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

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ABSTRACT

The U.S. Department of Energy/National Center for Atmospheric Research Parallel Climate Model is used to analyze the potential effects of climate change on the hydrology and water resources of the Colorado River Basin. An ensemble of three 105 year 'future' runs based on business as usual (BAU) global emission scenarios for greenhouse gases, along with a control run based on static 1995 atmospheric CO_2 concentrations and a historic run based on pre-industrial revolution atmospheric CO_2 were used. Transient monthly temperature and precipitation signals over the Colorado River basin were extracted from the BAU ensembles, bias corrected and statistically downscaled for input to the VIC macroscale hydrology model to obtain corresponding streamflow sequences. Results for the BAU scenarios are summarized into periods 1, 2, and 3 (2010 – 2039, 2040 - 2069, 2070 – 2098). The average annual temperature shift over the Colorado River basin between the simulated historical climate (1950-1999) and the control climate was 0.5 °C, while the shift from historical to Period 1, 2, and 3 was 1.0, 1.7, and 2.4 °C, respectively. Basin-average annual precipitation was reduced slightly for the future climate, by 1% for the control run relative to historical, and by 3, 6, and 3% for the future periods relative to the historical climate. Due to the small runoff ratio (runoff ÷ precipitation) for the current climate (about 13%), this reduction in precipitation causes a reduction in annual runoff in the control run of about 10%. Runoff in periods 1, 2, and 3 is reduced by 14, 18, and 17%, respectively, relative to historical. Higher wintertime temperatures also cause peak runoff in the basin to occur about one month earlier. Analysis of historical and VIC simulated flows with a water management model showed that reduced streamflows would have significant implications for the performance of the water resource system. Average simulated total basin storage declined by 27% for the control climate and 50% in periods 1 – 3 relative to historical. In the historical simulation, Colorado River

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Compact mandated releases from Glen Canyon to the lower basin were met in 100% of the years. In the control simulation, this dropped to 80%, while for the future periods it dropped to 59 – 75%. Annual hydropower output was also significantly reduced for the control, for which hydropower production was 68% of historical, with further reductions to 43%, 55%, 47% for periods 1-3 relative to historical.

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 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 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). 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.

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. 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).

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 correspond to what is termed by the Intergovernmental Panel on Climate Change (IPCC, 2001) as 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), and 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.

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 T42 resolution with a horizontal spatial resolution of 2.8 degrees 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). Lengthy PCM model runs made at the National Center for Atmospheric Research were made available for this study (Table 1). The particular model runs used include three 105-year ensembles starting at present and based on BAU emission scenarios. Each of these runs has unique initializations of the earth's chaotic atmosphere – ocean system and represent 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 pre-industrial revolution atmospheric CO_2 concentrations 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).

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 (about three degrees latitude by longitude) to the 1/8 degree resolution of the hydrology model by mapping from 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 hydrology model is grid cell-based and typically is run at spatial resolutions ranging from 1/8 to 2 degrees latitude by longitude. The model has two modes -- water balance, and full energy balance. The full energy balance mode iterates on the surface temperature to close the energy and water budgets at each time step, whereas the simplified water balance mode assumes a surface temperature equal to the air temperature, thus avoiding the need for iteration.

The full energy balance mode usually operates at three-hour time steps, which resolves the diurnal cycle, whereas water balance mode is often run at a daily time step. Both modes represent fluxes of water and energy at the land surface and close the water budget at each time step. 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 1). 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 3).

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 1. The model then uses specified operating policies 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 Lakes Powell and 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 4a shows that CRRM does a good job of simulating aggregated reservoir storage despite its simplifications while figure 4b 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 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.

RESULTS

3.1 PCM Climate Changes

Figure 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 (1950-1999) 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 5c). 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.

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 5b). The control run seasonal distribution of precipitation is very similar to observed (Figure 5d). 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 6 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).

3.3 Simulated Runoff Changes

Figure 7a 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 basin average annual 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, which we will show has major implications for reservoir system performance. Reductions in precipitation in periods 1, 2, and 3 leads to reductions in annual runoff of 14, 18, and 17% relative to historical.

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 7b. 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.

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 specified otherwise, upper basin consumptive use is fixed at the year 2000 amount of 5.2 BCM (4.2 MAF). Separate results are also presented with 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, PCM projects changes in temperature and precipitation that tend to be near the low end of the range. The results are for a historical simulation (using historical naturalized inflows from 1906 – 1990), a control run based on a 1995 climate, and the 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 8. 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.

When CRRM was run with the historical naturalized flows from 1906 – 1990 with current operating policies and year 2000 demands, average January 1 reservoir storage was 50.7 BCM (41.1 MAF)) with a minimum and maximum of 30.8 BCM (25.0 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.

These results show that the relatively modest changes in streamflow (10-18%) result in much larger changes in reservoir storage. This is mostly because 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. For instance, the average control climate storage is 13.0 BCM (10.5 MAF) less than historical, a reduction of about 25%. For all future periods, average storage was about half of historical. Minimum storage was about 30.9 BCM (25.0 MAF) or 42% of capacity for the historical climate and 26.4 BCM (21.4 MAF) or 37% for control. 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.

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). 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 requirement were met or exceeded. The average Lake Powell release for the historical period was 12.4 BCM (10.1 MAF), and all years had releases greater than or equal to the Compact requirement. The historical average annual release to Mexico was 3.9 BCM (3.2 MAF), and again all years met 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.

CAP, SNWA, and MWD Deliveries.

Since Glen Canyon Dam came online in the 1960s there have been no shortages imposed in the basin. However, simulations using the historical streamflows beginning in 1906 resulted in 18% of the years having level 1 shortages (imposed upon CAP & SNWA when Lake Mead drops below 343 m). Using historical inflows, at no time did the elevation of Lake Mead drop to 330 m and cause level 2 shortages (Figure 11). 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. 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.

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 Lakes Mead and 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.

The historical simulation produced an average annual hydropower output of 10,000 GW-hr while minimum annual generation was 7600 GW-hr and maximum was 16700 GW-hr (Figure 12). 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 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 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 13). In the historic run, 29% 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.

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 2). 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%.

Conclusions

The PCM's projected temperature increase and precipitation decrease for the control (1995) climate relative to historical conditions, and for BAU emission scenarios through 2098 resulted in reductions of annual streamflow 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 were a result of climate warming that has already occurred, but may not yet be fully evident due to the thermal inertial of the world's oceans. Results using a reservoir simulation model, CRRM, indicate that the reservoir system is quite sensitive to these reductions in streamflow and that future system performance will be degraded considerably. Among the results of the projected streamflow changes are:

In both the control and future simulations, the system was not able to meet demands, storage volumes were significantly reduced (by well over half for the future simulations), hydropower production was reduced by 50%, and Colorado River Compact release requirements could not be met with increasing frequency (e.g., Compact releases to Mexico, which were always met in the historic simulation, were not met in up to 75% of years in the simulations for the end of the next century).

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.

One common assumption is that increased reservoir storage capacity will improve reservoir system performance. However, in the case of the Colorado River, there is already a large amount of storage (four times the mean annual flow). More importantly, system shortfalls are the result of the long-term flow of the river being less than the amount of water allocated for consumptive uses as opposed to the result of periods of extended drought. Increasing reservoir storage capacity, even if it were feasible, would have little effect on system performance as both Lakes Powell and Mead simulated storages are well less than capacity in the future periods. In the face of reduced streamflows that appear likely to accompany future climate in this environment, reduction of consumptive uses appears to be the only viable means of preserving system reliability.

Acknowledgements

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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. Resc. 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. Resc. 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., Nijssenm 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 fo future snowpack in the western United States.” J. Amer. Water. Resc. Assn., 35(6), 1473-1484

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

Nijssen, B., G.M. O’Donnelll, 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. Lettenamier, 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. Lettenamier, 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.

Figure 1

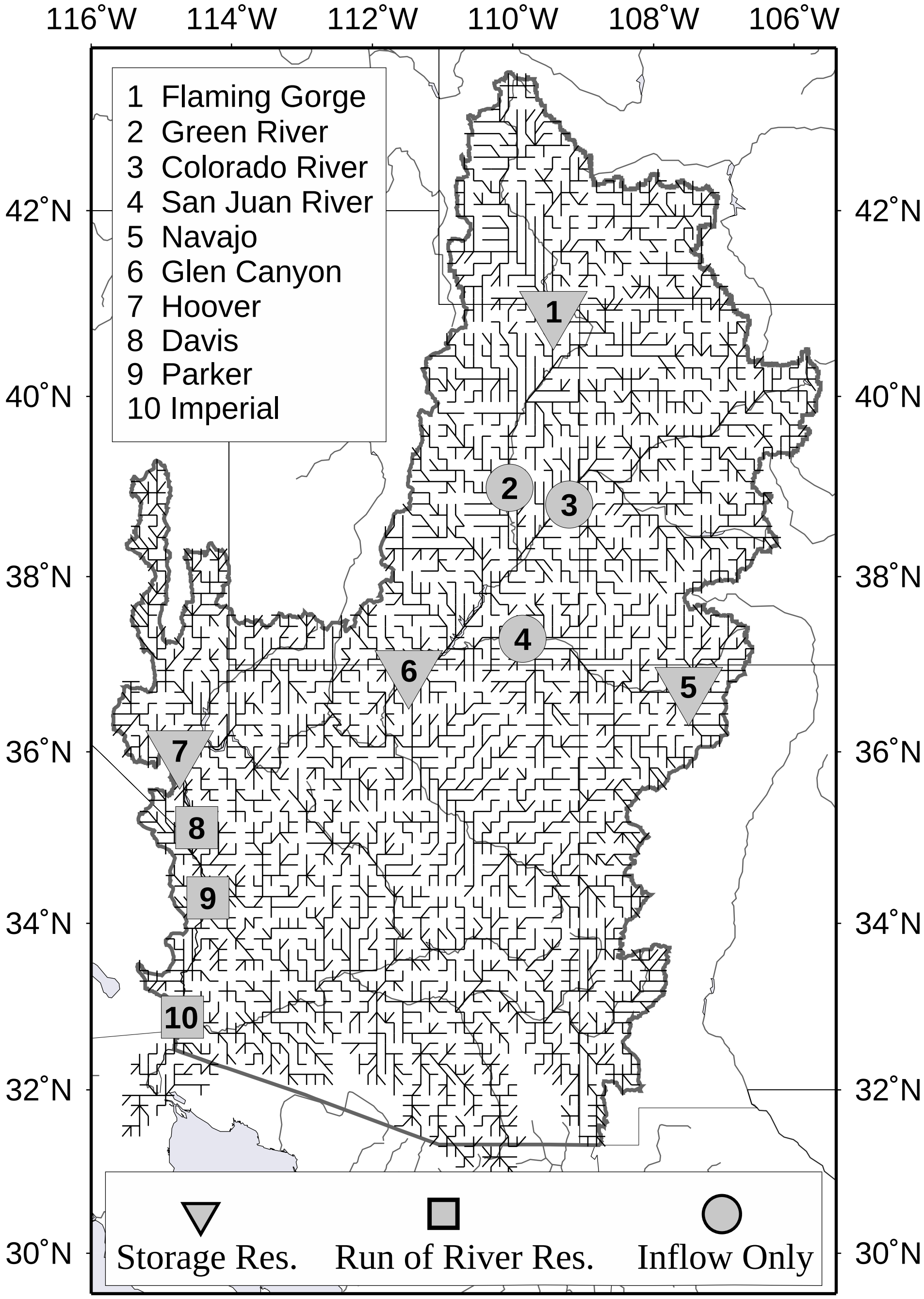

116°W
114°W
112°W
110°W
108°W
106°W
42°N
40°N
38°N
36°N
34°N
32°N
30°N
1 Flaming Gorge
2 Green River
3 Colorado River
4 San Juan River
5 Navajo
6 Glen Canyon
7 Hoover
8 Davis
9 Parker
10 Imperial
1
2
3
4
5
6
7
8
9
10
Storage Res.
Run of River Res.
Inflow Only

Figure 2

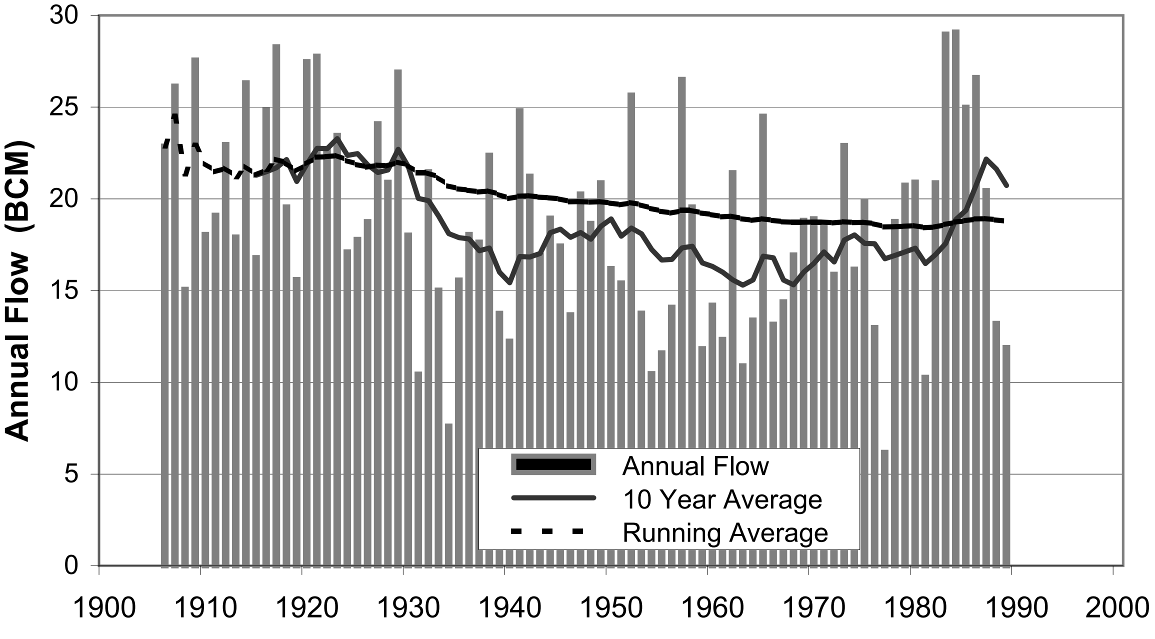
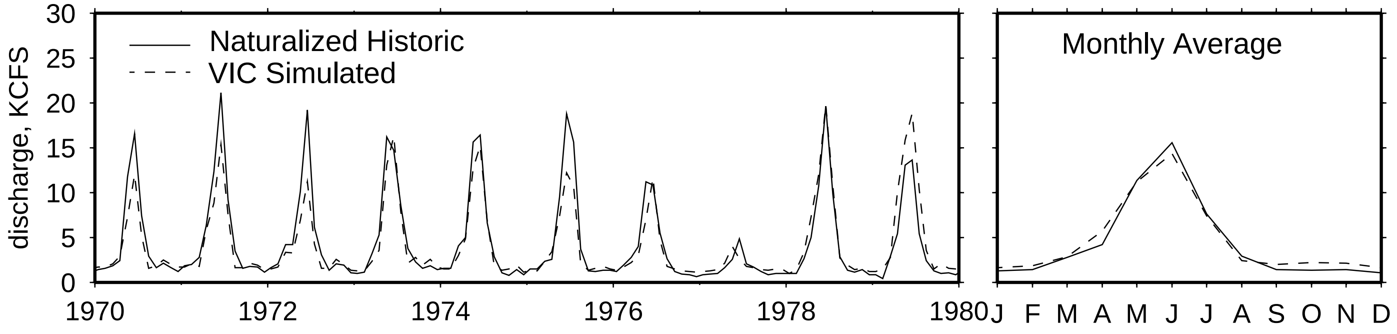
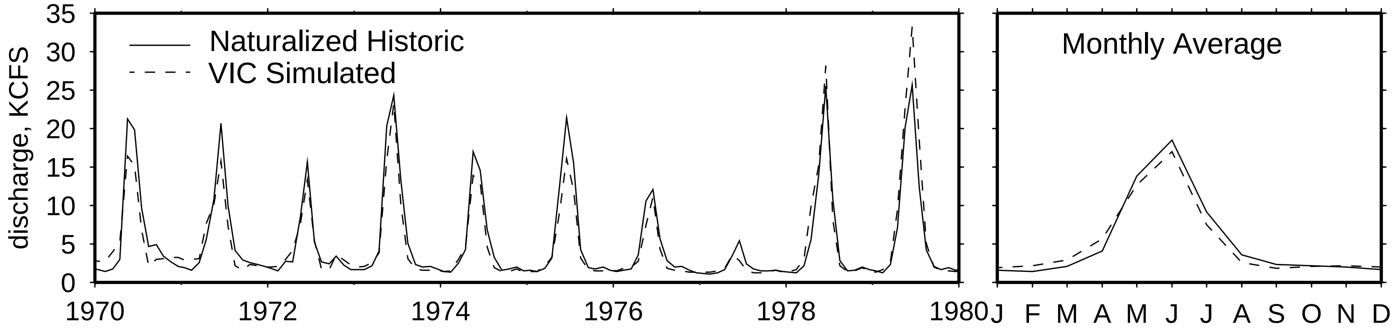

Annual Flow (BCM)
30
25
20
15
10
5
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Annual Flow
10 Year Average
Running Average

Figure 3

Green River at Green River, UT



Colorado River near Cisco, UT



Colorado River below Imperial, AZ

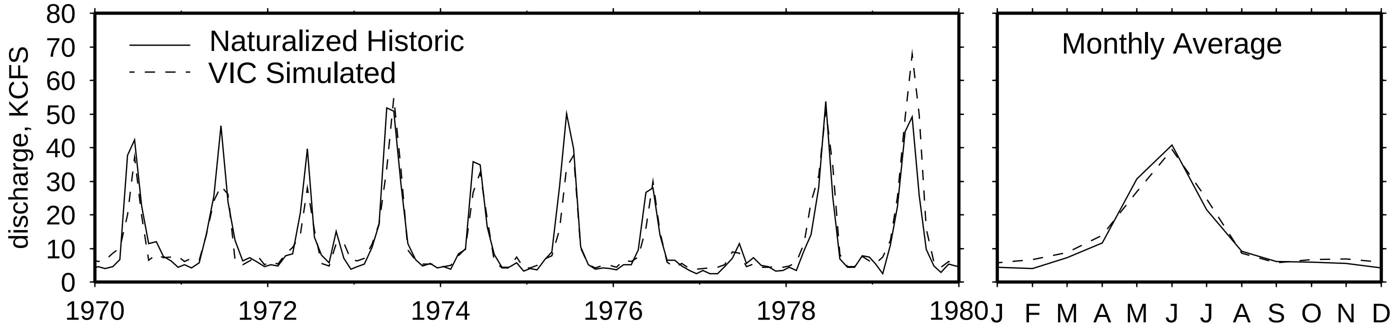
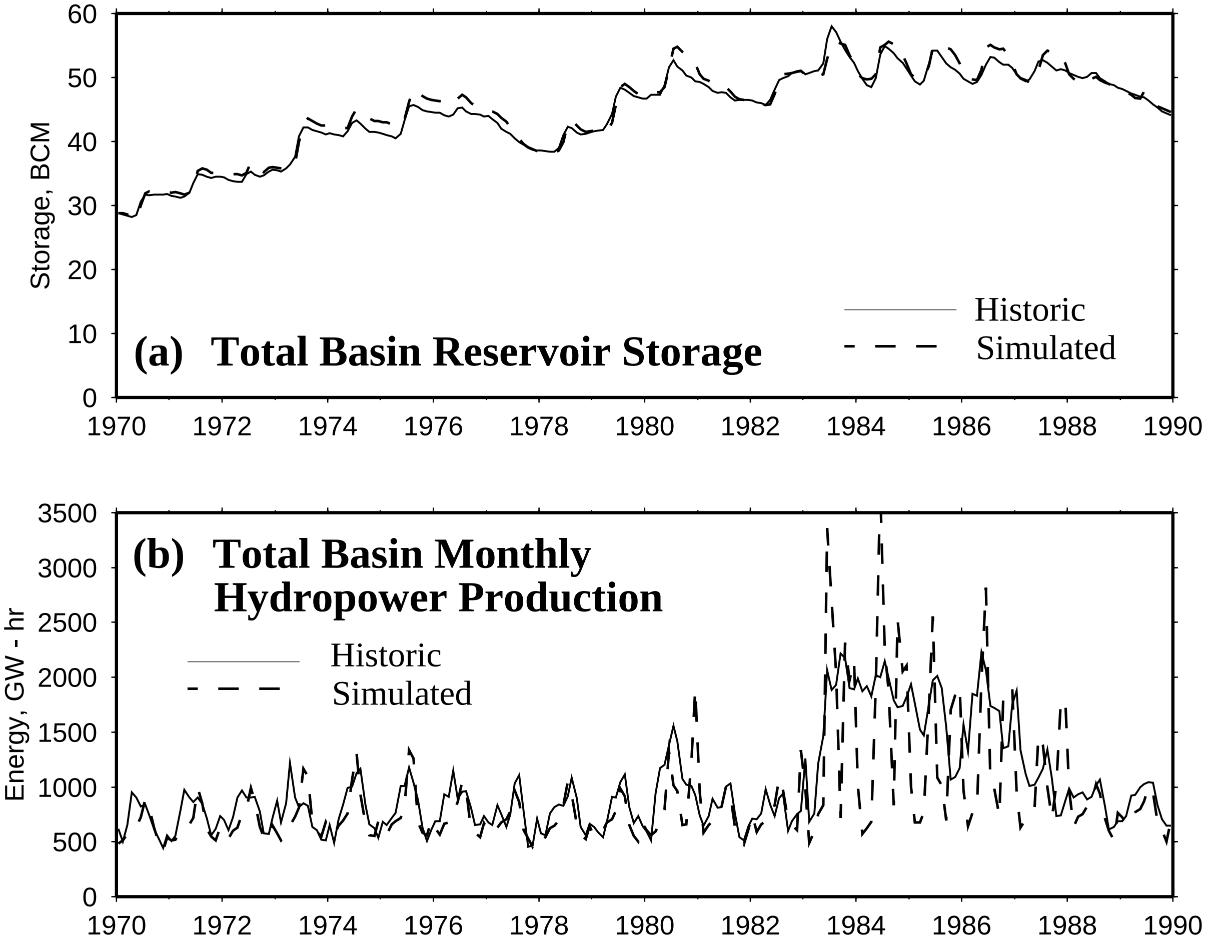


Figure 4



60
50
40
30
20
10
0
Storage, BCM
(a) Total Basin Reservoir Storage
Historic
Simulated
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
3500
3000
2500
2000
1500
1000
500
0
Energy, GW - hr
(b) Total Basin Monthly Hydropower Production
Historic
Simulated
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990

Figure 5

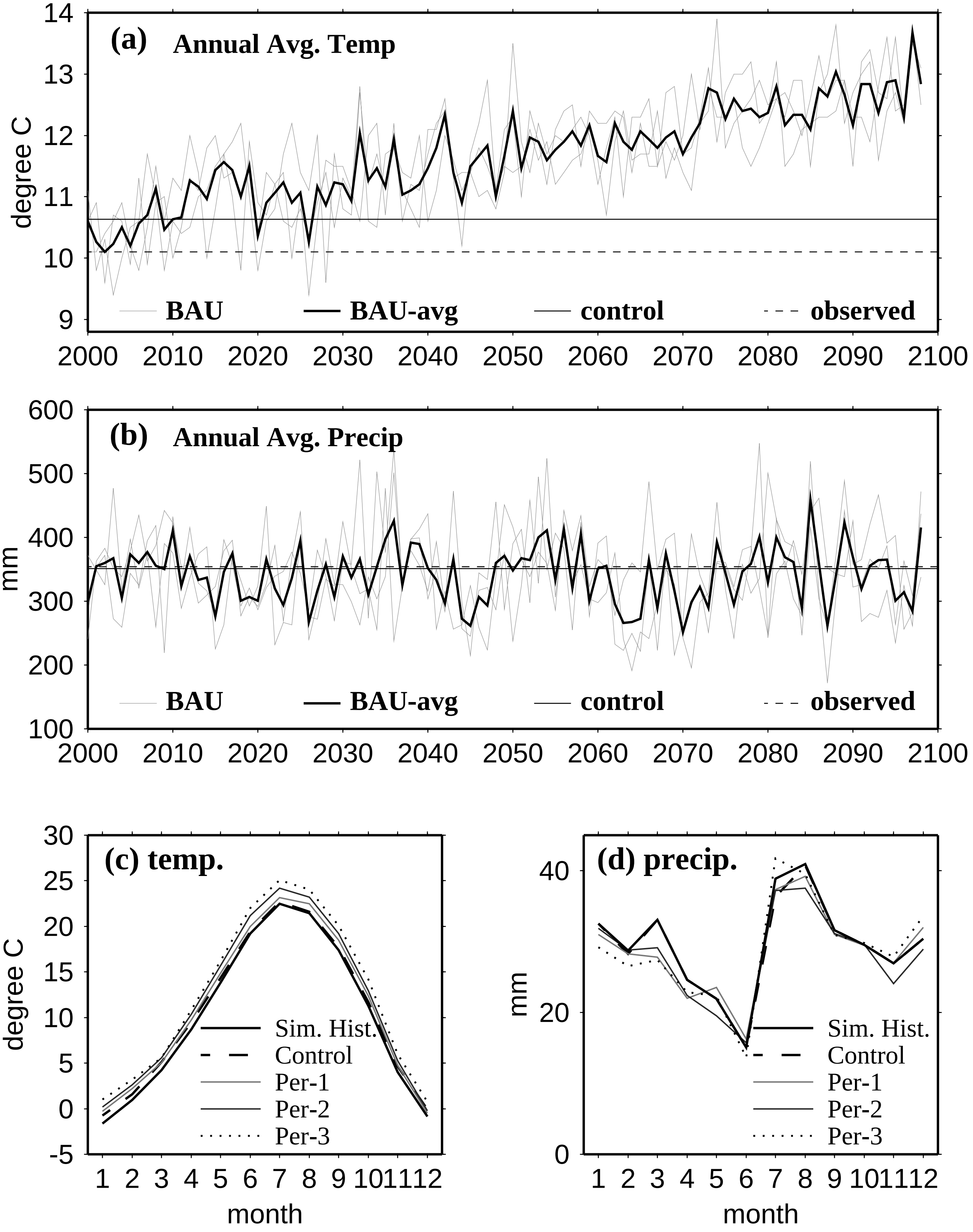

(a) Annual Avg. Temp
degree C
14
13
12
11
10
9
BAU
BAU-avg
control
observed
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
(b) Annual Avg. Precip
mm
600
500
400
300
200
100
BAU
BAU-avg
control
observed
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
(c) temp.
degree C
30
25
20
15
10
5
0
-5
Sim. Hist.
Control
Per-1
Per-2
Per-3
1 2 3 4 5 6 7 8 9 10 11 12
month
(d) precip.
mm
40
20
0
Sim. Hist.
Control
Per-1
Per-2
Per-3
1 2 3 4 5 6 7 8 9 10 11 12
month

Figure 6

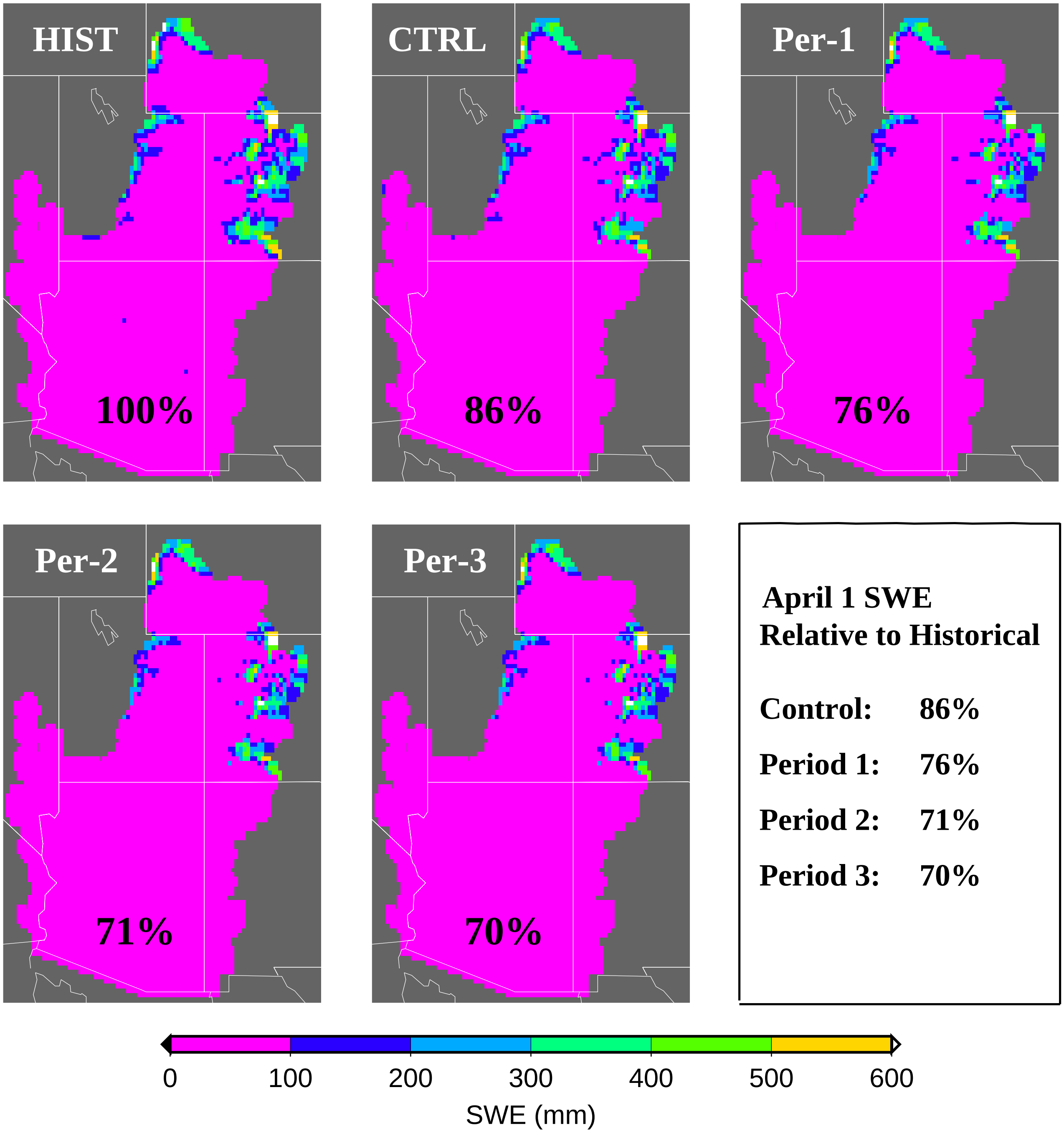
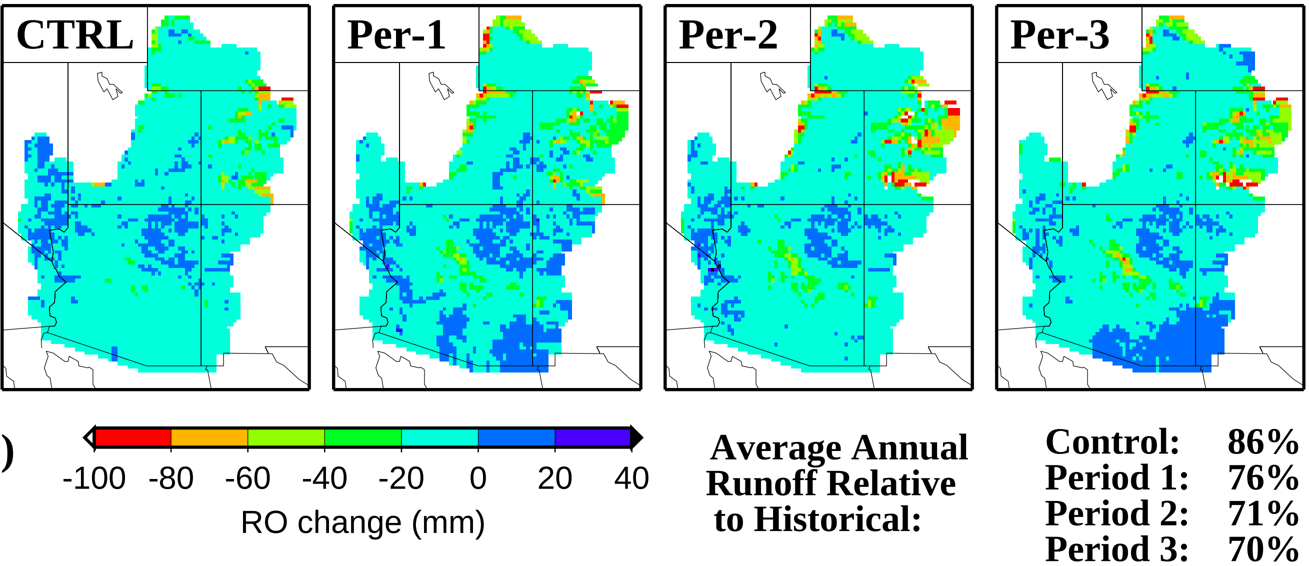

HIST
100%
CTRL
86%
Per-1
76%
Per-2
71%
Per-3
70%
April 1 SWE
Relative to Historical
Control: 86%
Period 1: 76%
Period 2: 71%
Period 3: 70%
0
100
200
300
400
500
600
SWE (mm)

Figure 7

(a)



Average Annual Runoff Relative to Historical:

Control:	**86%**
Period 1:	**76%**
Period 2:	**71%**
Period 3:	**70%**

(b)

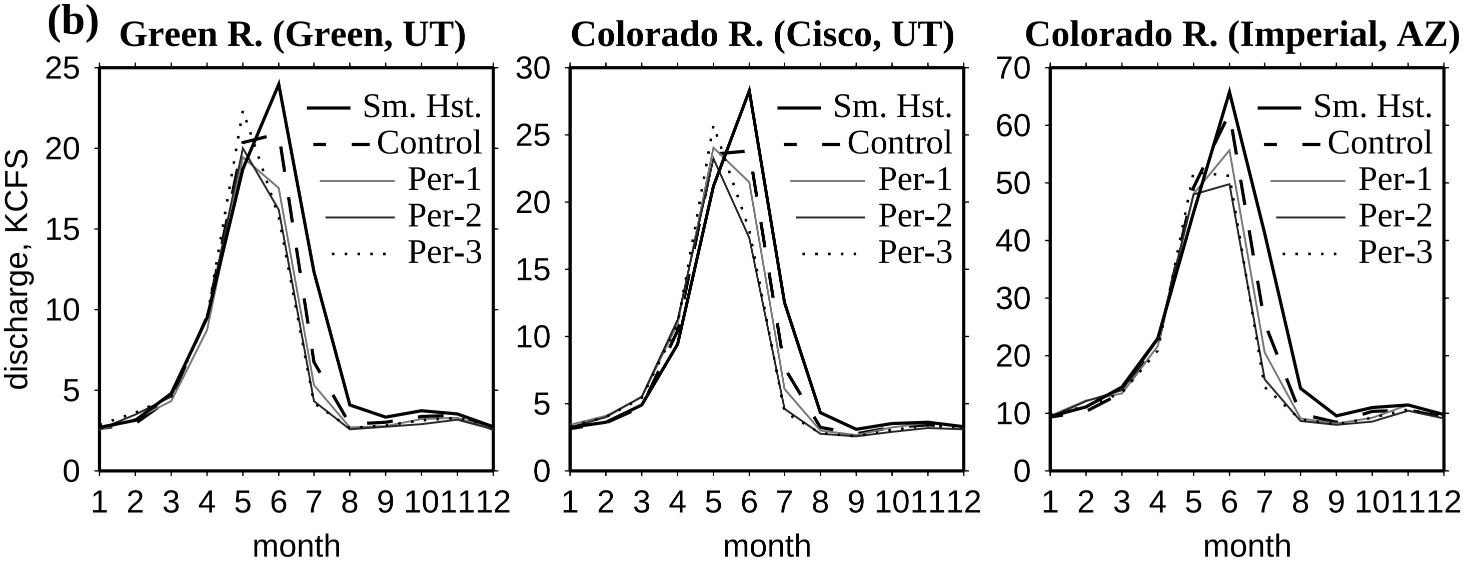
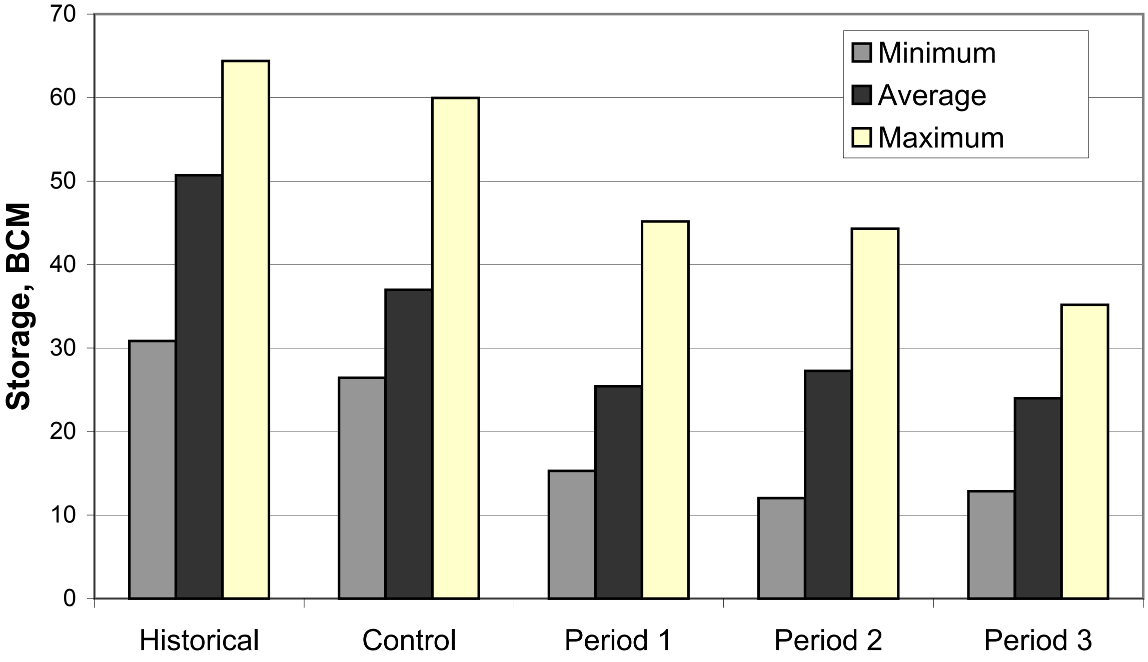
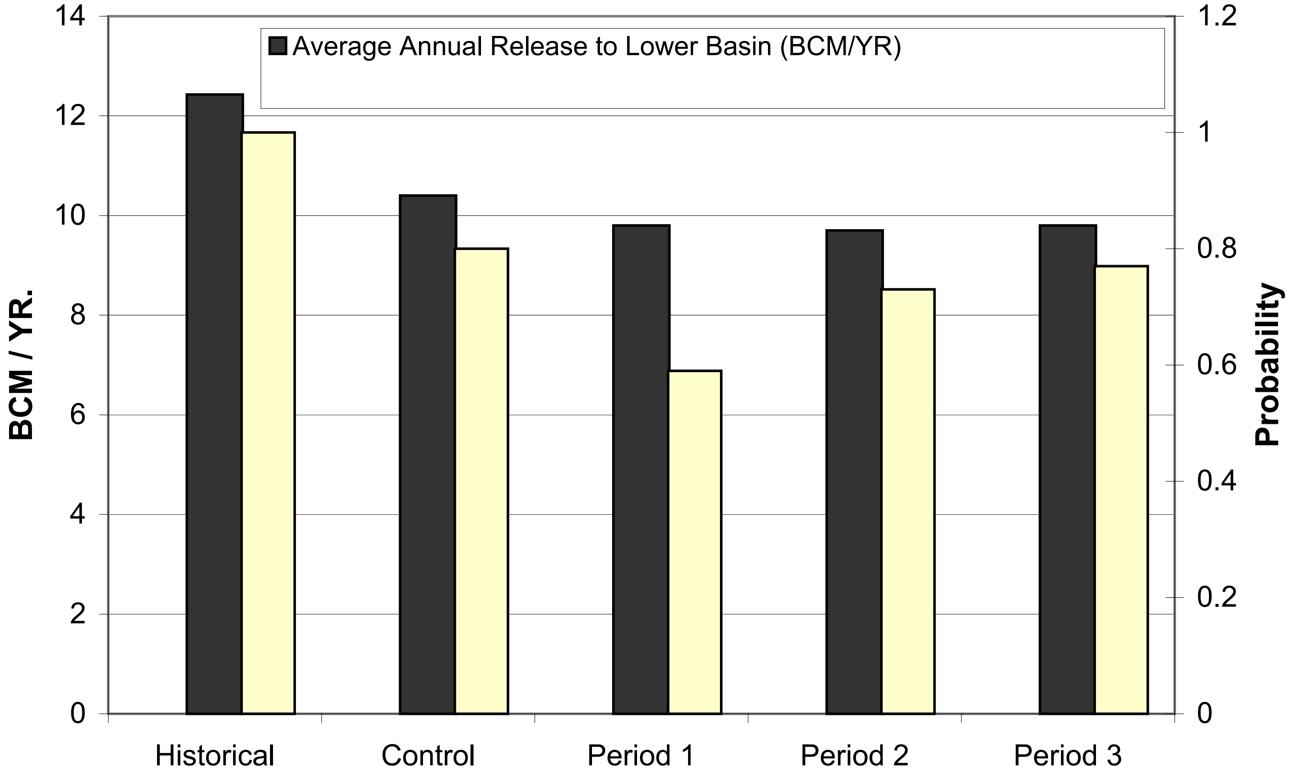


Figure 8



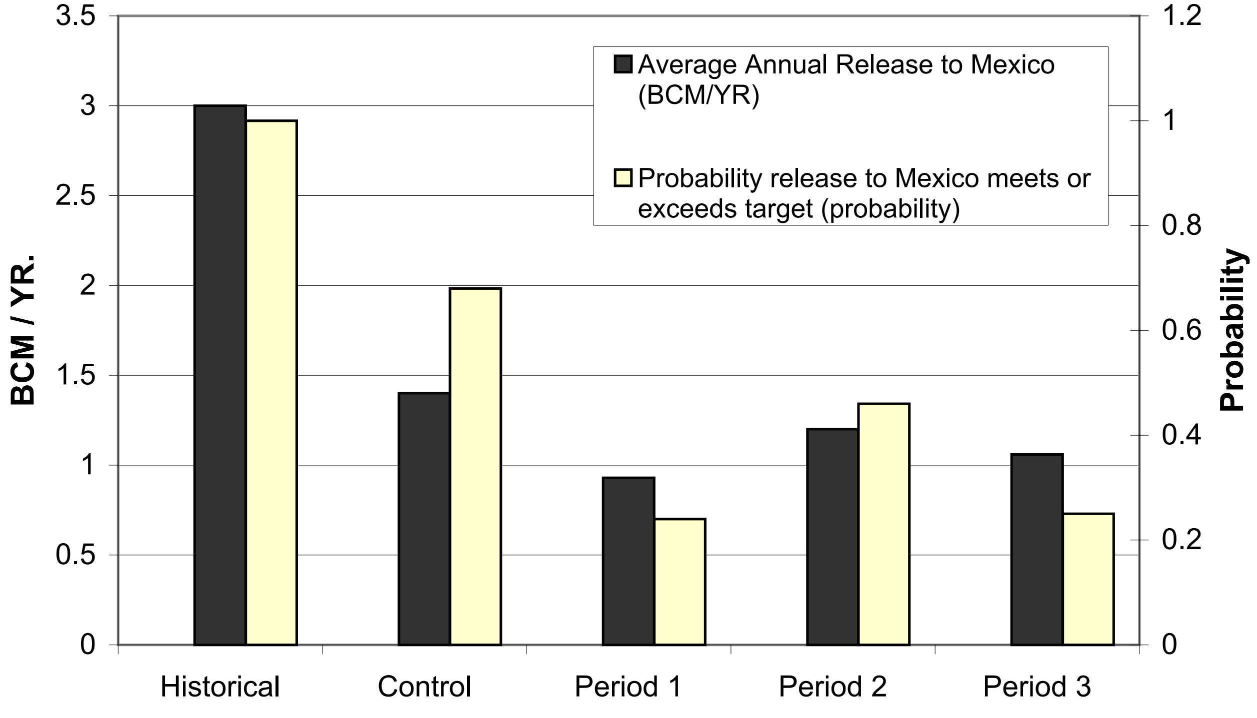
70
60
50
40
30
20
10
0
Storage, BCM
Minimum
Average
Maximum
Historical
Control
Period 1
Period 2
Period 3

Figure 9



■ Average Annual Release to Lower Basin (BCM/YR)
BCM / YR.
Probability
14
12
10
8
6
4
2
0
1.2
1
0.8
0.6
0.4
0.2
0
Historical
Control
Period 1
Period 2
Period 3

Figure 10



3.5
3
2.5
2
1.5
1
0.5
0
BCM / YR.
1.2
1
0.8
0.6
0.4
0.2
0
Probability
Average Annual Release to Mexico (BCM/YR)
Probability release to Mexico meets or exceeds target (probability)
Historical
Control
Period 1
Period 2
Period 3

Figure 11

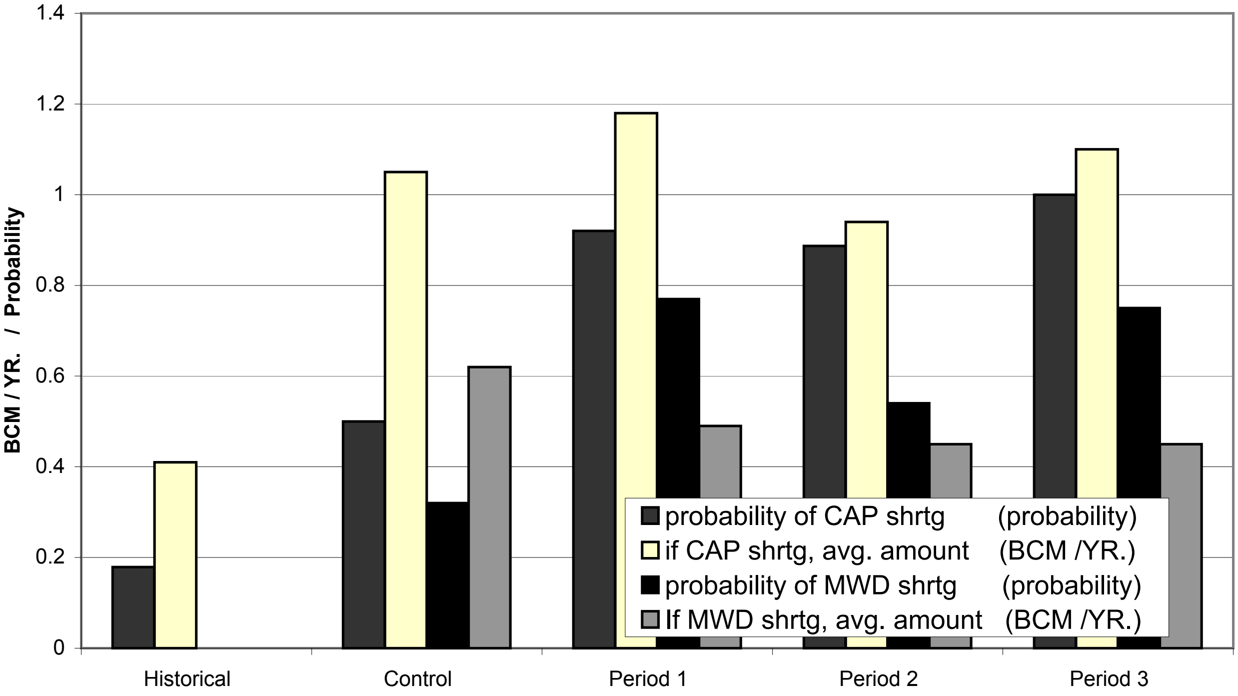
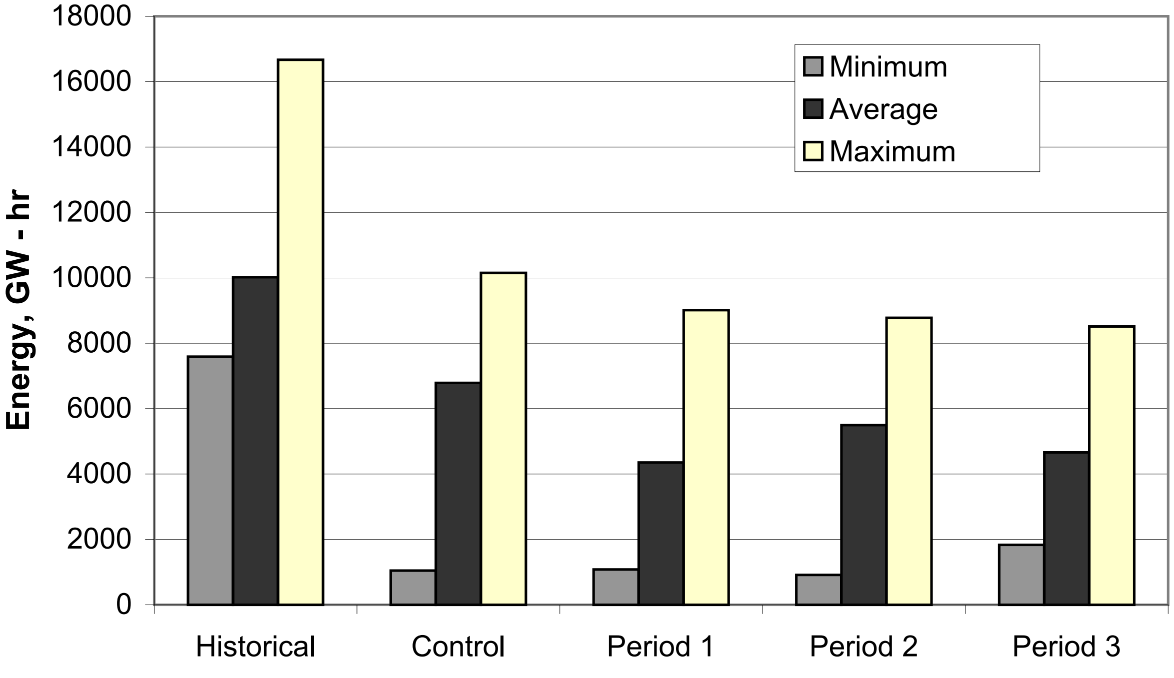
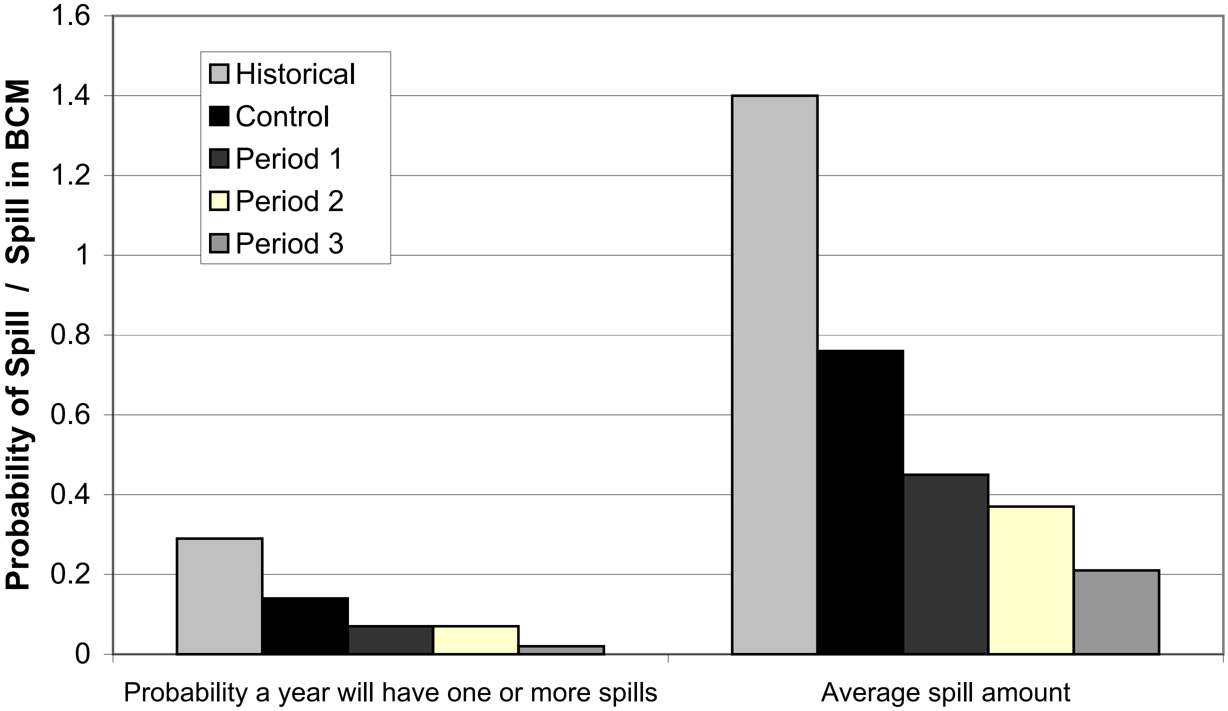

1.4
1.2
1
0.8
0.6
0.4
0.2
0
BCM / YR. / Probability
Historical
Control
Period 1
Period 2
Period 3
probability of CAP shrtg (probability)
if CAP shrtg, avg. amount (BCM /YR.)
probability of MWD shrtg (probability)
If MWD shrtg, avg. amount (BCM /YR.)

Figure 12



18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Energy, GW - hr
Minimum
Average
Maximum
Historical
Control
Period 1
Period 2
Period 3

Figure 13


Probability of Spill / Spill in BCM
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Historical
Control
Period 1
Period 2
Period 3
Probability a year will have one or more spills
Average spill amount