University of Washington
Department of Civil and Environmental Engineering

EFFECTS OF CLIMATE CHANGE ON THE HYDROLOGY AND WATER RESOURCE OF THE COLORADO RIVER BASIN

Niklas Smith Christensen
Dennis P. Lettenmaier

Water Resources Series
Technical Report No.176
October 2002

Seattle, Washington
98195

Department of Civil Engineering
University of Washington
Seattle, Washington 98195

EFFECTS OF CLIMATE CHANGE ON THE HYDROLOGY AND WATER RESOURCE OF THE COLORADO RIVER BASIN

Niklas Smith Christensen
And Dennis P. Lettenmaier

Water Resources Series
Technical Report No. 176

October 2002

University of Washington

Abstract

Effects of Climate Change on the Hydrology and Water Resources of the Colorado River

Niklas Smith Christensen

Chair of Supervisory Committee:
Professor Dennis P. Lettenmaier
Department of Civil and Environmental Engineering

The U.S. Department of Energy/National Center for Atmospheric Research Parallel Climate Model was used to assess potential effects of climate change on the hydrology and water resources of the Colorado River Basin based on three climate conditions: an ensemble of three 105 year transient simulations based on business as usual (BAU) global greenhouse gas emissions, a control run based on static 1995 greenhouse gas concentrations, and historic conditions. Transient monthly temperature and precipitation sequences for the Colorado River basin were extracted from the climate model simulations using a statistical bias correction and downscaling method, and were used to drive the Variable Infiltration Capacity (VIC) macroscale hydrology to produce streamflow sequences. Results for the BAU scenarios were summarized into Periods 1, 2, and 3 (2010 – 2039, 2040 - 2069, 2070 – 2098). Average annual temperature changes for the Colorado River basin were 0.5 °C warmer for control relative to historical, and 1.0, 1.7, and 2.4 °C warmer for Periods 1-3, respectively, relative to historical. Basin-average annual precipitation for the control climate was slightly (1%) less than historical, and 3, 6, and 3% less than historical for future Periods 1-3. Annual runoff in the control run was about 10% lower than for historical conditions, and 14, 18, and 17% less for Periods 1-3, respectively. Higher wintertime temperatures also caused peak runoff to occur about one month earlier. Analysis of VIC simulated historic, control, and probable future flows with a water management model showed that the reduced streamflows would significantly degrade performance of the water resource system. Average simulated total basin storage was reduced by 8% for the control climate and by about 35% in Periods 1 – 3 relative to historical. Colorado River Compact mandated releases from Glen Canyon Dam to the lower basin were met in 80% of years for the control simulation (vs. 92% in historical), and only in 59 – 75% of years for the future runs. Annual hydropower output was also significantly reduced for the control and future simulations.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Table Number Page

Acknowledgements:

This research was funded by the U.S. Department of Energy's Accelerated Climate Prediction Initiative under Grant No. 354967-AQO. This publication was also supported by the Joint Institute for the study of the Atmosphere and Ocean (JIASAO) under NOAA Cooperative Agreement #NA17RJ1232, Contribution #992. Hydrosphere Resource Consultants graciously provided access to their Colorado River reservoir model (CORN) source code, from which some of the reservoir operating information used in CRRM were extracted.

Chapter 1: INTRODUCTION

The Colorado River drains parts of seven states and Mexico (Figure 1). The river is regulated by 12 major reservoirs to provide water supply, flood control and hydropower to a large area of the U.S. Southwest. Much of the Colorado River basin is arid, with naturalized annual streamflow (i.e., streamflow that would have occurred in the absence of water management) averaging only 45 mm/yr over the 630,000 km^2 drainage area. High elevation snow pack in the Rocky Mountains contributes about 70% of the annual runoff, and the seasonal runoff pattern throughout most of the basin is heavily dominated by winter snow accumulation and spring melt. On average, 90 percent of the annual streamflow is generated in the upper basin (above Lee Ferry, AZ). There is also considerable temporal variability in the naturalized flow of the Colorado River. Annual flow from 1906 through 2000 had a minimum of 6.5 billion cubic meters (BCM) or 5.3 million acre-feet (MAF), a maximum of 29.6 BCM (24.0 MAF), and an average of 18.6 BCM (15.1 MAF) (Figure 2). Tree ring reconstructions dating to 1512 suggest that the long-term annual average flow may be closer to 16.7 BCM (13.5 MAF) (USDOI, 2000). Aggregated reservoir storage in the basin is 74.0 BCM (60.0 MAF), or about four times the naturalized mean annual flow. Of the over 90 reservoirs on the river and its tributaries, by far the largest are Lake Mead (formed by Hoover Dam) and

Lake Powell (formed by Glen Canyon Dam), which have a combined storage capacity of 64 BCM (51.9 MAF), or 85 percent of the basin total.

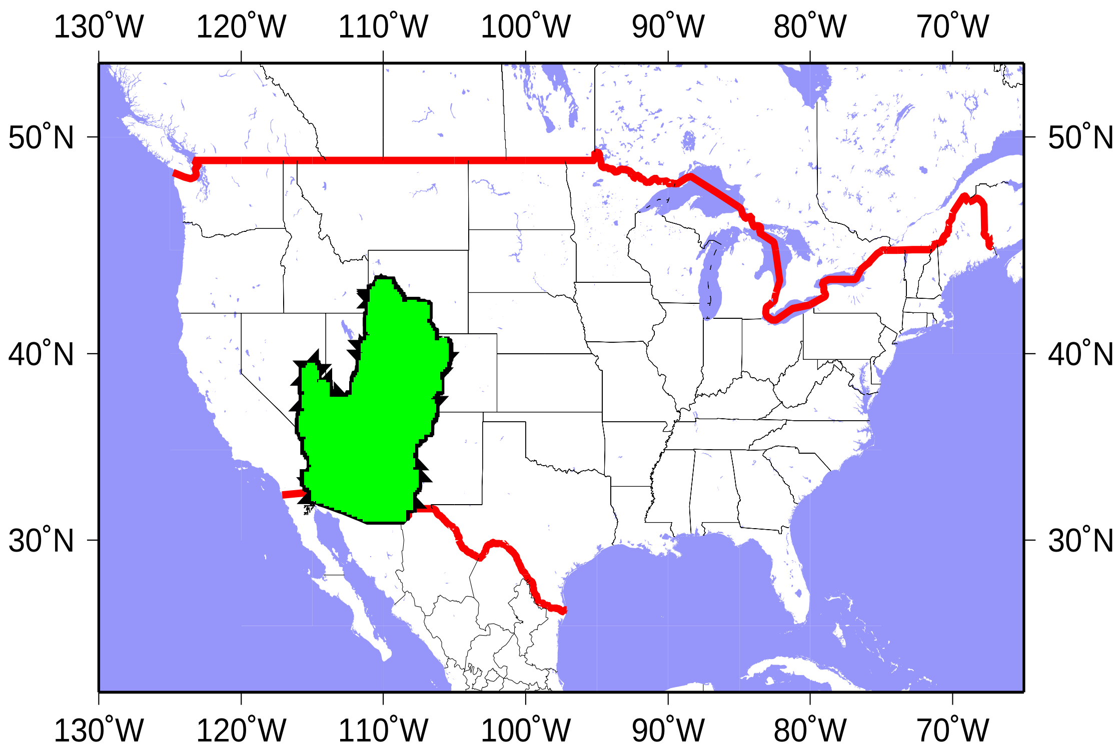

Figure 1 Colorado River Basin.

The Colorado River has one of the most complete allocations of its water resources of any river in the world and is also one of the most heavily regulated (USDOI, 2000). The Colorado River Compact of 1922 apportioned consumptive use of water between the upper (Wyoming, Utah, Colorado, and New Mexico) and lower (California, Arizona, and Nevada) basin states after measuring the discharge of the river during what turned out to be a period of abnormally high flow. The estimated mean flow of 22 BCM (18 MAF) was apportioned 9.3 BCM (7.5 MAF) for consumptive use to both the upper and lower basins. The 1944 United States – Mexico treaty guaranteed an annual flow of not less than 1.9 BCM (1.5 MAF) to Mexico, except in times of extreme shortage. Rarely since the signing of the Compact has the river had a 10-year average flow equal to the total of the upper and lower basin and Mexico allocations (Figure 2).

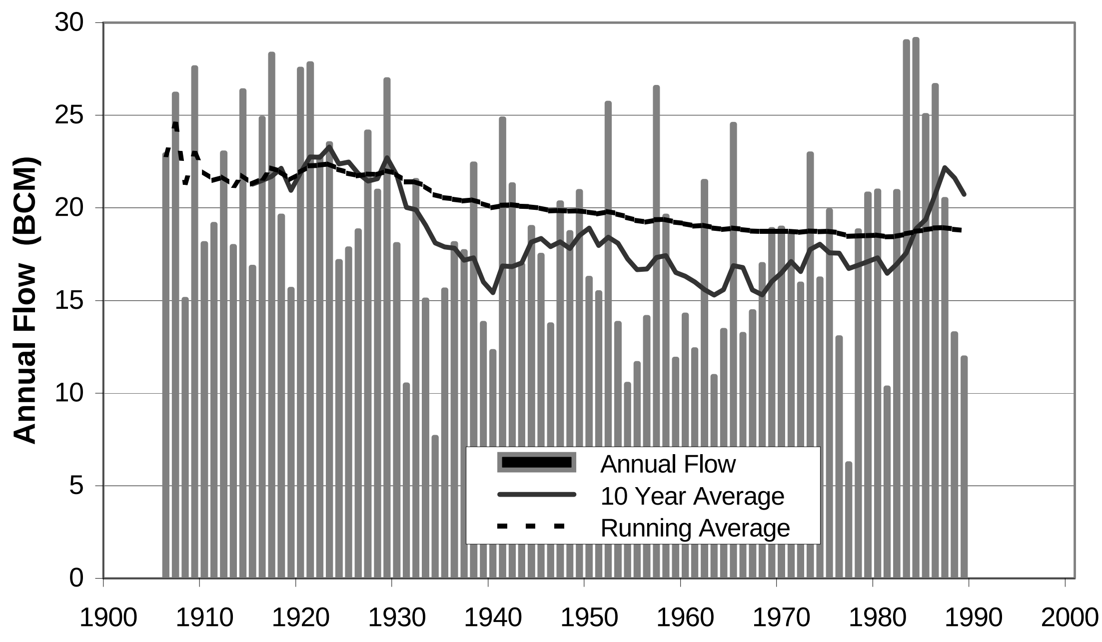

Figure 2 Annual, 10 year average, and running average of natural flow at Lee Ferry, AZ stream Gage.

Climate change is of particular concern in the Colorado Basin due both to the sensitivity of the snow accumulation processes that dominate runoff generation within the basin and the basin's high water demand relative to supply (Loaiciga, 1996). General Circulation Models of the atmosphere-ocean-land system predict increases in global mean annual air temperature between 1.4 and 5.8 degrees Celsius over the next century (IPCC, 2001). Previous studies (Gleick and Chaleki, 1999; McCabe and Wolock, 1999; Hamlet and Lettenmaier, 1999; Lettenmaier et al., 1992) have found that small increases in temperature in snowmelt-dominated basins can cause considerable timing shifts in runoff. The climate model used in this study also predicts a reduction in annual precipitation volume. These projected effects along with increased evapotranspiration due to higher temperatures could have significant implications for the managed water resources of the Colorado River. Although the storage to runoff ratio of the system may negate some of the effects of the timing shift, the basin is especially susceptible to reduced streamflow volumes due to the almost complete allocation of streamflow (on average) to consumptive uses.

This study used ensemble simulations from the DOE/NCAR Parallel Climate Model (PCM) (Barnett et al, 2001) to obtain projected climate realizations for the basin through 2098. These General Circulation Model (GCM) simulations are based on transient greenhouse gas (primarily CO_2 and methane) concentrations that use the Intergovernmental Panel on Climate Change (IPCC, 2001) “business as usual” (BAU) emissions – i.e., the global emissions of greenhouse gases that would occur in the absence of any effective mitigation. The precipitation and temperature signals from the PCM were statistically downscaled using methods outlined by Wood et al (2002). These were then used to force the Variable Infiltration Capacity (VIC) macroscale hydrologic model (Liang et. al, 1994) to create plausible sequences of streamflows over the next century. These streamflows were then analyzed with a simplified version of the Colorado River Simulation System (USDOI, 1985) to ascertain the sensitivity of the reservoir system (flood control, water supply, hydropower, etc.) to altered streamflow scenarios.

Chapter 2: APPROACH

2.1 PCM Scenarios

The PCM is a General Circulation Model of the coupled atmosphere, land, ocean, and sea ice system. It operates on what is termed T42 resolution with a horizontal spatial resolution of 2.8 degrees (~300 km) and 18 vertical levels in the atmosphere. The model predicts the evolution of moisture and energy fluxes and state variables in the coupled system, including precipitation and temperature at the land surface, which are the two key model output variables used in this study. Details of the PCM are provided by Washington et al (2000). PCM model runs made at the National Center for Atmospheric Research were made available for this study (Table 1). The model runs used include three 105-year ensembles that begin in 1995 and are based on BAU emission scenarios. Each of these runs has unique initializations of the earth's atmosphere – ocean condition and represents different plausible evolutions of climate given the same emission scenario. These are the same runs that were used in companion papers by Payne et al (2002) and Van Rheenan et al (2002). In addition to the three future ensemble members, a control run fixed at 1995 atmospheric CO_2 concentrations representing a steady state 1995 climate and a historical simulation based on actual atmospheric CO_2 concentrations from 1870 - 2000 were also used (Dai et al, 2002). A 50 year segment of the historical run was used to derive the statistics necessary to correct for bias in the ensemble simulations using methods similar to those described by Wood et al (2002). As in Payne et al (2002) and Van Rheenan et al (2002), results were summarized into three periods (Period 1, 2010-2039; Period 2, 2040-2069, Period 3, 2070-2098).

Table 1: Summary of Climate Scenarios

Run	Description	Period
B06.28	Historical (CO_2 + aerosols at 1870 – 2000 levels)	1870 - 2000
B06.45	Climate Control (CO_2 + aerosols at 1995 levels)	1995 - 2048
B06.44	Climate Change (BAU6, future forcing scenario)	1995 - 2098
B06.46	Climate Change (BAU6, future forcing scenario)	1995 - 2098
B06.47	Climate Change (BAU6, future forcing scenario)	1995 - 2098

The reader is referred to Wood et al (2002) for details of the method used to translate the climate signal from the ensemble runs into daily forcing input into the hydrologic model. In brief, though, the method maps monthly observed and simulated temperature and precipitation probabilities at the PCM spatial scale (2.8 degrees latitude by longitude) to the 1/8 degree resolution of the hydrology model by mapping from cumulative probability distributions of the climate model output to equivalent climatalogical probability distributions. The application of the bias correction method in the Colorado River basin differs slightly from the methods utilized by Payne et al (2002) and Van Rheenan et al (2002) for the Pacific Northwest and California, respectively, in the sense that the BAU minus observed temperature differences were removed as opposed to the BAU minus control. This was done because of the significant warming already realized in the control run relative to historic observations – effectively the downscaling method projects changes relative to observed historical (rather than control) onto the hydrological model grid. The climate model signal was then temporally disaggregated to create a daily forcing time series for the hydrology model. This method facilitates investigation of the implications of the true transient nature of climate warming as opposed to the more common methods employed where decadal temperature and precipitation shifts are averaged to give a step-wise evolution of climate (e.g. Hamlet and Lettenmaier, 1999).

2.2 Application of the VIC model to the Colorado River basin

The VIC model can be run in either a full energy balance mode at a three hourly timesteps or in a water balance mode at a daily timestep. In energy balance mode, the model iterates on the surface temperature to close the energy and water budgets at each time step, whereas the simplified water balance mode assumes that surface temperature equals air temperature, thus avoiding the need for iteration. Both modes represent fluxes of water and energy at the land surface and close the water budget at each time step. The model is grid cell-based and typically is run at spatial resolutions ranging from 1/8 (~13 km) to 2 (~210 km) degrees latitude by longitude. Outputs from the model include surface runoff and baseflow, which are post processed with the routing model of Lohmann et al (1998a; b) to simulate streamflow at selected points within the basin. Details and examples of VIC model applications can be found in Nijssen et al (1997), Maurer et al. (2001), Nijssen et al. (2001), and Hamlet and Lettenmaier (1999)

For this study, VIC was implemented at 1/8 degree spatial resolution and was run in water balance mode at a daily time step. At 1/8 degree spatial resolution, the Colorado River basin is represented by 4518 cells totaling 630,000 km^2. Runoff generated by VIC was routed to all modeled reservoirs within the basin as well as three gauging only stations (Figure 3). Model calibration was performed by adjusting parameters that govern infiltration and baseflow recession to match naturalized streamflows (effects of water management removed) obtained from the U.S. Bureau of Reclamation (1985) at selected control points for the same period of record (Figure 4). The overlapping period of record for VIC historical simulations and observed naturalized flows is 1950-1989. During this period, VIC cumulative streamflow at Imperial Dam is 768 BCM (623 MAF) while observed naturalized flow is 776 BCM (630 MAF). This represents a 1% bias in VIC towards slightly under-predicting streamflow.

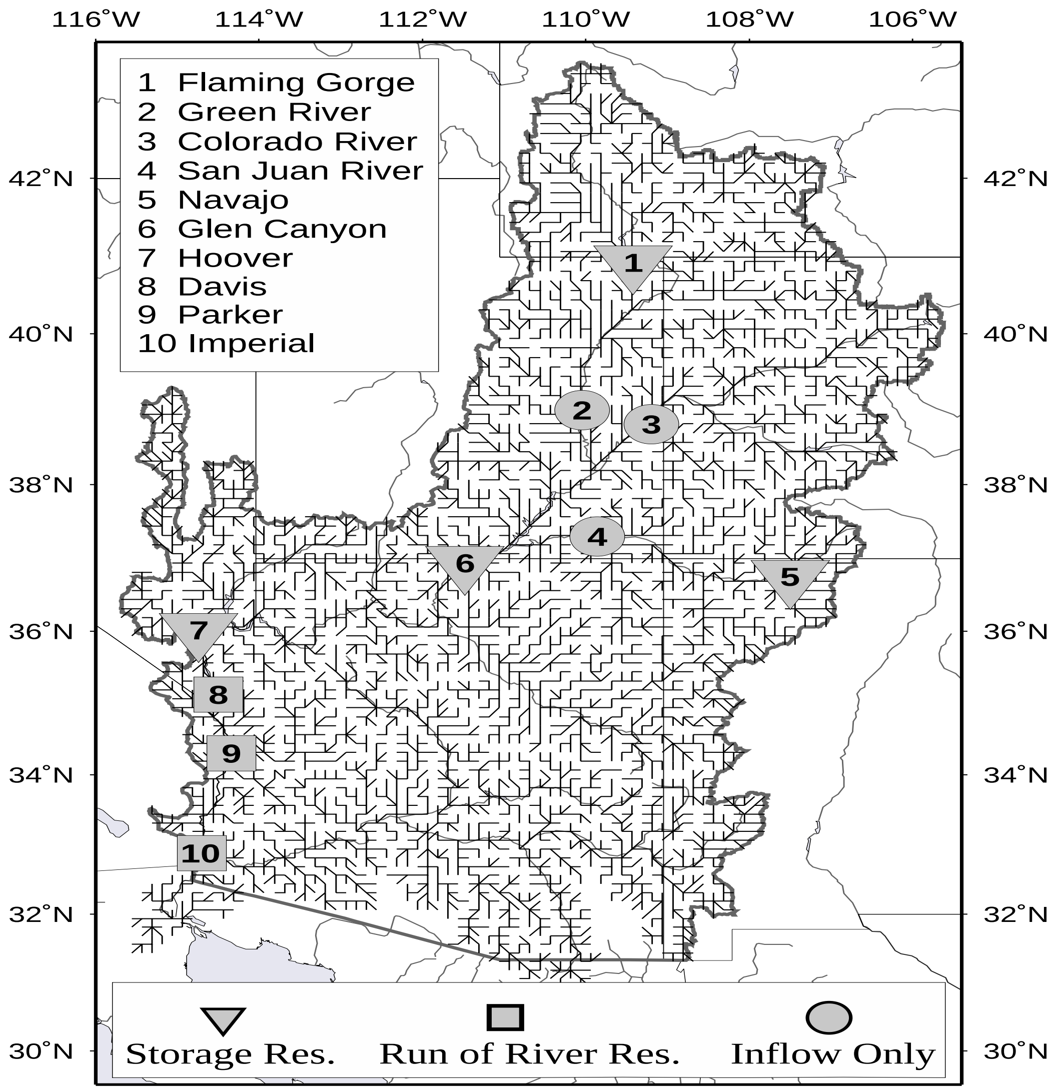

Figure 3 Colorado River Basin with 1/8 degree VIC routing network and major system reservoirs.

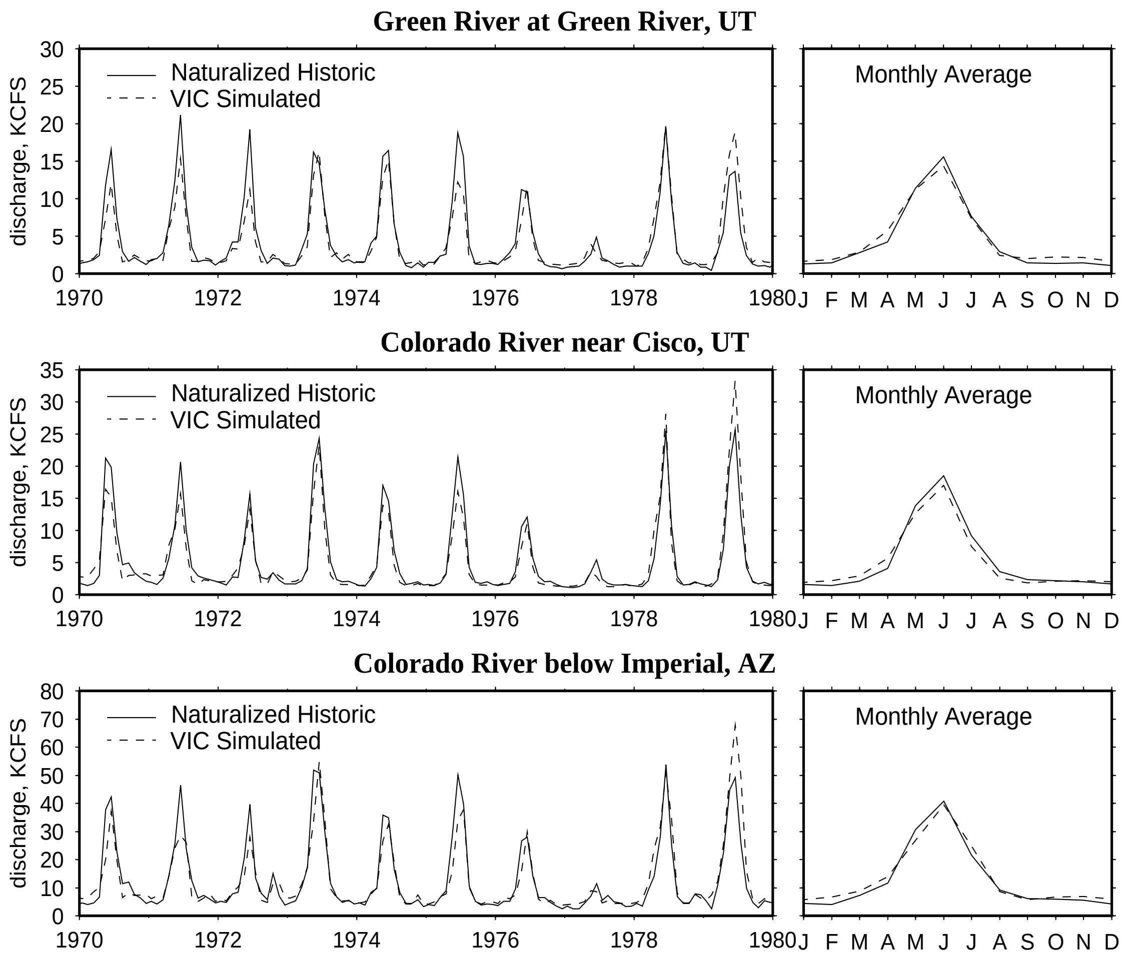

Figure 4 VIC simulated and naturalized historic observed streamflows at Green River, UT, Cisco, UT, and Imperial, AZ for 1970-1980.

2.3 Colorado River Reservoir Model

The Colorado River Reservoir Model (CRRM) developed for this study is a simplified version of the USBR Colorado River Simulation System (CRSS) that represents the major physical water management structures and operating policies for the system. It simulates the movement and distribution of water within the basin on a monthly time step. Input to the model is naturalized or unregulated streamflow (either historical or simulated by VIC) at the inflow points shown in Figure 3. The model then uses specified operating procedures to simulate reservoir levels, releases, hydropower production, and diversions. By changing the naturalized inflows from historical or control to one of the three transient ensemble runs, the system can be analyzed with respect to its ability to operate reliably under simulated 'future' hydrological conditions.

The Colorado River is among the most heavily regulated in the world. Since 1922 there have been over 50 court decisions, state statues, interstate compacts, and international treaties that now comprise what is known as the *Law of the River*. The main regulation affecting operation of the basin reservoirs is a mandatory release of 10.2 BCM (8.23 MAF) per year from Glen Canyon Dam for the lower basin's consumptive use and one half of Mexico's allotment, and an annual release from Imperial Dam into Mexico of 1.9 BCM (1.5 MAF) (USDOI, 2000). As specified in CRSS operating procedures (USDOI, 1985), CRRM requires Glen Canyon dam to make releases regardless of the reservoir level relative to its minimum power pool of 1201 m. Only when the reservoir is at its dead storage volume are releases to the lower basin curtailed. Lake Powell has never been drawn down this far and the actual operating procedures if this level were approached are still a matter of contention. Compact deliveries from the lower basin into Mexico are met completely unless Lake Mead is drawn down to its minimum power pool elevation of 330 m. At this elevation, shortages are imposed to the (Los Angeles) Metropolitan Water District (MWD) and Mexico while the reductions already imposed on the Central Arizona Project (CAP) and Southern Nevada Water Authority (SNWA) at the elevation of 343 m are increased. Although these depletions can be reduced to zero in the model, actual operations in the basin are unlikely to do so. CRRM, like the CRSS, does not impose shortages on the Upper Basin but rather passes them on to the lower basin even though this could be ruled a violation of the Colorado River Compact (Hundley, 1975). Model operating policies that recognize the upper basin has present perfected water rights (water rights obtained before June 25, 1929 and given highest priority) to only 2.5 BCM (2 MAF) would not impose the same shortages upon the lower basin and Mexico.

Because a large part of the total system storage volume is in Lake Powell and Lake Mead, not all the physical or operational complexities of the river system need to be represented in CRRM to provide a capability to assess the effects of future climate change on reservoir system performance. The actual reservoir system is abstracted into four equivalent reservoirs: Flaming Gorge, Navajo, Lake Powell, and Lake Mead. Of these, the modeled characteristics of Lake Powell and Navajo Reservoir are essentially equivalent to those of the true reservoirs, whereas the equivalent Flaming Gorge includes Fontenelle's storage capacity and Lake Mead includes the storage volumes of downstream reservoirs that are not explicitly represented. Hydropower is simulated at three of the four reservoirs (Navajo has no hydropower production, and hydropower at upstream reservoirs is insignificant) as well as at run-of-the-river reservoirs at Parker and Davis.

CRRM represents reservoir evaporation as a function of reservoir surface area and mean monthly temperature and is satisfied before any other water demand. Although water demand may well increase as climate change evolves and population expands, most results in this study utilize the Multi Species Conservation Program (MSCP) (USDOI, 2000) baseline fixed at year 2000 (so as not to obfuscate effects of PCM projected streamflows). However, where specifically noted, results from separate runs utilizing a linear increase in demands through 2060 as specified by the MSCP, then holding demands steady from 2060-2098 are presented. In both scenarios, lower basin demands are the full entitlement of 9.2 BCM (7.5 MAF). Annual upper basin demands for runs using the 2000 baseline are fixed at 5.2 BCM (4.2 MAF). The specified runs that utilize increasing demands begin with upper basin demands of 5.2 BCM (4.2 MAF) and increase to 6.7 BCM (5.4 MAF).

The MSCP provides the USBR's best estimate of projected withdrawals and consumptive uses of Colorado River water.

The model uses individual monthly return ratios for each of 11 aggregated withdrawal points to represent return flows to the river. If there is insufficient water within a river reach or reservoir to meet a demand, the upstream reservoir will make a supplemental release to attempt to fulfill the withdrawal. The next reservoir upstream is also allowed to make releases to meet this shortfall, however, beyond this point, travel time makes further upstream releases impractical.

Present perfected water rights are not explicitly modeled in CRRM. Instead priority is given to upstream users except in the case of lower basin shortages. As specified in the *Law of the River,* when Lake Mead is at or below an elevation of 343 m, level one shortages are imposed and deliveries to CAP are reduced from 1.7 BCM (1.4 MAF) to 1.2 BCM (1 MAF) and annual deliveries to the SNWA are reduced from 0.35 BCM (0.28 MAF) to 0.32 BCM (0.26 MAF). Level two shortages are imposed at a Lake Mead elevation of 330 m and deliveries to CAP, SNWA, MWD, and Mexico are reduced proportionally, to zero if need be, in attempt to keep Lake Mead at or above its minimum power pool. If Lake Powell has a greater active storage volume than Lake Mead, CRRM equalizes the two as specified by the Criteria for

Coordinated Long-Range Operations of Colorado River Reservoirs (USDOI, 1985). CRRM requires the evacuation of 6.6 BCM (5.4 MAF) of flood control space in the system by January of every year.

Validation and calibration of the model was performed by comparing observed reservoir conditions and operations from 1970 – 1990 with CRRM simulations driven by historic naturalized inflows for the same period. This period was chosen because Glen Canyon Dam came on line in the 1960s and naturalized inflows do not exist for the period after 1990. Figure 5a shows that CRRM simulations mimic historical aggregated reservoir storage despite its simplifications while Figure 5b shows total basin monthly hydropower production. The mid-1980s saw abnormally high flows in the basin and full reservoir storages. CRRM does not have a capability to utilize inflow forecasting and therefore does not recreate individual monthly hydropower production very well under these scenarios. However, because historic and simulated annual values are comparable (Figure 5c) and the control and BAU ensemble used in this study do not achieve full reservoir levels, CRRM arguably represents hydropower production adequately for the purposes of this study.

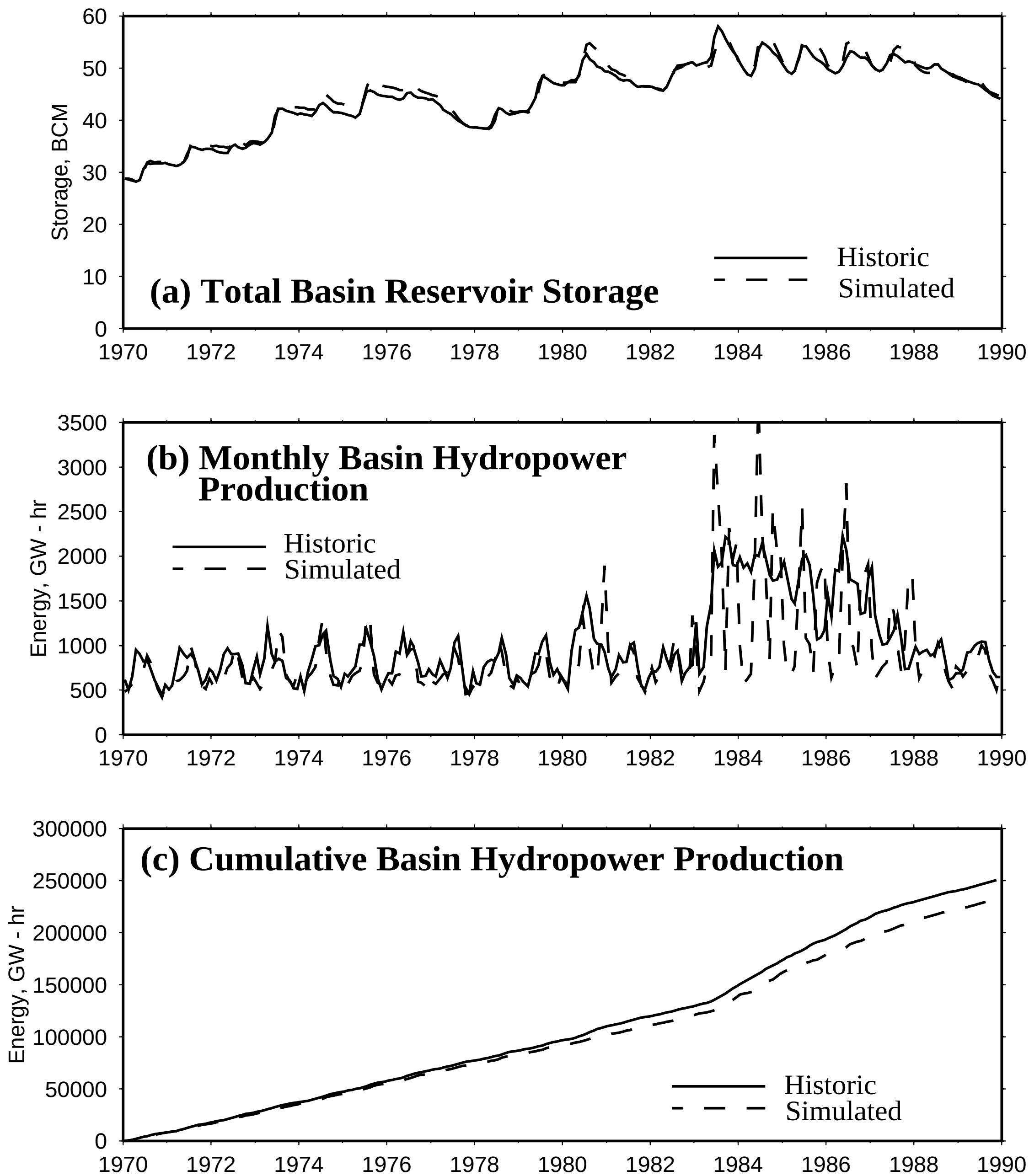

Figure 5 (a) CRRM simulated and observed total basin storage for 1970-90; (b) CRRM simulated and observed total basin monthly hydropower production for 1970-90; (c) CRRM simulated and observed cumulative hydropower production for 1970-1990.

Chapter 3: RESULTS

3.1 PCM Climate Changes

Figure 6 shows the basin-average annual temperature and precipitation time series for the individual BAU ensemble members, as well as the long-term observed (1950-1999) and control run averages. The control run represents a static 1995 climate and has a temperature approximately 0.5^{o} C warmer than the observed, reflecting warming that has occurred in the last 50 years. Most of this warming in the control run has taken place in the winter and spring months (Figure 6c). Average temperature for the BAU ensemble members is 1.0, 1.7, and 2.4 °C warmer than average historical observations during periods 1, 2, and 3, respectively. There is considerable interannual and interdecadal variability in temperature, with the most pronounced warm periods coming in the beginning of each period and with a cool interval in the middle part of period 1.

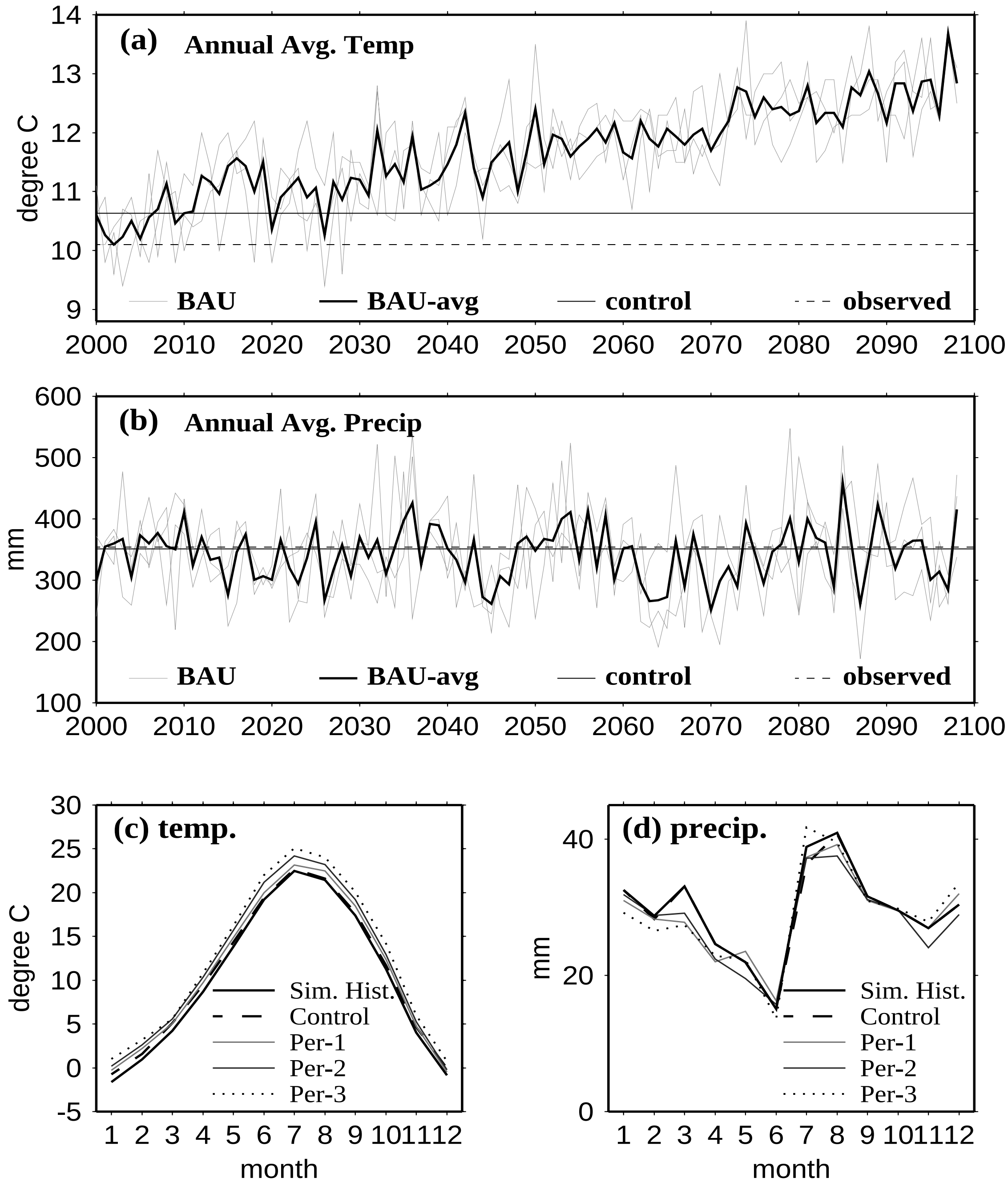

Figure 6 (a) Downscaled Colorado River basin average annual temperature for BAU ensemble climate simulations, with historic and control means shown for reference; (b) same for precipitation; (c) mean annual cycle of basin-average temperature for historic, control, and BAU Periods 1 - 3 (mean of 3 ensembles); (d) same for precipitation.

Control run basin wide annual average precipitation is 1% (3.2 mm/yr.) less than the downscaled historical average. Precipitation in periods 1,2, and 3 is 3% (10 mm/yr.), 6% (20 mm/yr.), and 3% (10 mm/yr.) lower than historical, respectively. Period 2 has the lowest precipitation due to the fact that decades 2040 and 2060 are unusually dry (Figure 6b). The control run seasonal distribution of precipitation is very similar to observed (Figure 6d). The same general pattern is true of the BAU ensembles, however, precipitation amounts are less for all three periods during the winter and period three has a late summer peak that is greater than both the observed and control.

3.2 Simulated Snowpack Changes

Figure 7 shows average April 1 snow water equivalent (SWE) for simulated historical (1950-1999) conditions, as well as the control, and future periods 1, 2, and 3. The simulated basin-average SWE for the control run is 86% of the historical, while BAU periods 1, 2, and 3 have 76%, 71%, and 70%, respectively, of historical April 1 SWE. The reduced SWE in the control run relative to historical is due mostly to higher wintertime temperatures while the reduced SWE in the BAU ensembles is attributable to both higher temperatures and reduced wintertime precipitation. Snow cover extent remains mostly unchanged in the high elevation Rockies but is reduced in the high plains of western Colorado where snow cover generally is thin. These results are consistent with Brown et. al. (2000).

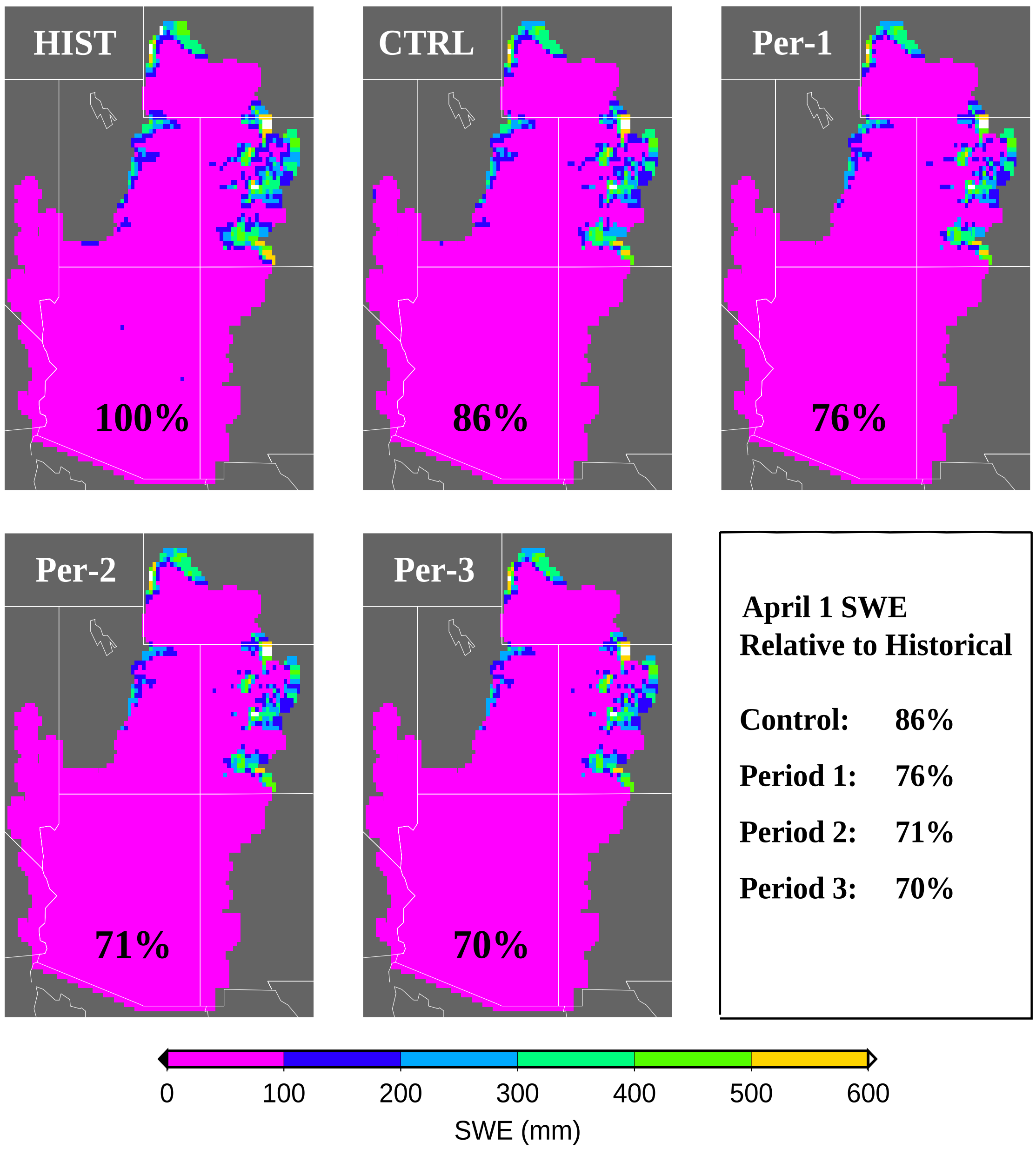

Figure 7 Simulated April 1 snow water equivalent for historical, control, and Periods 1-3 (mean of 3 ensembles).

3.3 Simulated Runoff Changes

Figure 8a shows annual average runoff for the control and periods 1-3 relative to historical. The runoff ratio for the Colorado River is low, which is typical of semi-arid watersheds. Historical average annual basin precipitation is 355 mm, of which 310 mm evaporates, leaving 45 mm to runoff, for a runoff ratio of about 13 percent. The average annual precipitation in the control run is 351 mm, with 310 mm of evapotranspiration, leaving 41 mm to runoff. Although the difference in runoff of 4 mm seems insignificant, it represents a reduction of almost 10 percent in the mean annual flow. Additional decreases in precipitation and increases in temperature during periods 1, 2, and 3 lead to further reductions in runoff. Annual average basin precipitation, evapotranspiration, and runoff for all periods are given in Table 2.

Table 2: Annual average precipitation, evapotranspiration, and runoff for historic (HIST), control (CTRL), and future Periods 1-3 (in mm/yr).

	Precip.	Evap.	Runoff	% precip relative to historical	% evap. relative to historical	% runoff relative to historical
HIST.	354	310	45	n/a	n/a	n/a
CTRL.	351	311	41	99	100	90
Per. 1	344	305	39	97	98	86
Per. 2	334	298	37	94	96	82
Per. 3	344	306	37	97	99	83

In addition to reduced runoff volume, runoff timing is shifted as a result of earlier spring snowmelt in the BAU ensembles as shown in Figure 8b. Winter runoff in period 1 is similar to the historical and control runoff whereas runoff for periods 2 and 3 is greater due to the higher wintertime temperatures, which result in precipitation falling as rain instead of snow. In the upper basin the control and historical runoff peaks in June whereas runoff for the BAU ensemble periods peaks in May. This same trend toward early runoff as temperatures increase is seen in the lower basin. Mid and late summer flows for periods 1 – 3 are significantly lower than historical due to the earlier snowmelt and lower soil moistures, and the reduction in summer flow more than cancels increased winter and spring flow, resulting in reduced annual flow.

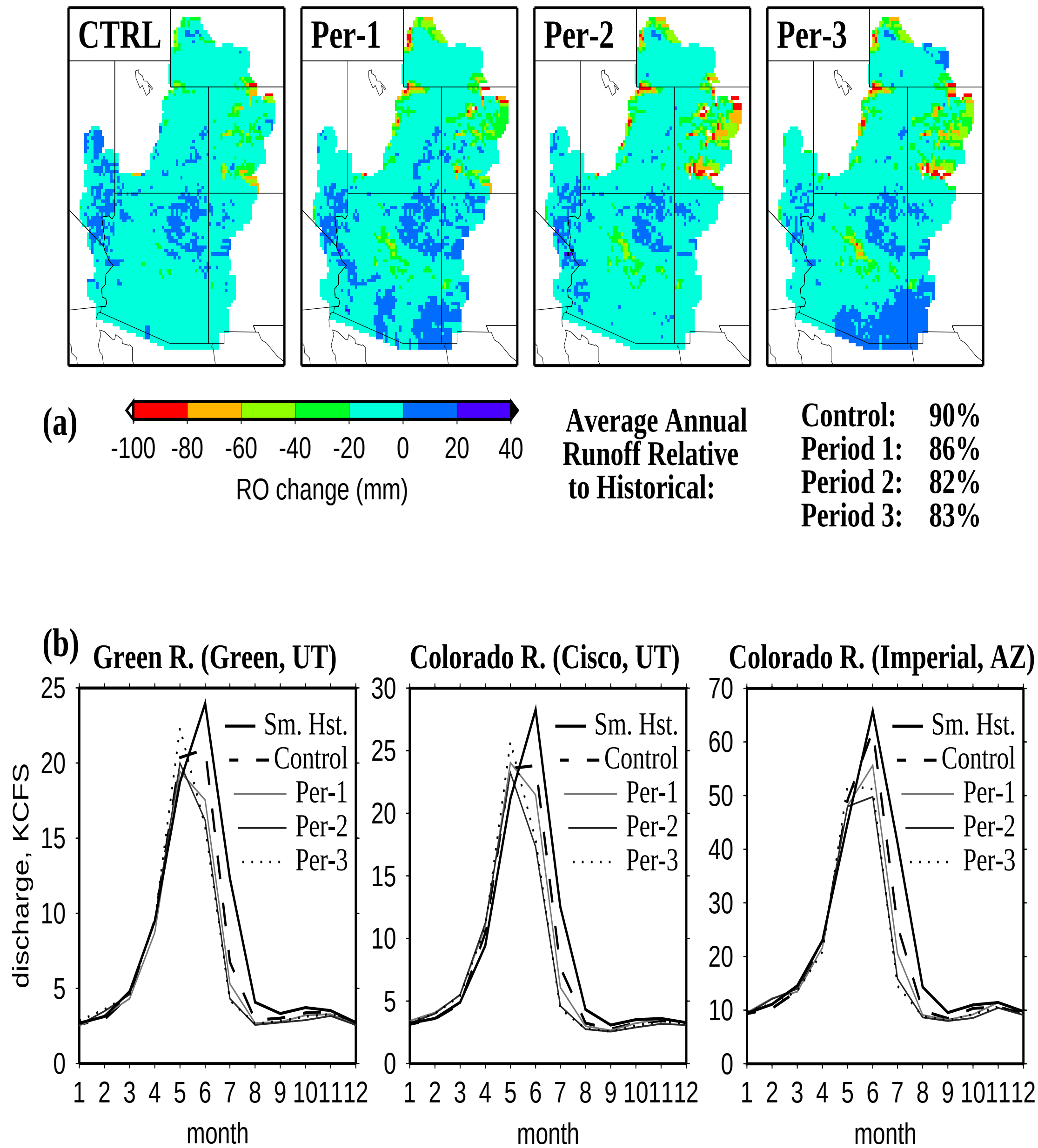

Figure 8 (a) Spatial distribution of predicted changes in mean annual runoff for control and BAU Periods 1-3 (averaged over 3 ensembles) relative to historic, and (b) mean monthly hydrograph for the Green River at Green River, UT, Colorado River near Cisco, UT, and the Colorado River below Imperial, AZ for historic, control, and BAU period 1-3 simulations (BAU results averaged over 3 ensembles).

3.4 Water Resource System Effects

The reliability of the Colorado River water resource system is extremely sensitive to reductions in annual inflow volume since the historical streamflow is essentially fully allocated. 20.3 BCM (16.5 MAF) have been allocated for consumptive use while the average historical inflow from 1906-1990 is only 20.5 BCM (16.6 MAF). This consumptive use does not account for reservoir evaporation, which takes up to an additional two BCM out of the system annually. The system has been able to operate reliably in the past because the upper basin has not utilized its full entitlement. In the results below, unless otherwise specified, upper basin use is fixed at the year 2000 amount of 5.2 BCM (4.2 MAF) and total basin consumption is 17.1 BCM (13.9 MAF). Separate results are also presented with Upper Basin demands increasing up to 6.7 BCM (5.4 MAF) in year 2060.

In this section we show selected results for reservoir storage, *Law of the River* compliance, water deliveries, hydropower production, and probability of uncontrolled spills. Although these results are consistent with previous climate change studies of the basin (Gleick et al, 1993), they should not be taken as predictions as to how the system will operate in the future, but rather as general sensitivities to possible future inflows. However, it should also be recognized that among the various GCM scenarios prepared for the 2001 IPCC report, the PCM projected changes in temperature and precipitation tend to be near the low end of the range.

The results are summarized into the following periods; a historic simulation (using VIC simulated inflows from 1950 - 2000), a 50 year control run based on 1995 climate, and the future BAU ensembles summarized into periods 1, 2, and 3. For the future periods, the numbers presented are the average of the results for the three ensemble members in the respective periods.

Storage

Minimum, average, and maximum January 1 reservoir storages are shown for historical, control, and the average of the ensemble runs for periods 1, 2, and 3 in Figure 9. Initial reservoir levels in each run correspond to the actual state of the system in January of 1970 (total system storage of 35.5 BCM (28.8 MAF)). The initial reservoir levels at the beginning of periods 1, 2 and 3 are the values simulated by CRRM and vary considerably due to the particular sequences of inflows and releases leading up to the respective periods.

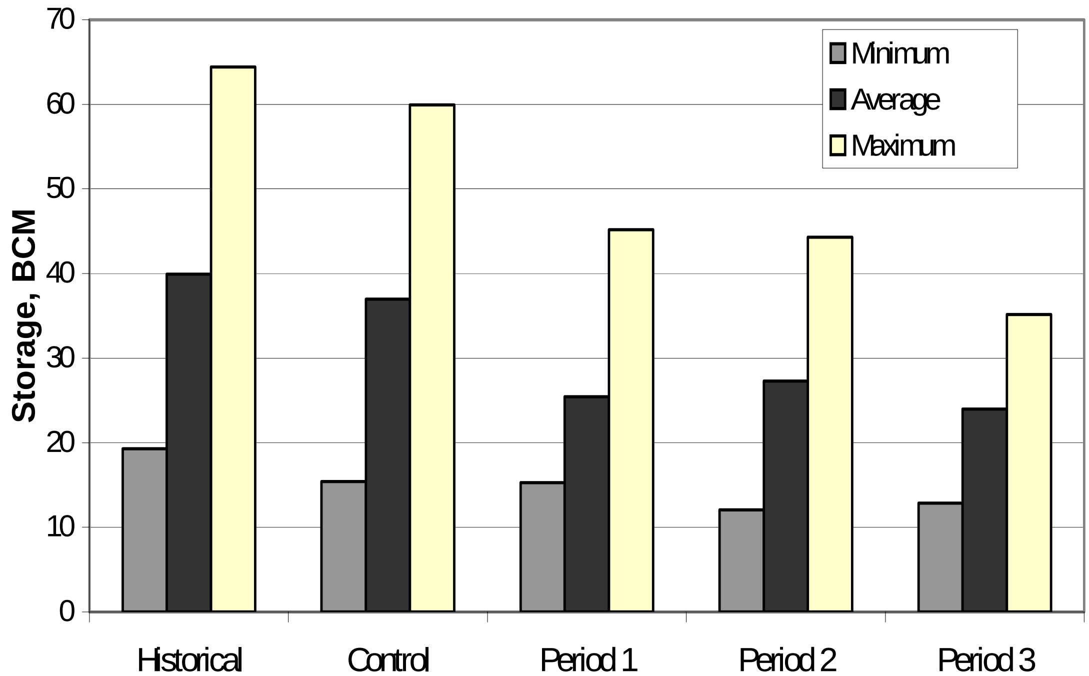

Figure 9 Simulated minimum, average, and maximum total basin storage for historical, control, and BAU Period 1-3 simulations (BAU results averaged over 3 ensembles).

When CRRM was forced with VIC simulated historic streamflow from 1950 – 2000, current operating policies, and year 2000 demands, average January 1 reservoir storage was 39.9 BCM (32.4 MAF) with a minimum and maximum of 19.3 BCM (15.7 MAF) and 64.4 BCM (52.2 MAF), respectively. For the control climate, average storage was 37.0 BCM (30.8 MAF), with a minimum of 15.3 BCM (12.4 MAF) and maximum of 59.9 BCM (48.6 MAF). Average storages for periods 1, 2, and 3 were 25.5 BCM (20.7 MAF), 27.3 BCM (22.1 MAF), and 24.0 BCM (19.5 MAF) with minima of 15.3 BCM (12.4 MAF), 12.0 BCM (10.0 MAF), and 12.9 BCM (10.5 MAF) and maxima of 45.2 BCM (36.7

MAF), 44.3 BCM (35.9 MAF), and 35.2 BCM (28.5 MAF), respectively. Although Period 1 had the highest natural flow, Period 2 had the highest average storage. This is because one of the ensemble sequences (B0644) was relatively wet in Period 1, resulting in initial Period 2 average reservoir levels that were about 5.0 BCM (4.1 MAF) and 8 BCM (6.5 MAF) higher than Periods 1 and 3, respectively. Period 3 reservoir levels were the lowest, due primarily to having the lowest average initial reservoir storage coupled with inflows lower than those in period 1.

Withdrawals and releases made under current operating policies (which in turn reflect the Law of the River) are based on nearly full allocation of the river's discharge under historical conditions. While a 10% decrease in streamflow will cause a similar reduction in average storage, further reductions in streamflow cross the threshold where consumptive uses exceed the amount available for withdrawal. This causes reservoir storage to be driven by inter-annual variability and, on long-term average, decrease at a rate higher than streamflow decreases. For example, the average control climate storage is 2.9 BCM (2.4 MAF) less than historical, a reduction of about 9%. For all future periods, average storage was around 14.0 BCM (11.4 MAF) less, or 64% of historical. Minimum storage was 30% of capacity for the historical climate and 24% for control. Period 1-3 minima were all in the range of 15-20% of capacity, which is about equal to the inactive capacity of Lake Mead and the dead pool of Lake Powell.

Compact Compliance

The main operating objectives set forth in the *Law of the River* are a mandatory annual release of 10.1 BCM (8.23 MAF) from Lake Powell into the lower basin and 1.9 BCM (1.52 MAF) released to Mexico from Imperial Dam (USDOI, 1985). CRRM imposes delivery shortages (for both Upper and Lower Basin deliveries in this section and CAP & MWD withdrawals in the next section) in its historic simulation even though the need for such reductions has never occurred in the basin to date. It does so for two main reasons; 1) CRRM models CAP withdrawals (1.8 BCM/yr.) during the whole period, not just from the date (1985) when CAP actually came online. This includes the 1953-1964 period which the USBR considers the most critical drought of record, 2) The entire simulation uses year 2000 demands, which exceed the actual demands during much of the historical period. Figures 10 and 11 show CRRM simulated average releases to the Lower Basin and to Mexico, respectively, as well as the percentage of years in which the compact requirement were met or exceeded.

The average Lake Powell release for the historical period was 11.5 BCM (9.3 MAF), and 92% years had releases greater than or equal to the Compact requirement. The historical average annual release to Mexico was 2.3 BCM (1.9 MAF) with 72% of years meeting or exceeded the Compact requirement. The control run had an average release from the upper basin of 10.4 BCM (8.4 MAF), and 80% of the years satisfied the Compact requirement. The average release into Mexico was 1.4 BCM (1.1 MAF) (less than the Compact requirement), with violations occurring in 32% of the years. Average annual releases from Lake Powell were reduced to about 9.7 BCM (7.9 MAF) during periods 1 – 3. The percent of years in which releases exceed the Compact minimum were 59, 73, and 77 for periods 1, 2, and 3, respectively. Average reliability for period 1 was low due to ensemble B0647 being dry during this period and having compact violations 70% of the time while period 3 reliabilities were quite good, relatively speaking, because run B0644 was quite wet during this period and had no compact violations. The reliability of releases to Mexico was also significantly reduced during all future periods. Average deliveries to Mexico in periods 1, 2, and 3 were 0.9 BCM (0.8 MAF), 1.2 BCM (1.0 MAF), and 1.1 BCM (0.9 MAF), respectively. The percent of years in which full releases were made dropped to 24, 46, and 25 for periods 1, 2, and 3, respectively.

The 50-year historic simulation had a cumulative release to the lower basin that exceeded the compact requirement by 66.2 BCM (53.7 MAF) and a cumulative release that exceeded the required flow at the U.S.- Mexico border by 20.3 BCM (16.5 MAF). The 50-year control run had a cumulative release excess to the lower basin of 12.6 BCM (10.2 MAF) and a cumulative delivery shortfall to Mexico of 23.3 BCM (18.9 MAF). The 30 year future periods had cumulative lower basin delivery shortfalls of 11.4 BCM (9.2 MAF) in period 1, 14.8 BCM (12.0 MAF) in period 2, and 11.2 BCM (9.1 MAF) in period 3. Cumulative shortfalls in deliveries to Mexico were 28.1 BCM (22.8 MAF) in period 1, 19.7 BCM (16.0 MAF) in period 2, and 25.3 BCM (20.5 MAF) in period 3.

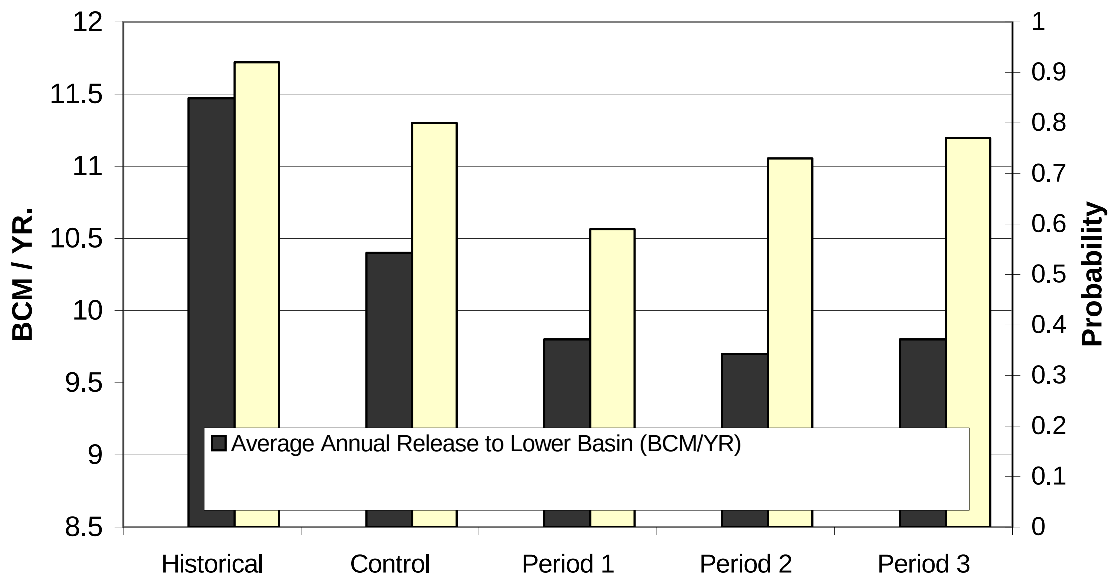

Figure 10 Simulated average annual release from Glen Canyon Dam to the lower basin and probability that release targets are met for historical, control, and BAU Period 1-3 simulations (BAU results averaged over 3 ensembles).

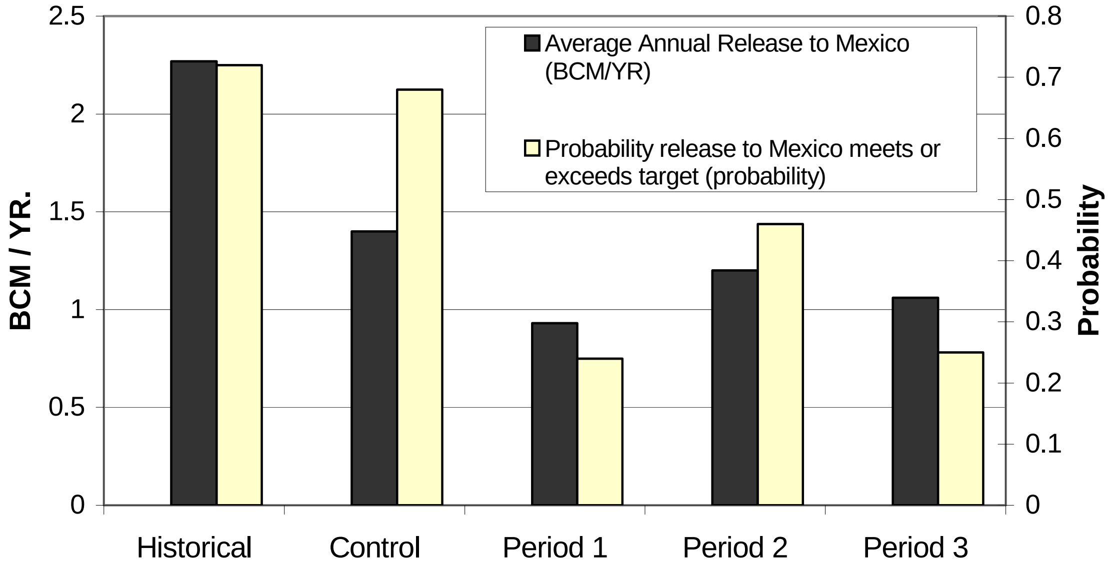

Figure 11 Simulated average annual release from Imperial Dam to Mexico and probability that release targets are met for historical, control, and BAU Period 1-3 simulations (BAU results averaged over 3 ensembles).

CAP, SNWA, and MWD Deliveries

Simulations using VIC 1950-2000 streamflows along with year 2000 demands resulted in 60% of the years having level 1 shortages (imposed upon CAP & SNWA when Lake Mead drops below 343 m). During the historical simulation, the elevation of Lake Mead dropped to 330 m, resulting in level 2 shortages, 28% of the time (Figure 12). The first half of the control run was wet with high storage volumes and no shortages. The second half was considerably drier resulting in imposition of level 1 shortage restrictions 50% of the time and level 2 shortages 32% of the time. However, as shown in Figure 12, even though the probability of level 1 and level 2 shortfalls was similar for the historical and control simulations, the magnitude of shortfalls was generally larger in the control than in the historical simulations. In periods 1, 2, and 3, level 1 shortages occurred in almost all years (92%, 89%, and 100%, respectively). Level 2 restrictions are also frequent (77%, 54%, and 75% in periods 1, 2, and 3, respectively). Although period 2 inflow was the lowest, its average CAP, SNWA, and MWD reliability was the highest because of both its high initial storage and because ensemble members B0644 and B0646 were relatively wet and reliable during this period.

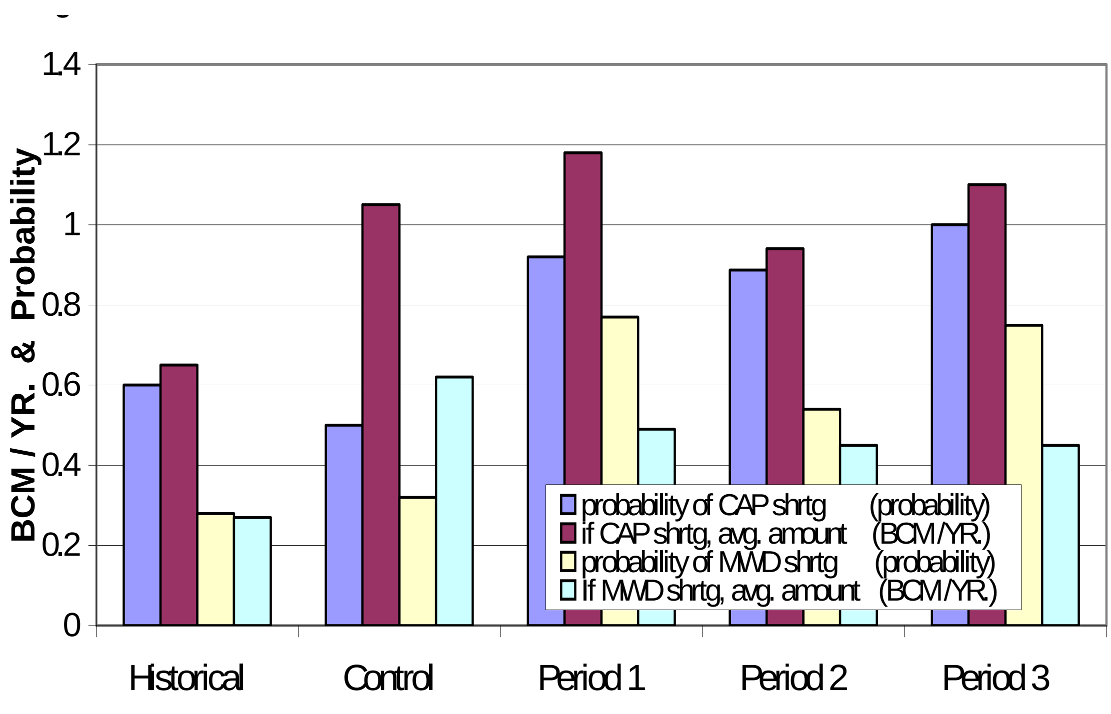

Figure 12 Probability of a delivery shortage to CAP and MWD and average amount of shortfall for historical, control, and BAU Period 1-3 simulations (BAU results averaged over 3 ensembles).

During the 50-year historic simulation, CAP had a cumulative shortfall of 19.6 BCM (15.9 MAF) while there was a cumulative shortfall of 3.8 BCM (3.1 MAF) in deliveries to the MWD. In the 50 year control run, CAP and MWD have cumulative delivery shortfalls of 26.2 BCM (21.2 MAF) and 9.8 BCM (7.9 MAF), respectively. The 30-year ‘future’ periods had cumulative delivery shortfalls to CAP of 32.6 BCM (26.4 MAF), 25.0 BCM (20.3 MAF), and 31.8 BCM (25.8 MAF), and to MWD of 11.3 BCM (9.2 MAF), 7.3 BCM (5.9 MAF), and 9.8 BCM (7.9 MAF).

Hydropower

Hydropower production is a function of both reservoir elevation (head) and streamflow volume. Because of Lake Mead’s relatively high inactive storage (amount of storage that cannot be withdrawn for hydropower) of 12.3 BCM (10.0 MAF), the basin’s hydropower production is very sensitive to reduced storage and streamflow. Although Lake Mead and Lake Powell can be drawn down below their minimum power pool and therefor produce no electricity, Flaming Gorge remained relatively full throughout all simulations. Davis and Parker are run of the river dams that have a fixed head of 130’ and 70’, respectively.

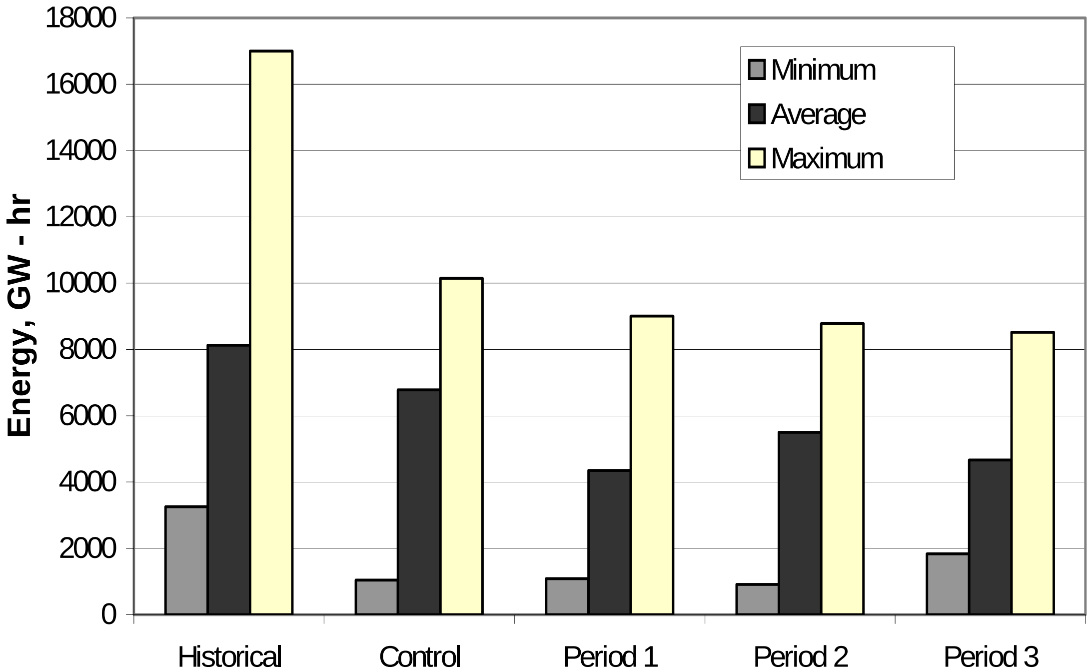

Figure 13 Simulated minimum, average, and maximum total basin energy production for historical, control, and BAU Period 1-3 simulations (BAU results averaged over 3 ensembles)

The historical simulation produced an average annual hydropower output of 8,123 GW-hr while minimum annual generation was 3253 GW-hr and maximum was 16998 GW-hr (Figure 13). The control run has an average output of 6800 GW-hr, a minimum of 1100 GW-hr, and maximum of 10,200 GW-hr. Periods 1, 2 and 3 had an average output of 4400 GW-hr, 5500 GW-hr, and 4700 GW-hr, a minimum of 1000 GW-hr, 1000 GW-hr, and 1800 GW-hr, and a maximum of 9000 GW-hr, 8800 GW-hr, and 8500 GW-hr, respectively. The historical minimum, average, and maximum values were considerably higher due to the fact that neither Lake Mead nor Powell dropped below its minimum power pool elevation concurrently. The control and BAU simulations had similar annual minimum productions corresponding to years in which both Glen Canyon and Hoover were below minimum power pool. Period 2 had the highest average annual hydropower production of the three future periods as a result of its relatively high average total basin storage.

Spills

Due to lower inflow volumes and greater storage space available, the system is less likely to have uncontrolled spills (releases that do not generate hydropower) in the future (Figure 14). In the historic simulation, 18% of years had one or more months with a spill while the control run had only 14% of years with a spill. Spill probability was reduced to 7%, 7%, and 2% for periods 1, 2, and 3, respectively.

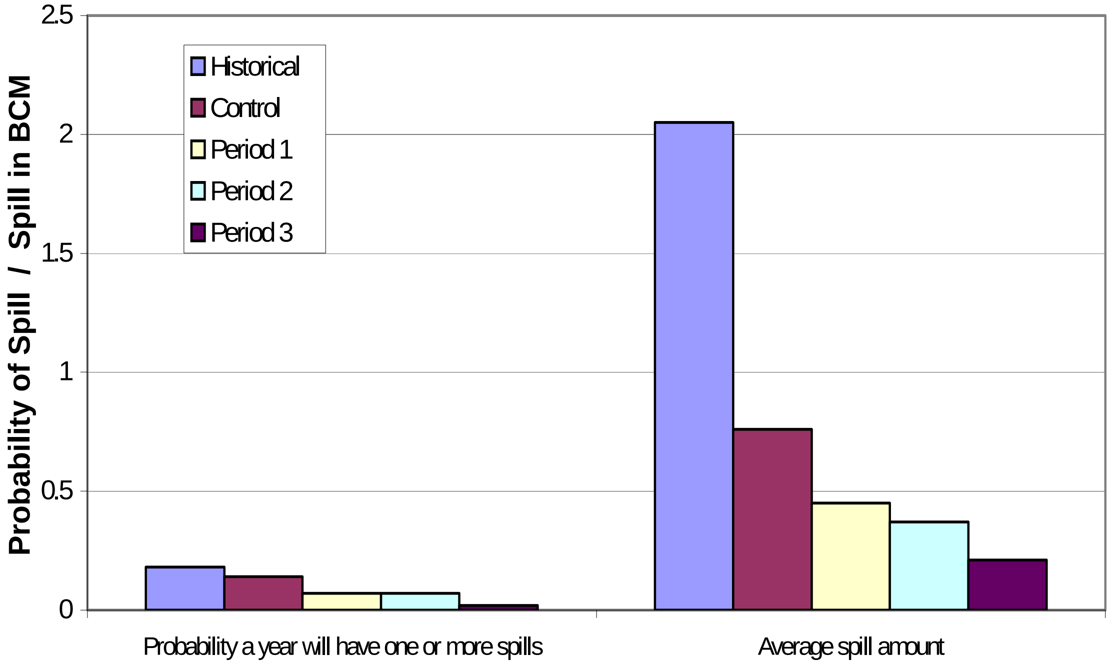

Figure 14 Probability a given year will have an uncontrolled spill (release that does not generate hydropower) and average amount of spill for historical, control, and BAU Period 1-3 simulations (BAU results averaged over 3 ensembles).

Sensitivity to Increased Upper Basin Demands

The results above correspond to upper basin demands fixed at the MSCP 2000 Baseline amount of 5.2 BCM (4.2 MAF). A subset of the simulations reported above were run with a linear increase in these demands over time to 6.7 BCM (5.4 MAF) by 2060, after which they were held constant. Demands in the lower basin and Mexico remained fixed at 9.2 BCM (7.5 MAF) and 1.9 BCM (1.5 MAF), respectively.

Under the increasing upper basin demand scenario, average storage dropped by 1.7 BCM (1.4 MAF) in period 1 and by 4.8 BCM (3.9 MAF) in periods 2 and 3 (Table 3). This represents reductions ranging from 7 – 20%. Releases from Glen Canyon to the lower basin were reduced by 0.33 BCM (0.27 MAF) on average for period 1, 0.67 BCM (0.54 MAF) for period 2, and by 0.75 BCM (0.61 MAF) for period 3. Reliability of releases to Mexico decreased by 3% in period 1 and 19% in periods 2 and 3. Annual delivery volume to Mexico was reduced by 0.14 BCM (0.11 MAF), 0.23 BCM (0.19 MAF), and 0.38 BCM (0.31 MAF) for periods 1 – 3, respectively. The reliability of deliveries to CAP, SNWA, and MWD were also reduced by 5 – 20%.

Table 3: Summary of changes in system performance for Periods 1-3 when increasing Upper Basin demands to 5.2 BCM (4.2 MAF).

	Change in average basin storage (BCM)	Change in Glen Canyon mean release (BCM)	Change in Glen Canyon release reliability	Change in Mexico delivery reliability	Change in MWD delivery reliability
Per. 1	- 1.7	- .33	-.08	- .03	- .05
Per. 2	- 4.8	- .67	- .14	- .19	- .20
Per. 3	- 4.8	- .75	- .30	- .18	- .19

Sensitivity of Results to Initial Reservoir Storage

In all results presented to this point, CRRM's initial total basin storage volume was set to 35.5 BCM. This amount corresponds to the actual January 1, 1970 storage in the basin (Navajo Reservoir; 1.3 BCM, Flaming Gorge Reservoir; 1.9 BCM, Lake Powell; 11.5 BCM, and Lake Mead; 20.8 BCM). For this reason, the initial storage in periods 1, 2, and 3 (which are 13, 43, and 73 years, respectively, after the initial year of the future runs) differ from each other. This in turn effects the simulated performance of the reservoir system. The rationale for prescribing initial reservoir storage in this way was that it reflects the evolution of climate over the 21st century as simulated by PCM in each of the three ensembles. However, this results in the initial storage "inheriting" characteristics of flows before the period of interest, and may complicate interpretation of the results, especially given that the Colorado River system has a large storage to runoff ratio, which increases the importance of initial storage. Therefore, a subset of runs were preformed in which reservoir levels were reset to 35.5 BCM at the beginning of each period. Tables 4 and 5 summarize changes in simulated total basin storage and hydropower production associated with the changes in initial storage. In general, the changes are modest, especially in period 1. Percent changes in minimum and maximum values of storage and hydropower are dominated by extremes in the individual ensemble members and when averaged do not duplicate the same trend as the change in average initial storage. However, average storage and hydropower production increases and decreases corresponding to respective increases and decreases in average initial storage values.

Table 4: Percent change in average (over 3 ensembles) initial storage, and ensemble-average minimum, average, and maximum storage for Periods 1-3 resulting from re-initialization of reservoir storage at beginning of each period.

	Change in average initial storage	Minimum	Average	Maximum
Per. 1	14 %	0 %	3 %	- 1 %
Per. 2	- 2 %	- 14 %	- 7 %	- 16 %
Per. 3	25 %	21 %	6 %	- 2 %

Table 5: Percent change in average (over 3 ensembles) initial storage, and ensemble-average minimum, average, and maximum annual hydropower production in Periods 1-3 resulting from re-initialization of reservoir storage at beginning of each period.

	Change in average initial storage	Minimum	Average	Maximum
Per. 1	14 %	0 %	7 %	1 %
Per. 2	- 2 %	0 %	- 8 %	- 2 %
Per. 3	25 %	- 3 %	10 %	- 1 %

Chapter 4: CONCLUSIONS

The PCM projected temperature increases and precipitation decreases for the control (1995) climate relative to historical conditions, and for BAU emission scenarios through 2098, would result in reductions of annual streamflow in the Colorado River basin on the order of 10% for the control run and 14 - 18% over the next century. The temperature, precipitation, and runoff changes from historical to control are a result of climate warming that has already occurred, but may not yet be fully evident in statistical analyses due to natural variability. Results from our reservoir simulation model, CRRM, indicate that the reservoir system is quite sensitive to these reductions in streamflow and that system performance may already be degraded relative to historic estimates, and will further degrade in the future. More specifically:

The system becomes less able to meet demands in the control and future simulations. Storage volumes were reduced by 35% and hydropower production was reduced by 41% for the BAU simulations, and Colorado River Compact release requirements could not be met with increasing frequency.

Increasing demand, examined in a simulation where upper basin demands increased to 6.7 BCM (5.4 MAF) from the current 5.2 BCM (4.2 MAF) further degraded system performance beyond the substantial reductions associated with climate change alone. Average total basin storage was reduced further (up to 5 BCM (4 MAF)) and system reliability decreased by up to 30% for releases to the lower basin and by up to 19% for releases to Mexico. The 1.5 BCM (1.2 MAF) upper basin demand increase can be considered modest, and is well within the upper basin states' entitlement under the Compact.

The Colorado River system has a large amount of storage (over 4 times the mean annual flow), with few feasible sites where additional storage could be provided. Nonetheless, simulated system shortfalls are the result of the long-term flow of the river being close to, or less than, consumptive uses. This is a situation that could not be resolved with additional reservoir storage capacity even if feasible sites were available.

Given the large system demands relative to mean flows, reduction of consumptive uses appears to be the only viable means of preserving system reliability. Irrigation withdrawals account for 96% of all consumptive uses of Colorado River water. If PCM projected climate and associated hydrologic changes come to pass, reductions in this number on the order of 15% may be required to ensure that the system continues to operate reliably in the future.

References:

Barnett, T.P., D.W. Pierce, and R. Schnur, 2001: "Detection of anthropogenic climate change in the world's oceans," Science 292, 270-274

Brown, R.D., 2000: "Northern Hemisphere Snow Cover Variability and Change, 1915-97." Journal of Climate, 13(13), 2339-2355.

Dai, A, W.M. Washington, G.A. Meehl, T.W. Bettge and W.G. Strand, 2002: "Climate change simulations using a new ocean initialization method." Climate Change, submitted.

Gleick, P.H. and E.L. Chaleki, Dec. 1999: "The impacts of climate change for the water resources of the Colorado and Sacramento-San Joaquin River Basins." J. Amer. W. Resourc. Assn., 35 (6), 1429-1441

Hamlet, A.F. and D.P. Lettenmaier, Dec. 1999: "Effects of climate change on hydrology and water resources of the Columbia River Basin." J. Amer. W. Resourc. Assn., 35 (6), 1597-1623

Hundley, N., Jr. 1975: Water in the West, University of California Press, Berkeley, CA.

IPCC: Houghton, J.T. and Y. Ding, eds., 2001: Climate Change 2001: The Scientific Bias. Cambridge: Cambridge UP

Lettenmaier, D.P., K.L. Brettman, L.W. Vail, S.B. Yabusaki, and M.J. Scott, 1992: "Sensitivity of Pacific Northwest Water Resources to Global Warming" Northwest Environmental Journal 8(2), 265-283

Liang, X, D.P. Lettenmaier, E.F. Wood, and S.J. Burges, 1994: “A simple hydrologically based model of land surface water and energy fluxes for general circulation models.” J. Geophys. Res., 99(D7), 14,415-14,428

Loaiciga, H.A., Valdes, J.B., Vogel, R., Garvey, J., Schwarz, H., 1996: “Global Warming and the Hydrologic Cycle.” Journal of Hydrology, 174, 83-127.

Lohmann, D., Raschke, E., Nijssen B., Lettenmaier, D.P.:1998a “Regional Scale Hydrology: II. Application of the VIC-2L model to the Weser River, Germany,” Hydrological Sciences – Journal des Sciences Hydrologiques, 43, 143-158.

Lohmann, D., Liang, X., Wood, E.F., Lettenmaier, D.P., and others:1998b, “The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) Phase-2c Red-Arkansas River Basin Experiment: 3. Spatial and Temporal Analysis of Water Balance Fluxes.” J. Global and Planetary Change 19, 161-179

Maurer, E.P., D.P. Lettenmaier, and J.O. Roads, 1999: “Water Balance of the Mississippi Rive Basin from a Macroscale Hydrology Model and NCEP/NCAR reanalysis,” EOS, Transactions of the American Geophysical Union, 80(46), F409-410.

McCabe, G.J. and D.M. Wolock, Dec 1999: “General circulation model simulations of future snowpack in the western United States.” J. Amer. Water. Resourc. Assn., 35(6), 1473-1484

Nijssen, B., D.P. Lettenmaier, X. Liang, S.W. Wetzel, E.F. Wood, Apr 1997:"Streamflow simulations for continental-scale river basins." J. Amer. Water Resourc. Assn., 36(2),399-420

Nijssen, B., G.M. O'Donnell, A.F. Hamlet, and D.P. Lettenmaier, 2001: "Hydrologic sensitivities of global rivers to climate change." Climate Change, 50(1-2), 143-175

Payne, J.T., A.W. Wood, R.N. Palmer, and D.P. Lettenmaier, 2002: "Mitigating the effects of climate change on the water resources of the Columbia River Basin." Climate Change, submitted.

U.S. Department of Interior (USDOI), Bureau of Reclamation, 1985: Colorado River Simulation System: System Overview. USDOI Publication.

U.S. Department of Interior (USDOI), Bureau of Reclamation, 1989: Hydrologic Determination: Water Availability from Navajo Reservoir and the Upper Colorado River Basin for use in New Mexico. USDOI Publication.

U.S. Department of Interior (USDOI), Bureau of Reclamation, 2000: Colorado River Interim Surplus Criteria; Final Environmental Impact Statement, Volume 1. USDOI Publication.

Van Rheenen, N.T., A.W. Wood, R.N. Palmer, and D.P. Lettenmaier, 2002: "Potential implications of PCM climate change scenarios for California hydrology and water resources." Climate Change, submitted.

Washington, W.M., J.W. Weatherly, G.A. Meehl, A.J. Semtner, T.W. Bettge, A.P. Craig, W.G. Strand, J. Arblaster, V.B. Wayland, R. James, and Y. Zhang, Oct 2000; “Parallel climate model (PCM) control and transient simulations” Climate Dynamics, 16(10-11), 755-774

Wood, A.W., Leung, L-Y., Rau, S., and D.P. Lettenmaier, 2002: “Downscaling climate model surface precipitation and temperature: a comparison of methods.” Climate Change, submitted