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

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Abstract. The potential effects of climate change on the hydrology and water resources of the Colorado River basin are assessed by comparing simulated hydrologic and water resources scenarios derived from downscaled climate simulations of the U.S. Department of Energy/National Center for Atmospheric Research Parallel Climate Model (PCM) to scenarios driven by observed historical (1950–1999) climate. PCM climate scenarios include an ensemble of three 105-year future climate simulations based on projected 'business-as-usual' (BAU) greenhouse gas emissions and a control climate simulation based on static 1995 greenhouse gas concentrations. Downscaled transient temperature and precipitation sequences were extracted from PCM simulations, and were used to drive the Variable Infiltration Capacity (VIC) macroscale hydrology model to produce corresponding 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 climate, and 1.0, 1.7, and 2.4 °C warmer for Periods 1–3, respectively, relative to the historical climate. Basin-average annual precipitation for the control climate was slightly (1%) less than for observed historical climate, and 3, 6, and 3% less for future Periods 1–3, respectively. Annual runoff in the control run was about 10% lower than for simulated historical conditions, and 14, 18, and 17% less for Periods 1–3, respectively. Analysis of water management operations using a water management model driven by simulated streamflows showed that streamflows associated with control and future BAU climates would significantly degrade the performance of the water resources system relative to historical conditions, with average total basin storage reduced by 7% for the control climate and 36, 32 and 40% for Periods 1–3, respectively. Releases from Glen Canyon Dam to the Lower Basin (mandated by the Colorado River Compact) were met in 80% of years for the control climate simulation (versus 92% in the historical climate simulation), and only in 59–75% of years for the future climate runs. Annual hydropower output was also significantly reduced for the control and future climate simulations. The high sensitivity of reservoir system performance for future climate is a reflection of the fragile equilibrium that now exists in operation of the system, with system demands only slightly less than long-term mean annual inflow.

1. Introduction

The Colorado River heads in the Rocky Mountains and drains parts of seven states and Mexico (Figure 1), discharging to the Gulf of California. The river is regulated

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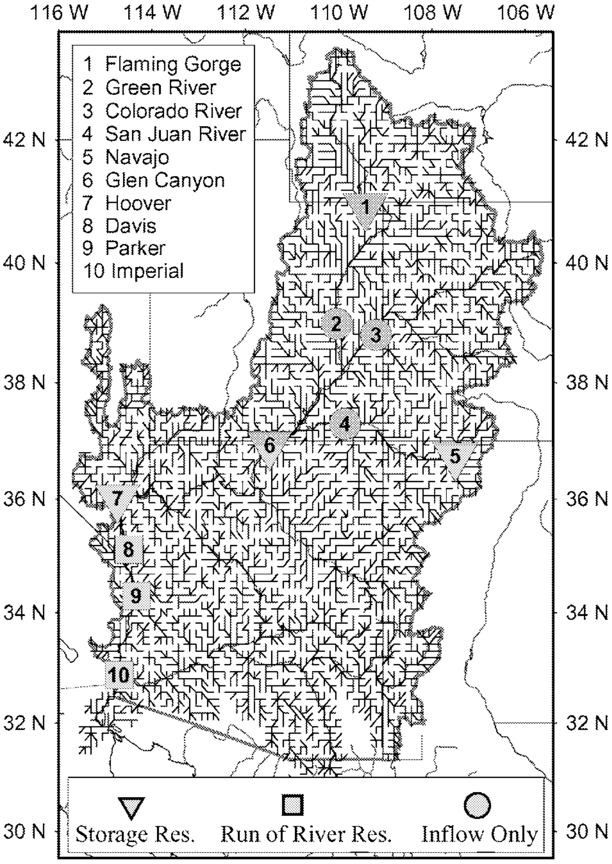

Figure 1. Colorado River basin with 1/8-degree VIC routing network and major system reservoirs.

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 (CORB) is arid, with naturalized annual streamflow (i.e., streamflow that would have occurred in the absence of water management) averaging only 40 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% of the annual streamflow is generated in the Upper Basin (above Lees 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). 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

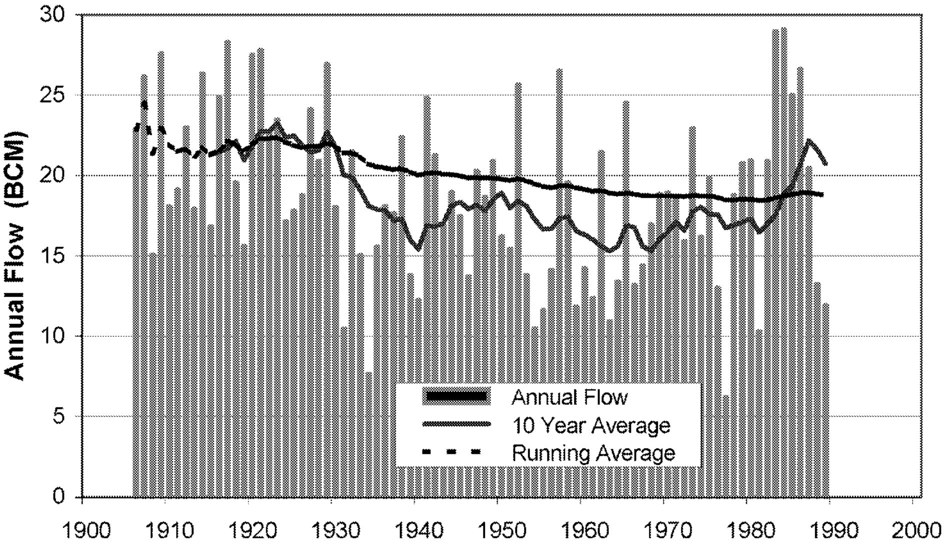

Figure 2. Annual, 10-year average, and running average of natural flow at Lees Ferry, AZ stream gage.

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% of the basin total.

The Colorado River has the most complete allocation 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. From the estimated mean flow of 22 BCM (18 MAF), the Upper and Lower Basin were each apportioned 9.3 BCM (7.5 MAF) for annual consumptive use. The 1944 United States–Mexico treaty guarantees an annual flow of not less than 1.9 BCM (1.5 MAF) to Mexico, except in times of extreme shortage. 'Extreme shortage' was not well defined in the treaty, nor, incidentally, was the possibility that future flows might be different than those that had been observed prior to signing of the Treaty or Compact. 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).

Climate change is of particular concern in the CORB 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 (GCMs) of the atmosphere predict increases in global mean annual air temperature between 1.4 and 5.8 °C over the next century (IPCC, 2001). Previous studies (McCabe and Wolock, 1999; Hamlet and Lettenmaier, 1999; Lettenmaier et al., 1992; Nash and Gleick, 1993; Gleick, 1987, 1985; Wilby et al., 1999; Wolock and McCabe, 1999) of hydrologic and water resources impacts of climate change, both in the Colorado basin and elsewhere, have been based on climate change scenarios that, while predicting increases in temperature, disagreed on the tendency and seasonality of precipitation changes, and on the size of the temperature increase for the next century. The temperature-related effects on streamflows shown in previous studies include an increased rain to snow ratio, an increase in winter runoff and a decrease in summer runoff, and earlier and faster snowmelt. Wolock and McCabe (1999) showed that Colorado River streamflows were highly sensitive to precipitation and temperature changes. Their study showed that for one GCM, a slight increase in precipitation combined with a general warming would result in decreasing streamflows, for another GCM that a large increase in precipitation along with increased temperature would result in substantially increased streamflows. Although a decrease in precipitation was not predicted by the GCM scenarios analyzed by Nash and Gleick (1991), decreases were evaluated via additional prescribed change experiments (e.g., 2 and 4 °C warming and 10 and 20% precipitation decrease) scenarios. Results of a 2° increase/10% precipitation decrease were a 20% reduction in runoff (Nash and Gleick, 1991), while the 4° increase/20% precipitation decrease produced a 30% runoff reduction (McCabe and Hay, 1995). Although the Nash and Gleick (1993) scenarios disagree on precipitation changes (increases and decreases), results suggest that precipitation increases would be offset by increased evapotranspiration, with the net effect being a reduction in runoff ranging from 8 to 20%. The diversity of scenarios considered by the assortment of climate change studies reflects considerable uncertainty in the magnitude of projected climate warming, and in both the magnitude and direction of precipitation change.

Precipitation decreases would compound the temperature-related effects (e.g., increased evapotranspiration, lower runoff) on the managed water resources of the Colorado River. Nash and Gleick (1993), for example, found a high sensitivity of reservoir system storage to changes in runoff, which suggests that the system is currently in a rather fragile balance. Their work also showed that violations of the Compact would potentially occur if runoff dropped by only 5%. Although the high storage to runoff ratio of the system may negate some of the effects of the timing shift associated with earlier runoff in a warmer climate, 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 an ensemble of three future simulations for the 21st century (1995–2099) from the DOE/NCAR coupled land-atmosphere-ocean Parallel Climate Model (PCM) (Washington et al., 2000; Dai et al., 2004; Pierce et al., 2004) and one control climate simulation based on a static 1995 climate. The precipitation and temperature signals from PCM were statistically downscaled using methods outlined in Wood et al. (2002) and Wood et al. (2004), and used to drive the Variable Infiltration Capacity (VIC) macroscale hydrologic model (Liang et al., 1994, 1996) to create continuous daily sequences of streamflows. These streamflows were then analyzed with a simplified version of the Colorado River Simulation System (USDOI, 1985) to assess the sensitivity of the reservoir system (flood control, water supply, hydropower, etc.) to the projected climate changes. We compare the hydrologic and water resource system results from the control and future climate scenarios to historical hydrologic and water resources simulations driven by 1950–1999 observed temperature and precipitation. The following sections describe the climate scenarios, downscaling approach and models used in the analysis (Section 2), results (Section 3), and discussion and conclusions (Section 4).

2. Approach

2.1. CLIMATE SCENARIOS

PCM (Washington et al., 2000; Dai et al., 2004; and Pierce et al., 2004) is a coupled atmosphere, land, ocean, and sea ice system operating on T42 resolution (a horizontal spatial resolution of 2.8°, ~300 km). The PCM climate scenarios used for hydrologic and water management analysis include:

- Three future climate ensembles (1995–2098) based on 'business as usual' (BAU) emission scenarios (see Dai et al., 2004, for details).
- One 50 year 1995 'control' climate (based on 1995 atmospheric greenhouse gas concentrations) scenario.

These are the same runs that are described in companion papers by Payne et al. (2004) for the Columbia River basin and VanRheenen et al. (2004) for the Sacramento-San Joaquin River basin. A 50 year segment (1950–1999) of a longer PCM historical climate scenario (1870–2000) was also used to derive statistics for adjusting climate model bias (see Section 3.1), but was not used directly in the hydrologic and water resources simulations. Instead, the baseline for comparison was the observed historical climate (temperature and precipitation from 1950–99), and associated simulations of hydrology and water resources system performance. As in Payne et al. (2004) and VanRheenen et al. (2004), results were summarized into three periods, denoted Periods 1–3: 2010–2039, 2040–2069 and 2070–2098.

The reader is referred to Wood et al. (2002) and Payne et al. (2004) 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 (about 3° latitude by longitude) to the ⅛-degree resolution of the hydrology model by mapping from probability distributions of the climate model output to equivalent climatological probability distributions. The application of the bias correction method in the CORB differs slightly from the methods utilized by Payne et al. (2004) and VanRheenen et al. (2004), however: for the CORB, the mean temperature difference between each BAU scenario and the PCM historical scenario (50 year period) was removed before, and replaced after, bias-correction, whereas for the other studies this difference was taken with respect to the PCM control climate. The hydrologically significant warming of the control climate would have compromised the bias-correction step, were the BAU-control climate differences used. Hence, the downscaling method projects BAU and control climate changes relative to observed historical climate (rather than BAU changes relative to control climate, as was the case for the Payne et al. and VanRheenen et al. studies) onto the finer hydrological model grid. The monthly climate model sequences were then temporally disaggregated to create a daily forcing time series for the hydrology model. This method facilitates investigation of the implications of the transient (i.e., temporally continuous) nature of climate warming, as opposed to more common methods in which one or two-decade average temperature and precipitation changes are applied to historical climate to give a step-wise evolution of climate change (e.g., Hamlet and Lettenmaier, 1999).

2.2. APPLICATION OF THE VIC MODEL TO THE COLORADO RIVER BASIN

The VIC hydrology model (Liang et al., 1994, 1996) is grid cell-based and typically run at spatial resolutions ranging from ⅛ to 2 degrees latitude by longitude (~13 to ~210 km). The VIC model is driven by gridded precipitation, temperature and wind time series, all of which have been archived at the ⅛-degree spatial resolution and sub-daily temporal resolution over the continental U.S. by Maurer et al. (2002). The model simulates snow accumulation and melt, soil moisture dynamics and evapotranspiration, as well as surface runoff and baseflow, which are subsequently routed through a grid-based flow network to simulate streamflow at selected points within the basin. Details and examples of VIC model applications, calibration approach, and streamflow routing 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 run at a daily time step. At ⅛-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 1). Model calibration was performed by adjusting parameters that govern infiltration and baseflow recession to match simulated streamflows with naturalized streamflows (effects of water management removed) obtained from the U.S. Bureau of Reclamation (2000) at selected control points for the same period of record (Figure 3). The overlapping period of record between VIC historical simulations and observed naturalized flows was 1950–1989. During this period, VIC cumulative streamflow at Imperial Dam was 768 BCM (623 MAF) while observed naturalized flow was 776 BCM (630 MAF). This represents a negligible (1%) bias in VIC towards slightly under-predicting streamflow. The

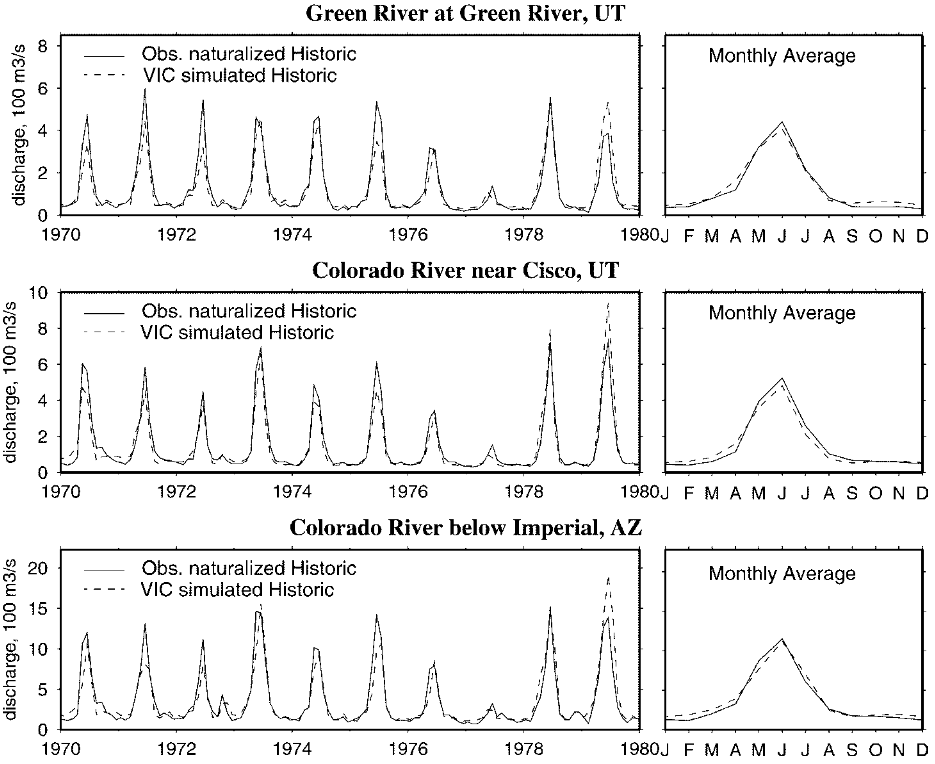

Figure 3. VIC simulated and naturalized historic observed streamflows at Green River, UT, Cisco, UT, and Imperial, AZ for 1970–1980.

relative biases at Green River and Colorado River near Cisco were slightly larger (3 and –9%, respectively).

2.3. COLORADO RIVER RESERVOIR MODEL

For this study, we developed the Colorado River Reservoir Model (CRRM). CRRM is a simplified version of the USBR Colorado River Simulation System (CRSS) (Schuster, 1987; USDOI, 1985) that represents the major physical water management structures and operating policies of the system. Both models simulate the movement and distribution of water within the basin on a monthly time step, using naturalized (unimpaired) streamflow time series at the inflow points shown in Figure 1 as input. The models use specified operating policies to simulate reservoir levels, releases, hydropower production and diversions. Reservoir evaporation is modeled as a function of reservoir surface area and mean monthly temperature. Evaporative losses are removed from system storage before other potential storage reductions, such as water deliveries, are considered.

The Colorado River is among the most heavily regulated in the world. Since 1922 there have been over 50 court decisions, state statutes, 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 consumptive use in the Lower Basin states (Arizona, Nevada and California) 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). Like CRSS, CRRM requires Glen Canyon dam to make releases regardless of the reservoir level relative to its minimum power pool (i.e., the minimum water storage at which power is generated) of 1201 m (USDOI, 1985). Only when the reservoir is at its dead storage volume (storage below which withdrawals are not possible) are releases to the Lower Basin curtailed. Lake Powell has never been drawn this low and the actual operating procedures if this level were to be approached are a matter of contention. Compact deliveries from the Lower Basin into Mexico are met completely unless Lake Mead is drawn to its minimum power pool elevation of 330 m. At this elevation, the Metropolitan Water District (Los Angeles) and Mexico's demands are constrained, while restrictions already imposed on the Central Arizona Project and Southern Nevada Water Authority (at the elevation of 343 m) are increased. Although these depletions can be eliminated in CRRM, actual operations in the basin are unlikely to do so. CRRM, like 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/yr (2 MAF/yr) would not impose the same shortages upon the Lower Basin and Mexico.

Because a large part of the total system storage volume is in Lakes Powell and Mead, not all the physical or operational complexities of the river system need to be represented in CRRM to enable assessment of climate change implications for 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.

Although water demand may well increase as climate change evolves and population expands, most results in this study are based on the Multi Species Conservation Program (MSCP) (USDOI, 2000) baseline demand for 2000, so as not to confound interpretation of climate change effects with transient demand effects. In Section 3.4.6, however, we examine system sensitivity to increased Upper Basin demands. In both demand scenarios (fixed and increasing), Lower Basin demands are the full entitlement of 9.2 BCM/yr (7.5 MAF/yr). Upper Basin demands for runs using the 2000 baseline are fixed at 5.2 BCM/yr (4.2 MAF/yr). Runs that utilize increasing demands begin with Upper Basin demands of 5.2 BCM/yr (4.2 MAF/yr) and increase to 6.7 BCM/yr (5.4 MAF/yr) in 2060, with demand constant thereafter. The MSCP provides the USBR's best estimate of projected withdrawals and consumptive uses of Colorado River water.

CRRM uses individual monthly return ratios for each of the 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.

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 Central Arizona Project (CAP) are reduced from 1.7 BCM/yr (1.4 MAF/yr) to 1.2 BCM/yr (1 MAF/yr) and annual deliveries to the Southern Nevada Water Authority (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 an 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. We do not explicitly evaluate the effects of shifts in the seasonality of demands or the overall potential of mitigating climate change effects via altered reservoir management, although in Section 4 we do note that both the effects of seasonal changes in demand and the potential for mitigation via altered operation are minimal, for reasons having to do with the large ratio of reservoir system active storage to mean annual reservoir inflow in the CORB.

Validation of CRRM 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. Note that this 21-year validation run is not the simulated historical climate analysis used for comparison to the control and future climates; the latter run spans the period 1950–99.

Figure 4a shows that CRRM reproduces observed historical aggregated reservoir storage despite its simplifications; while Figure 4b shows total basin monthly hydropower production. CRRM simulates well the storage capacity with a –1% monthly error and 0% accumulated error relative to observed historical for the period 1970–1990. The mid 1980s brought abnormally high flows in the basin and full reservoir storages. CRRM does not have a capability to utilize inflow forecast-

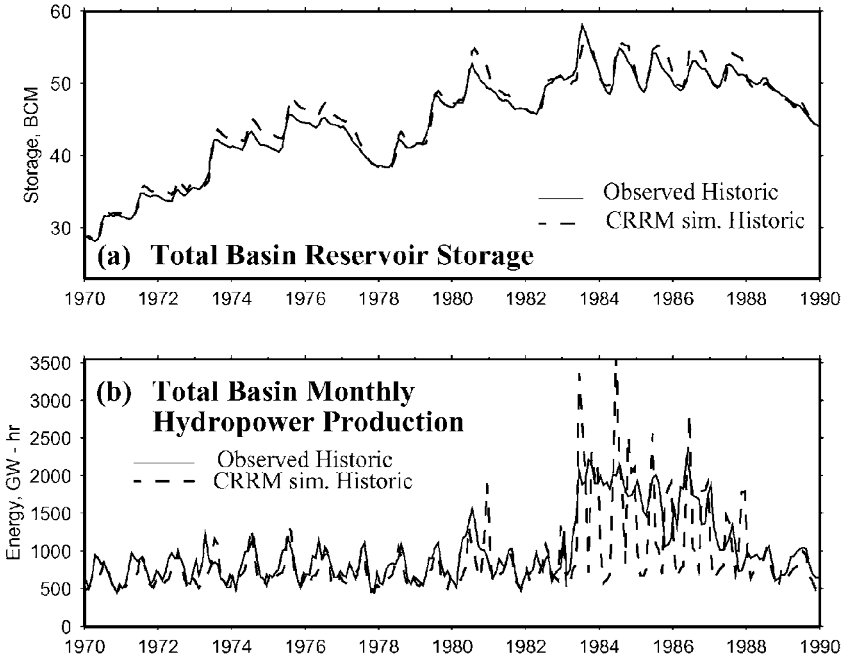

Figure 4. (a) CRRM simulated and observed total basin storage for 1970–90; (b) CRRM simulated and observed total basin monthly hydropower production for 1970–90.

ing and therefore does not simulate monthly variations in hydropower production very well under high inflow conditions (21% relative error on a monthly scale). However, because observed and simulated historical annual values are comparable (12% accumulated error over the period 1970–1990, relative to observed historical), and because the control and BAU climate scenarios used in this study do not lead to full reservoir levels, CRRM arguably represents hydropower production adequately for the purposes of this study.

3. Results

Downscaled PCM climate scenario results were compared to a 1950–99 baseline of observations – daily precipitation and temperature time series – included in the $1/8$-degree gridded hydroclimatic analysis of Maurer et al. (2002), from which averages and other statistics were calculated. The hydrologic results for the downscaled PCM scenarios (control and BAU) were compared to the hydrologic variables (snow water equivalent and runoff, primarily, but also evaporation) simulated by VIC when driven at a daily time step by the gridded observed precipitation and temperature. This historical baseline hydrologic simulation and the averages derived from it span 1950–99, matching the observed historical climate baseline.

3.1. DOWNSCALED CLIMATE CHANGES

Figures 5a,b show the basin-average annual temperature and precipitation time series for the individual BAU ensemble members, as well as the long-term observed (1950–99) and control climate averages. The control run represents a static 1995 climate and has a temperature approximately 0.5 °C warmer than the mean of the historical observations, which arguably reflects warming that has occurred in the last 50 years. Most of the control run warming occurs in the late winter and spring (Figure 5c). Average temperature for the BAU ensemble members is 1.0, 1.7 and 2.4 °C warmer than average observed climate during Periods 1, 2, and 3, respectively. There is considerable inter-annual and inter-decadal variability in temperature.

Control climate basin-wide annual average precipitation is 1% (3.2 mm/yr) less than the observed historical (1950–99) average. Precipitation in Periods 1–3 is 3% (10 mm/yr), 6% (20 mm/yr), and 3% (10 mm/yr) lower than the observed, respectively. Period 2 has the lowest precipitation due to the fact that decades 2040 and 2060 are relatively dry (Figure 5b). The control climate seasonal distribution of precipitation is very similar to the observed (Figure 5d), and the same general pattern is true of the BAU ensembles, although precipitation amounts are less for all three periods during the winter and Period 3 has an average late summer peak that is greater than in both the observed and control climates.

The results presented above are basin averages, but regional variations exist: the future climate change scenarios predict a 0–10% increase of precipitation in the Rocky Mountain headwaters of the Colorado, which is consistent with previous studies (Nash and Gleick, 1991; McCabe and Hay, 1995), but a 10–15% precipitation decrease in northwestern Arizona. Averaged over the entire basin, the precipitation generally decreases for the future climate scenarios, although as shown in Section 3.3 the regional differences can have important implications for projected streamflow changes.

3.2. SNOWPACK CHANGES

Snowpack is reported as snow water equivalent (SWE), the depth (mm) of water the snowpack would produce if melted. Figure 6 shows average April 1 SWE for simulated historical (1950–1999) conditions, for the control climate and for future climate Periods 1–3. The simulated basin-average SWE for the control run is 86% of the historical SWE, while BAU Periods 1, 2, and 3 have 76, 71, and 70%, respectively, of historical April 1 SWE. The reduced control climate SWE relative to historical SWE is due mostly to higher spring temperatures, while the reduced SWE in the BAU ensembles is attributable to both higher temperatures and reduced winter and/or spring precipitation (Figure 5). The parts of the domain with relatively high April 1 SWE in the historical run all show SWE reductions in the control and future climate scenarios, and the greatest reductions are in southern Colorado, and in Periods 2 and 3. April 1 snow covered area, on the other hand,

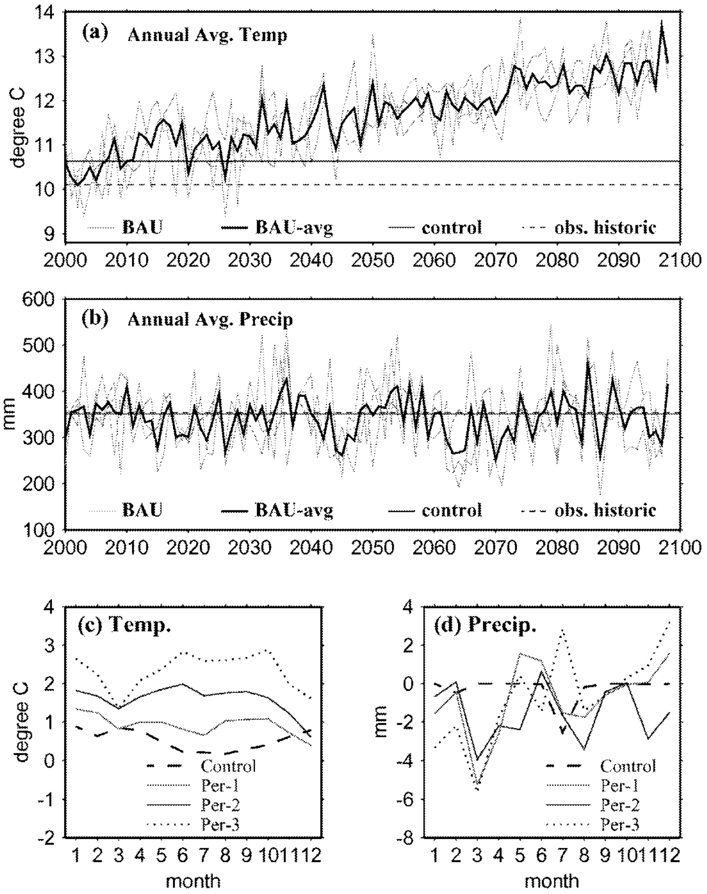

Figure 5. (a) Downscaled Colorado River basin average annual temperature for BAU ensemble climate simulations (Period 1, 2010–2039; Period 2, 2040–2069, Period 3, 2070–2098), with simulated historic and control means shown for reference; (b) same for precipitation; (c) mean annual cycle of basin-average temperature for simulated historic, control, and BAU Periods 1–3 (mean of 3 ensembles); (d) same for precipitation.

remains mostly unchanged in the high elevation Rockies but is reduced in the high plains of western Colorado where snow cover is generally thin. These results are consistent with Brown et al. (2000), Wilby et al. (1999), McCabe and Wolock (1999) and Nash and Gleick (1993).

3.3. RUNOFF AND STREAMFLOW CHANGES

Figure 6 shows annual average changes in runoff for the control climate and for Periods 1–3 (Period 1, 2010–2039; Period 2, 2040–2069, Period 3, 2070–2098) relative to simulated historical runoff. The runoff ratio for the Colorado River is low, which is typical of semi-arid watersheds. Historical basin average annual

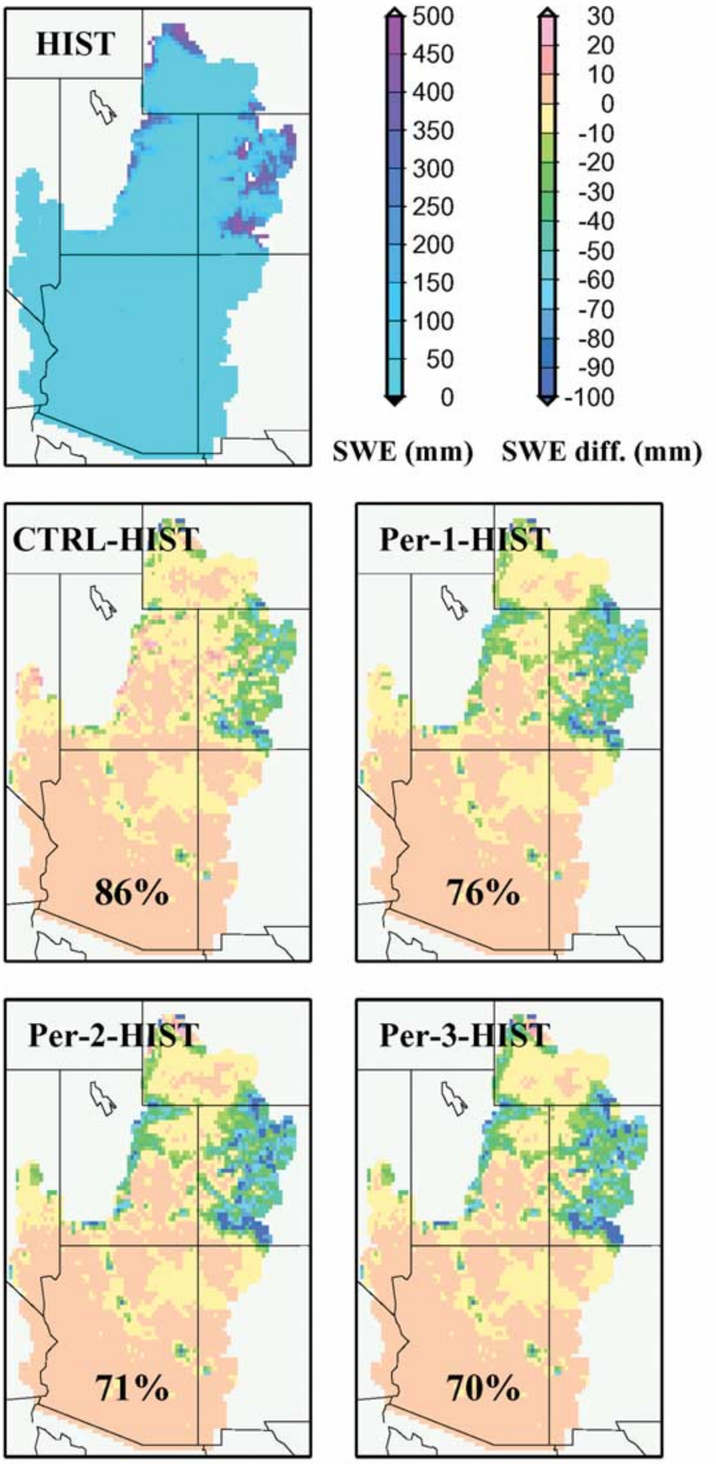

Figure 6. Simulated April 1 snow water equivalent for simulated historical, control, and Periods 1–3 (the mean of 3 ensembles: 2010–2039, 2040–2069, 2070–2098).

Table I

Annual average precipitation, evapotranspiration, and runoff for historic (HIST), control (CTRL), and future Periods 1–3 (in mm/yr)

	Precipitation, mm (% relative to HIST)	Evaporation, mm (% relative to HIST)	Runoff, mm (% relative to HIST)	Runoff ratio (%)
HIST	354 (n/a)	310 (n/a)	45 (n/a)	12.7
CTRL	351 (99)	311 (100)	41 (90)	11.6
Period 1	344 (97)	305 (98)	39 (86)	11.3
Period 2	334 (94)	298 (96)	37 (82)	11.1
Period 3	344 (97)	306 (99)	37 (83)	10.8

precipitation is 355 mm, of which 310 mm evaporates, leaving 45 mm to runoff, for a runoff ratio of about 13%. The average annual precipitation in the control run is 351 mm, with 310 mm of evapotranspiration, leaving 41 mm to runoff. Annual average basin precipitation, evapotranspiration, and runoff for all periods are given in Table I, which shows that the temperature-driven increases in evapotranspiration result in a progressive decline in runoff ratio from the historical climate to the control and BAU climates.

Although the difference in runoff of 4 mm might appear insignificant, it represents a reduction of almost 10% in the mean annual flow, which we will show has major implications for reservoir system performance. Reductions in precipitation and increases in temperature in Periods 1, 2, and 3 lead to reductions in annual runoff of 14, 18, and 17%, respectively, relative to simulated historical runoff. This impact is about double that shown by Nash and Gleick (1991, 1993) who predicted a more or less proportionate response of streamflow to precipitation changes. However, a variety of water balance studies (e.g., Schaake, 1990; Sankarasubramanian and Vogel, 2001) have shown that particularly in arid and semi-arid climates, there is an amplification of changes in precipitation into runoff changes, because evaporation is more or less extracted ‘from the top’. For instance, considered as an elasticity (percent change in runoff divided by percent change in precipitation), the multiplier for the southwestern U.S. as shown by Sankarasubramanian and Vogel (2001) was typically in the range 2–4, which is consistent with our results. Furthermore, an analysis of spatial patterns in our simulation results showed that in the high elevation headwaters that are the source of a disproportionate fraction of the total runoff, earlier snowmelt lead to considerable enhancement in the modeled evapotranspiration, further reducing the runoff ratio locally.

In addition to changes in runoff volume, streamflow timing is shifted as a result of earlier spring snowmelt in the BAU ensembles, as shown in Figure 7b. Earlier

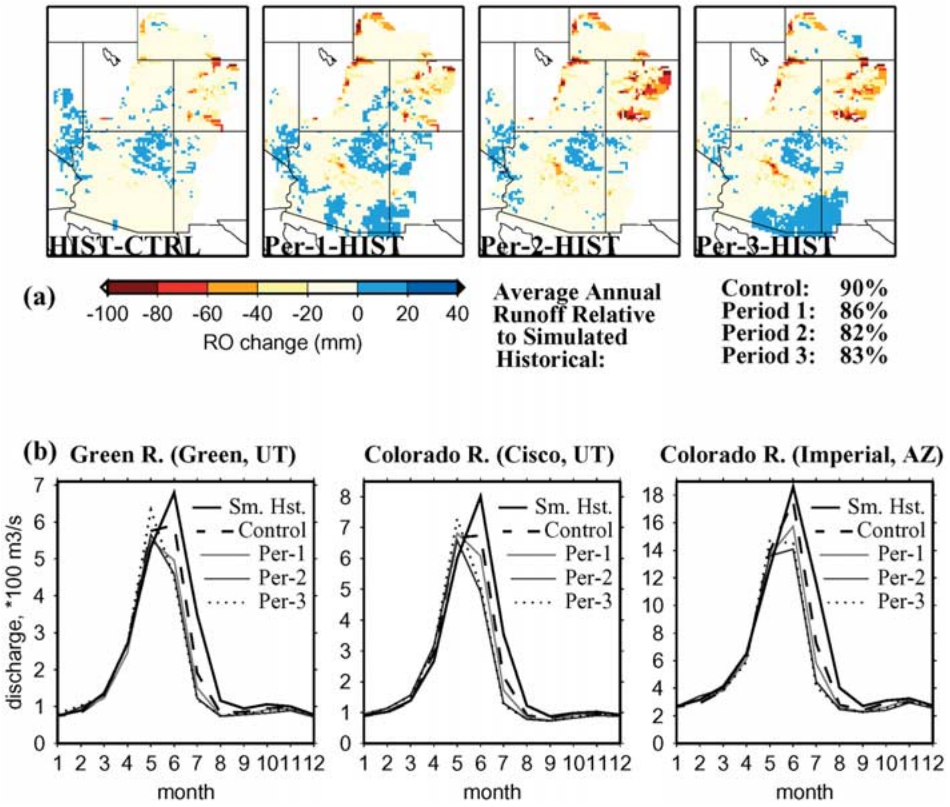

Figure 7. (a) Spatial distribution of predicted changes in mean annual runoff for control and BAU Periods 1–3 (averaged over 3 ensembles) relative to simulated historic, and (b) mean monthly hydrograph for the Green River at Green River, UT, Colorado River near Cisco, UT, and the Colorado River below Imperial, AZ for simulated historic, control, and BAU Period 1–3 simulations (BAU results averaged over 3 ensembles).

spring freshet for Periods 1–3 and the control climate is due to higher spring temperatures, which results in precipitation falling as rain instead of snow and an earlier snowmelt of a lighter snow pack. In the Upper Basin, the historical climate streamflows peak in June, whereas streamflow for the control climate has roughly equivalent flows in May and June, and BAU climate streamflows peak in May. Control and BAU climate streamflows all show significant summer volume reductions. In the Lower Basin (at Imperial, AZ), the progressive shift in peak is not as distinct, although the volume reductions are similar. This might be due to a larger temperature difference in the Upper Basin between BAU climate averages and the control and historical climates. In Period 2 the lowest peak seasonal flows and fall/early winter flows are generally lower than in the other periods, partly due to low precipitation (Figure 5d). These results are qualitatively similar to those of previous studies based both on GCM-derived and prescribed change scenarios (Nash and Gleick, 1991, 1993; Wilby et al., 1999; Wolock and McCabe, 1999).

3.4. WATER RESOURCE SYSTEM EFFECTS

The reliability of the Colorado River water resource system is extremely sensitive to reductions in annual inflow volume because the historical streamflow is almost 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 2 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, Upper Basin consumptive use is fixed at the year 2000 amount of 5.2 BCM (4.2 MAF) which results in a total system demand of about 18.0 BCM (including reservoir evaporation), or about 90% of the mean historical flows. Results presented later (Section 3.4.6) evaluate system performance with Upper Basin demands increasing to 6.7 BCM (5.4 MAF) in year 2060, for a total system demand, including reservoir evaporation, of 19.2 BCM.

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 (Nash and Gleick, 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 Intergovernmental Panel on Climate Change (IPCC) report, PCM projects changes in temperature and precipitation that tend to be near the low end of the range.

The PCM scenario (control and BAU average climate) results are compared to a baseline historical water resources system simulation (CRRM driven by VIC simulated historical streamflows, spanning 1950–99). Results presented for Periods 1–3 are the BAU averages of each scenario's minimum, average and maximum. Results for CRRM simulations with current operating policies and fixed year 2000 demands are presented in Sections 3.4.1 to 3.4.5; results for the increased demand scenario are presented in Section 3.4.6 and initial condition sensitivity analysis is reported in Section 3.4.7.

3.4.1. *Storage*

Figure 8 shows the January 1 annual storage for the control run, the three CRRM climate change simulations, the average of the three simulations, and the 1950–90 CRRM historical storage average, minimum and maximum. 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 (respectively 2010–2039; 2040–2069; 2070–2098) are the values simulated by CRRM and vary considerably due to the particular sequences of inflows and releases leading up to the respective periods.

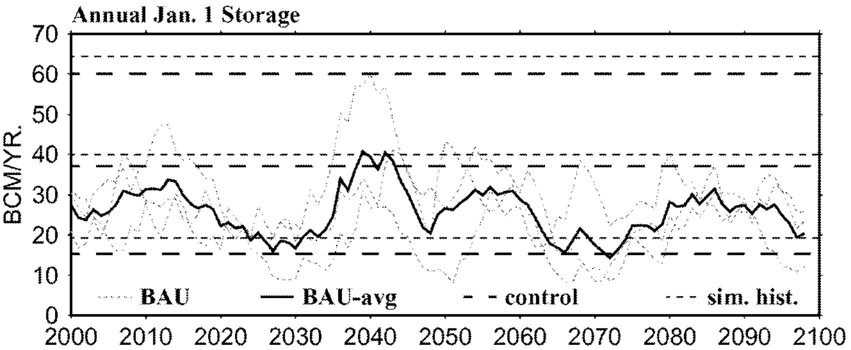

Figure 8. Simulated total January 1 storage. Historical and control period mean annual minimum, average and maximum are shown, with monthly time series from the BAU simulation ensembles and BAU ensemble average. BAU ensemble mean storage values for Periods 1–3 are 24.1, 26.3 and 22.8 BCM/yr, respectively.

When CRRM was forced with VIC simulated historic streamflow from 1950–1999, 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 7% less relative to simulated historical, and was respectively 36, 32 and 40% less for Periods 1, 2, and 3. These results show that the relatively modest changes in streamflow (10–18%) result in much larger changes in reservoir storage. Decreases are quite drastic but are to be expected given the fact that system demands under historical conditions only barely exceed system inflows, and for changes in streamflow of greater than about 10%, system inflow is less than demand which is certain, given enough time, to result in reservoir system failures. Similar results were found by Nash and Gleick (1993); specifically they found using CRSS that a 10–20% reduction in natural runoff would cause mean annual reductions in storage of 30 to 60%.

The control run and Periods 1 and 2 have a large variability in the storage relative to simulated historic. Although Period 1 had the highest natural flow, Period 2 had the highest average storage. This is because one of the ensemble sequences was relatively wet in Period 1, resulting in initial Period 2 average reservoir levels that were about 5.0 BCM (4.1 MAF) and 8.0 BCM (6.5 MAF) higher than Periods 1 and 3, respectively. Period 3 has less storage variability between the maximum and minimum storages relative to simulated historical and also has the lowest reservoir levels. This is due primarily to having the lowest average initial reservoir storage coupled with inflows lower than those in Period 1. Minimum storage was 30% of capacity for the historical climate and 24% for control. For future Periods 1–3, minima were all in the range of 12–15 BCM (9–12 MAF) or 15–20%, which is about equal to the inactive capacity of Lake Mead and the dead pool of Lake Powell – i.e., the system effectively fails at least once in each of the future climate ensembles.

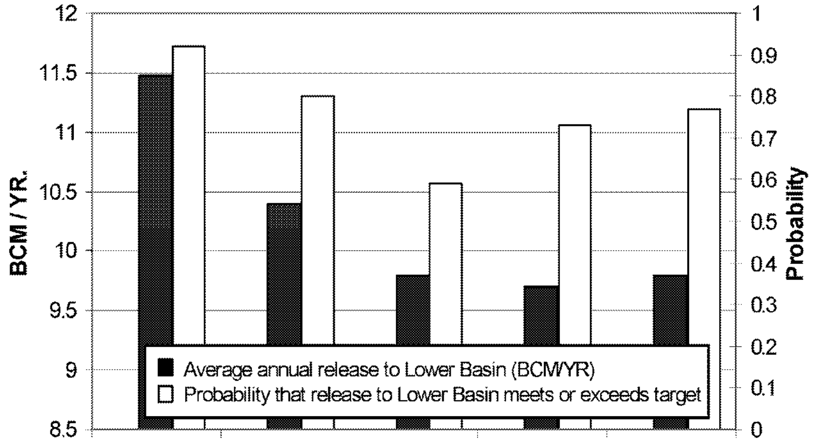

Figure 9. Simulated average annual release from Glen Canyon Dam to the Lower Basin and probability that release targets are met for simulated historical, control, and BAU Period 1–3 simulations (BAU results averaged over 3 ensembles).

3.4.2. *Compact Compliance*

The main operating objectives set forth in the *Law of the River* are a mandatory moving 10-year average release of 10.1 BCM/yr (8.23 MAF/yr) from Lake Powell into the Lower Basin and 1.9 BCM/yr (1.52 MAF/yr) released to Mexico from Imperial Dam (USDOI, 1985). CRRM imposes delivery shortages (for both Upper and Lower Basin deliveries in this section and Central Arizona Project and Metropolitan Water District withdrawals in the next section) in its historic simulation even though the need for such reductions has never actually occurred in the basin to date. It does so for two main reasons: (1) CRRM models Central Arizona Project withdrawals (1.8 BCM/yr) during the entire period, not just from the date (1985) when Central Arizona Project 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 9 and 10 show average releases to the Lower Basin and to Mexico, respectively, as well as the percentage of years in which the compact requirements were met or exceeded.

The average Lake Powell release for the historical period was 11.5 BCM/yr (9.3 MAF/yr), with 92% of years having releases greater than or equal to the Compact requirement. The simulated historical average annual release to Mexico was 2.3 BCM/yr (1.9 MAF/yr) with 72% of years meeting or exceeding the Compact requirement. The control run had an average release from the Upper Basin of 10.4 BCM/yr (8.4 MAF/yr), with 80% of the years satisfying the Compact requirement. The average release into Mexico was 1.4 BCM/yr (1.1 MAF/yr) (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/yr (7.9 MAF/yr) during Periods 1–3. The percent of years in which releases exceed the Compact minimum

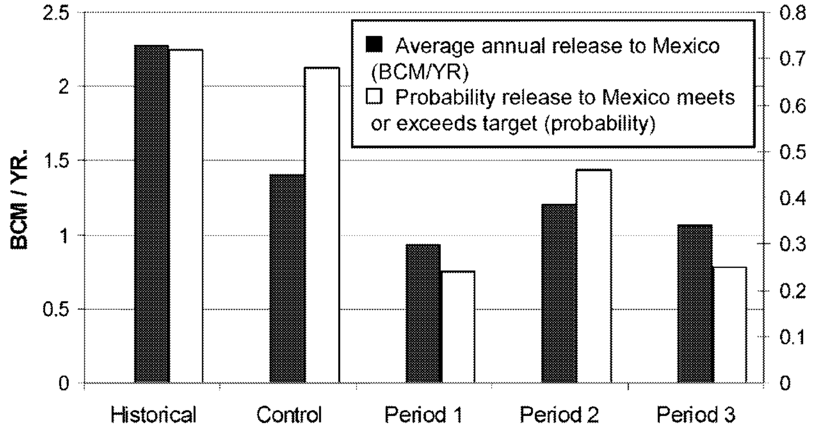

Figure 10. Simulated average annual release from Imperial Dam to Mexico and probability that release targets are met for simulated historical, control, and BAU Period 1–3 simulations (BAU results averaged over 3 ensembles).

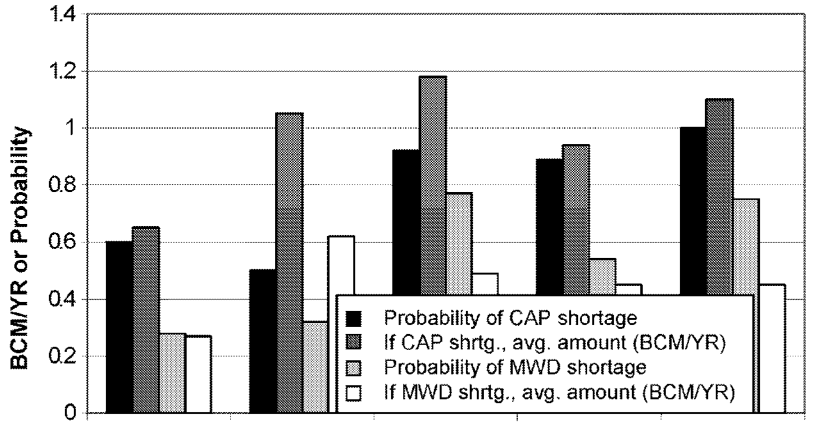

Figure 11. Probability of a delivery shortage to Central Arizona Project and Metropolitan Water District; and average amount of shortages for simulated historical, control, and BAU Period 1–3 simulations (BAU results averaged over 3 ensembles).

were 59, 73, and 77 for Periods 1, 2, and 3, respectively. Average reliability for Period 1 was low due to one of the three ensembles being dry during this period and having compact violations 70% of the time while Period 3 reliabilities were quite good, relatively speaking, because one ensemble 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/yr (0.8 MAF/yr), 1.2 BCM/yr (1.0 MAF/yr), and 1.1 BCM/yr (0.9 MAF/yr), respectively. The percent of years in which full releases were made dropped to 24, 46, and 25 for Periods 1, 2, and 3, respectively.

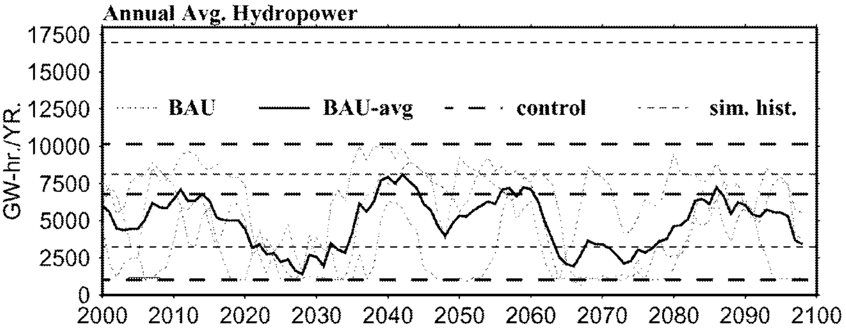

Figure 12. Simulated total energy production. Historical and control period mean annual minimum, average and maximum are shown, with monthly time series from the BAU simulation ensembles and BAU ensemble average. BAU ensemble mean hydropower for Periods 1–3 are 3909, 4191 and 2913 GWhr/yr, respectively.

3.4.3. *Central Arizona Project (CAP), Southern Nevada Water Authority (SNWA), and Metropolitan Water District (MWD) Deliveries*

Simulations using simulated 1950–99 streamflows along with year 2000 demands resulted in 60% of the years having Level 1 shortages (imposed upon CAP and SNWA when Lake Mead drops below 343 m). During the historical simulation, 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 simulated historical and control simulations, the magnitude of shortfalls was generally larger in the control than in the historical simulation. In Periods 1, 2, and 3, Level 1 shortages occurred in almost all years (92%, 89%, and 100%, respectively). Level 2 restrictions were 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 two of the three ensemble members were relatively wet and reliable during this period. This agrees once again with Nash and Gleick (1993), who concluded that if runoff drops 5% (ours is 10–18%), full scheduled deliveries would be met in only 25% of the years and that in half of the years, only minimum levels would be delivered.

We note that CRRM has prescribed seasonality of demands that does not change with evolving climate. It is quite likely that the pattern of demands would respond somewhat to climate change. However, such changes are likely to have minimal effect on reservoir system performance, because the total system storage is much larger (a factor of about four) than the mean annual inflow, and therefore reservoir system performance responds effectively only to multi-year variability in inflows.

3.4.4. *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 streamflow and storage. While Lakes Mead and Powell were drawn down below their minimum power pool and therefore produced no electricity in some simulations, Flaming Gorge remained relatively full throughout all simulations. Davis and Parker are run of the river dams with relatively fixed head.

The historical simulation produced an average annual hydropower output of 8,100 GW-hr/yr while minimum annual generation was 3,300 GW-hr/yr and maximum was 17,000 GW-hr/yr (Figure 12). The control run had an average output of 6800 GW-hr/yr, i.e., a reduction of 16% relative to simulated historical, a minimum of 1100 GW-hr/yr, and maximum of 10,200 GW-hr/yr. Periods 1–3 had average outputs of 4400, 5500 and 4700 GW-hr/yr, respectively, which is a decrease of 56, 45 and 53% relative to simulated historical. The simulated 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 in the historical simulation. 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 (2040–2069) had the highest average annual hydropower production of the three future periods as a result of its relatively high average total basin storage. For comparison, Nash and Gleick (1993) found that a 2° increase in temperature with a small increase in precipitation resulted in reductions in power generation of 60%, which is an even more drastic reduction than we found.

3.4.5. *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 13). In the historic run, 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.

3.4.6. *Sensitivity to Increased Upper Basin Demands*

The previous results are for Upper Basin demands fixed at the MSCP year 2000 values of 5.2 BCM/yr (4.2 MAF/yr). A subset of the simulations reported above were run with a linear increase in these demands over time to 6.7 BCM/yr (5.4 MAF/yr) in 2060, after which they were held constant. Annual demands in the Lower Basin and Mexico remained fixed at 9.2 BCM/yr (7.5 MAF/yr) and 1.9 BCM/yr (1.5 MAF/yr), 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

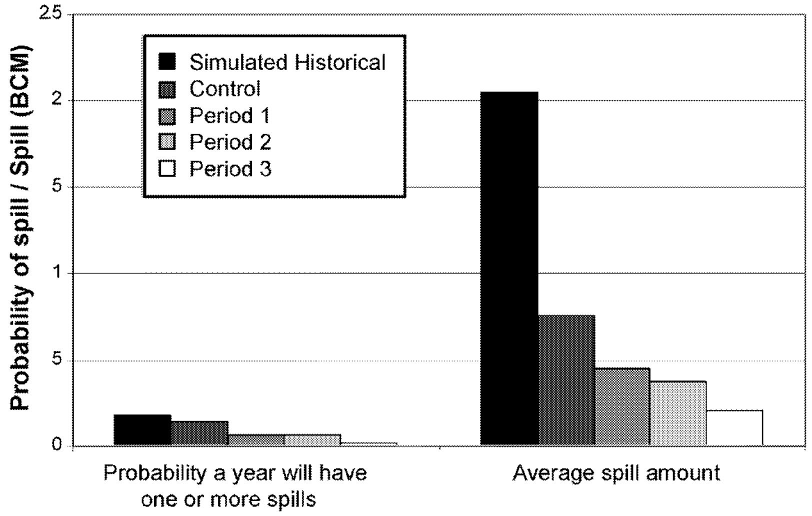

Figure 13. Probability a given year will have an uncontrolled spill (release that does not generate hydropower) and average amount of spill for simulated historical, control, and BAU Period 1–3 simulations (BAU results averaged over 3 ensembles).

Table II

Summary of changes in reservoir system performance for Periods 1–3, with increasing Upper Basin demands, relative to the year 2000 fixed demand CRRM simulations

	Change in average basin storage (BCM/yr)	Change in Glen Canyon mean release (BCM/yr)	Change in Glen Canyon release reliability	Change in Mexico delivery reliability	Change in MWD delivery
Period 1	–1.7	–0.33	–0.08	–0.03	–0.05
Period 2	–4.8	–0.67	–0.14	–0.19	–0.20
Period 3	–4.8	–0.75	–0.30	–0.18	–0.19

and 3 (Table II) relative to the previous year 2000 fixed demand simulations. This represents reductions ranging from 7 to 20%. Releases from Glen Canyon to the Lower Basin were reduced by 0.33 BCM/yr (0.27 MAF/yr) on average for Period 1, 0.67 BCM/yr (0.54 MAF/yr) for Period 2, and by 0.75 BCM/yr (0.61 MAF/yr) for Period 3. Reliability of releases to Mexico decreased by 3% in Period 1 and 19% in Periods 2 and 3. Annual delivery volumes to Mexico were reduced by 0.14 BCM/yr (0.11 MAF/yr), 0.23 BCM/yr (0.19 MAF/yr), and 0.38 BCM/yr (0.31 MAF/yr) for Periods 1–3, respectively. The reliability of deliveries to Central Arizona Project, Southern Nevada Water Authority, and Metropolitan Water District were also reduced by 5 to 20%.

Table III

Annual average precipitation, evapotranspiration, and runoff for historic (HIST), control (CTRL), and future climate periods

	Temp. change, °C	Precip.	Evap.	Runoff	Storage	Hydropower	Probability of spills/ years
HIST	n/a	354 mm/yr	310 mm/yr	45 mm/yr	39.9 BCM/yr	8,123 GW-hr/yr	18%/yr
CTRL	+0.5	–1%	0%	–10%	–7%	–16%	12%
Period 1	+1.0	–3%	–2%	–14%	–36%	–56%	7%
Period 2	+1.7	–6%	–4%	–18%	–32%	–45%	7%
Period 3	+2.0	–3%	–1%	–17%	–40%	–53%	6%

3.4.7. *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 affects the simulated performance of the reservoir system. The rationale for prescribing initial reservoir storage in this way is 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 was performed in which reservoir levels were reset to 35.5 BCM at the beginning of each period. Tables II and III 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 increase and decrease corresponding to respective increases and decreases in average initial storage values.

4. Discussion and Conclusions

For the Colorado River basin, our results show that climate change over the next century as predicted by PCM would lead to a situation where total system demand (water deliveries plus reservoir evaporation) would exceed (decreasing) reservoir inflows, bringing about a substantial degradation in system performance. A large body of literature (now some years old; see Burges and Linsley, 1971 for a review), not to speak of basic physical reasoning, shows that no reservoir system can deliver, over the long term, water demands that exceed the mean inflows, and that the reliability of a reservoir system decreases rapidly as demands approach the mean inflow. The high sensitivity of the Colorado River reservoir system quite simply results from the fact that the current demands are not much less than the mean inflows, and so decreasing the mean inflow slightly results in substantial degradation of system performance. The situation would be further exacerbated by increasing the demands, e.g., as the Upper Basin states move toward their full entitlements.

The Colorado River basin represents one of the endpoints among the three Accelerated Climate Prediction Initiative (ACPI) water resources studies reported in this volume. The Columbia River basin (Payne et al., this volume) has relatively high runoff per unit area and low reservoir storage relative to the mean annual inflow. Its performance is therefore quite sensitive to changes in the seasonal distribution in inflows that would be associated with earlier snowmelt in a warmer climate. The Sacramento–San Joaquin River system, investigated by VanRheenen et al. (this volume), has intermediate runoff per unit area and reservoir storage relative to its mean inflows. The Colorado River reservoir system, by contrast, is highly insensitive to the seasonal pattern of reservoir inflows, and by implication, changes in the seasonal distribution of runoff associated with a warmer climate – reservoir system performance depends much more critically on the total annual inflows. Furthermore, although not investigated in this study, Maurer et al. (2003) have shown that the relative worth of reservoir system inflow forecasts generally decreases as the reservoir storage capacity relative to the mean inflow increases, hence performance of the system is not expected to be very sensitive to the quality of reservoir inflow forecasts (as a side note, CRRM effectively assumes perfect inflow forecasts). In general, because of the (relative) size of the reservoir system, it is unlikely that changes in reservoir operating policies can adequately mitigate the effects of climate change and associated hydrologic changes in the basin.

Given the relatively high sensitivity of system inflows to temperature change, and the minimal possibilities for mitigation of system performance degradations associated with reduced inflows, demand reductions would almost certainly be required were the PCM climate predictions to prove accurate. The need for such action cannot itself be taken as a prediction; it is only indicated as the sensitivity to the particular set of climate predictions associated with PCM as run with the BAU emissions scenario. As noted in studies referenced above for the Colorado

River basin, and by IPCC (2001) for global land areas, climate models essentially all predict warming over the next century. However, predictions of precipitation change, especially over the interior of the continents (e.g., Colorado River basin), span the entire range from substantial (greater than 20% on annual average) decreases to substantial increases. PCM, by way of comparison, predicts modest decreases in precipitation, and modest increases in temperature. By implication, the predicted streamflow changes and associated reservoir storages over the Colorado basin from this study should, very roughly, be slightly to the low end (i.e., modest streamflow decreases) of the spectrum of sensitivities over all GCMs. We hasten to add, though, that this is an inference rather than a direct result, and furthermore we must caution that all GCMs should not be weighted equally. We do, however, think it is reasonable to consider the results as a plausible indication of the future, and one to which water resources planning over the next century should be capable of responding.

Acknowledgements

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