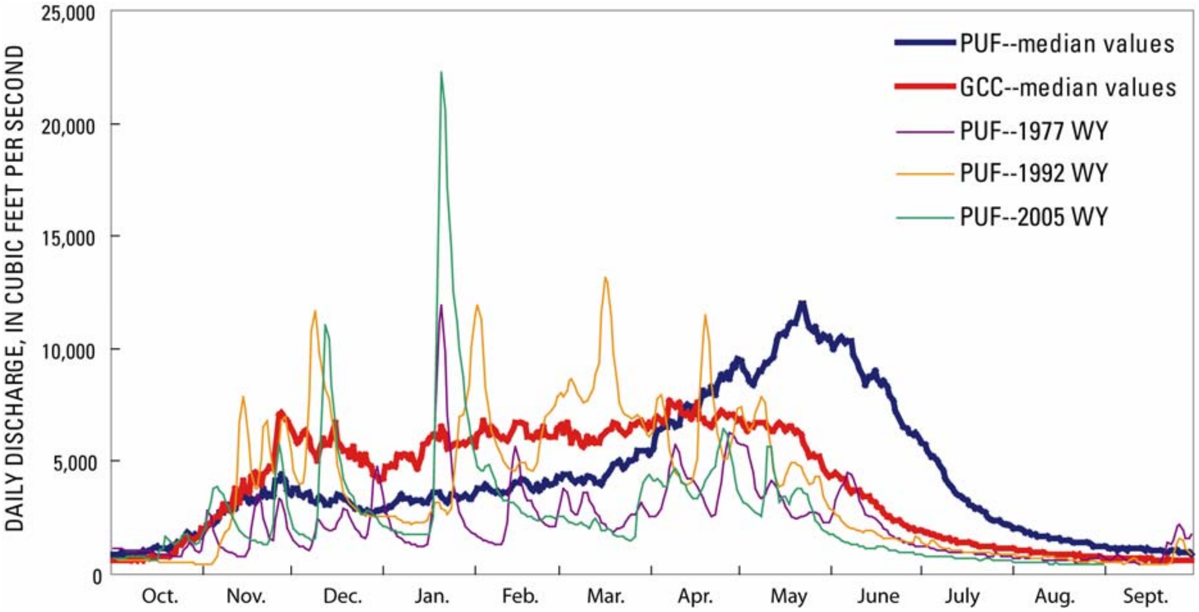

Figure 3. Simulated daily median unregulated discharge at Yakima River near Parker under the global climate change (GCC) scenario and the present unregulated flow (PUF) scenario for water years 1950-2005 and the simulated daily discharge for present unregulated flow scenario (PUF) for selected water years.

REFERENCES

Bureau of Reclamation. (2005). Yakima Basin Water Supply — March through July news releases: U.S. Bureau of Reclamation, Pacific Northwest Region, accessed December 2005 at URL: http://www.usbr.gov/newsroom/newsrelease/index.cfm.

Glantz, M. H. (1982). Consequences and Responsibilities in Drought Forecasting: The Case of Yakima, 1977, Water Resources Research, 18(1), pp. 3-13.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G. (1983). Precipitation-Runoff Modeling System—Users Manual: U.S. Geological Survey Water-Resources Investigations Report 83-4238, 207 p.

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.

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., 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.