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MITIGATING IMPACTS OF A SEVERE SUSTAINED DROUGHT ON COLORADO RIVER WATER RESOURCES[1]

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ABSTRACT: We evaluated the effects of institutional responses developed for coping with a severe sustained drought (SSD) in the Colorado River Basin on selected system variables using a SSD inflow hydrology derived from the drought which occurred in the Colorado River basin from 1579-1616. Institutional responses considered are reverse equalization, salinity reduction, minimum flow requirements, and temporary suspension of the delivery obligation of the Colorado River Compact. Selected system variables (reservoir contents, streamflows, consumptive uses, salinity, and power generation) from scenarios incorporating the drought-coping responses were compared to those from Baseline conditions using the current operating criteria. The coping responses successfully mitigated some impacts of the SSD on consumptive uses in the Upper Basin with only slight impacts on consumptive uses in the Lower Basin, and successfully maintained specified minimum streamflows throughout the drought with no apparent effect on consumptive uses. The impacts of the coping responses on other system variables were not as clear cut. We also assessed the effects of the drought-coping responses to normal and wet hydrologic conditions to determine if they were overly conservative. The results show that the rules would have inconsequential effects on the system during normal and wet years.

(KEY TERMS:water resources planning; water policy/regulation/decision making; drought; water management; water law; social and political; irrigation; water quality; simulation.)

INTRODUCTION

Several drought-coping responses for mitigating the impacts of a severe sustained drought (SSD) in the Colorado River Basin were developed during interactive games (Henderson and Lord, 1995). These responses include shorting Mexico deliveries, changing the operation of Lake Mead with respect to the shortage level, changing the operation of Lake Powell to include a reverse equalization rule, implementing minimum streamflows to preserve endangered species in river reaches, reducing salinity through various measures, water marketing to lessen the effects of the drought, water banking, and intrastate drought-management options.

In this paper, we assess, from a water resources perspective, the usefulness of three of the coping responses that had the most visible effect on mitigating the impact of the SSD across a wide range of hydrologic conditions, using a monthly simulation model of the Colorado River System, the Colorado River Model (CRM). The three measures are reverse equalization, minimum streamflow specifications, and salinity reduction.

The CRM was developed over a twelve-year period by Hydrosphere. It emulates the USBR Colorado River Simulation Model (CRSM) (Schuster, 1987; 1988a; 1988b). The model is based on a network flow archetype (Texas Water Development Board, 1972; Clasen, 1968; Barr *et. al.*, 1974) and represents 14 reservoirs, 29 inflow points, and 265 withdrawal points within the system. The CRM is configured to simulate the "Law of the River" – the various statutes, compacts, treaties, court decisions, regulations, agreements, and formal operating criteria that govern the use of water in the Colorado River and its tributaries. A previous version of the model was used by Brown *et al.* (1988, 1990) in a study of the disposition of streamflow increases from the Arapaho National Forest. A complete description of the Colorado River Model can be found in Hydrosphere (1994).

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PHYSICAL SYSTEM

The Colorado River basin drains approximately 243,000 square miles contained within the states of Colorado, Wyoming, Utah, New Mexico, Nevada, Arizona, California, and parts of the Mexican states of Baja, California, and Sonora (Figure 1). The basin is divided both geographically and politically at Lee Ferry, just downstream of the point where the river crosses the Arizona-Utah border. The Upper Basin includes lands in the states of Colorado, New Mexico, Utah, Wyoming, and a small part of Northern Arizona, and is the principal source of inflow into the Colorado River system. The Lower Basin includes lands in the states of Arizona, California, Nevada, and New Mexico.

Many reservoirs alter the natural flow of the Colorado River. The 14 reservoirs modeled in the CRM contain a total active capacity of 61,375,000 acre-foot. The two principal reservoirs, Lake Powell and Lake Mead (formed by Glen Canyon and Hoover Dams, respectively), provide over 50 million acre-feet (maf) of storage. Water is diverted from the river at hundreds of relatively small diversion points in the Upper Basin. The Lower Basin diversions tend to be larger and considerably fewer in number. A more complete description of the physical system can be found in Schuster (1987) and Hydrosphere (1994).

INSTITUTIONAL SETTING

The allocation of water within the Colorado River Basin is constrained within an institutional setting which has evolved from judicial, statutory, and administrative decisions collectively known as the Law of the River. These include the Colorado River Compact (CRC) (1922), the Boulder Canyon Project Act (1929), the California Seven Party Agreement (1931), the Mexican Water Treaty (1944), the Upper Colorado River Basin Compact (1948), the Colorado River Storage Project Act (1956), the Supreme Court Decree in Arizona v. California (1963), the U.S. Army Corps of Engineers Water Control Manual for Flood Control, water delivery contracts, and the Criteria for Coordinated Long-Range operation of Colorado River Reservoirs (Operating Criteria), among others. The CRC of 1922 apportioned the flow of the river between the Upper Basin States (Arizona, Colorado, New Mexico, Utah, and Wyoming) and the Lower Basin States (Arizona, California, and Nevada); the CRC also required that the Upper Basin deliver a 10-year moving average flow of 7.5 maf to the Lower Basin at Lee Ferry. Summaries of the other governing laws can be found in Meyers (1966) and Nathanson (1978).

INFLOW HYDROLOGY

Two inflow sets were used in this study. They represent natural flows at 29 inflow points in the Colorado River Basin. The first is the SSD inflow set used for evaluating the coping responses under a drought condition. The 38-year SSD inflow set was derived from the drought which occurred in the Colorado River basin from 1579-1616, which was found to be the most severe in the over 500 years of reconstructed streamflow period. The annual flows within the critical period (from 1579 to 1600) were rearranged in a descending order, resulting in a clustering of the low flows about a single point, and thereby producing the SSD configuration. It is the same as the inflow hydrology used in Harding *et al.* (1995) and is described in Tarboton (1995).

The second inflow set is a synthetic streamflow trace used for evaluating the coping responses under "normal" and "wet" hydrologic conditions. The synthetic trace was developed from the statistics of observed Colorado River flows for the period 1931 through 1983, which has a mean of 13.5 maf/yr at Lee Ferry. This mean value is approximately equal to the long-term mean of flows at Lee Ferry reconstructed from tree ring records from 1520 to 1961 (Stockton and Jacoby, 1976). The synthetic trace has a mean of 13.51 maf/yr, a median value of 13.09 maf, a minimum of 4.76 maf/yr, and a maximum of 34.92 maf/yr. It was developed using the statistical streamflow package SPIGOT (Grygier and Stedinger, 1990a; 1990b).

DEPLETIONS

The same set of depletions (diversions minus return flows) were used in all the simulations reported in this study. The depletion set cover a 38-year period at 265 locations within the basin. It is the same as that used in Harding *et al.* (1995) and is the "medium" level of projected future depletions described in Booker and Colby (1995). Total depletions increase over the 38-year period of the simulations, beginning with estimates of actual water use for 1992 and progressing to projected values for subsequent years. The depletion estimates were, for the most part, derived from data developed by the USBR for its 1991 Annual Operating Plan, dated July 22, 1991. The depletion level assumes demand growth is represented by the USBR schedule for years 1992 to 2030, but with agricultural uses fixed at 1992 levels. The Las Vegas, Nevada, depletion is assumed to grow with projected population increases. The Central Arizona Project (CAP) depletion fluctuates over the study

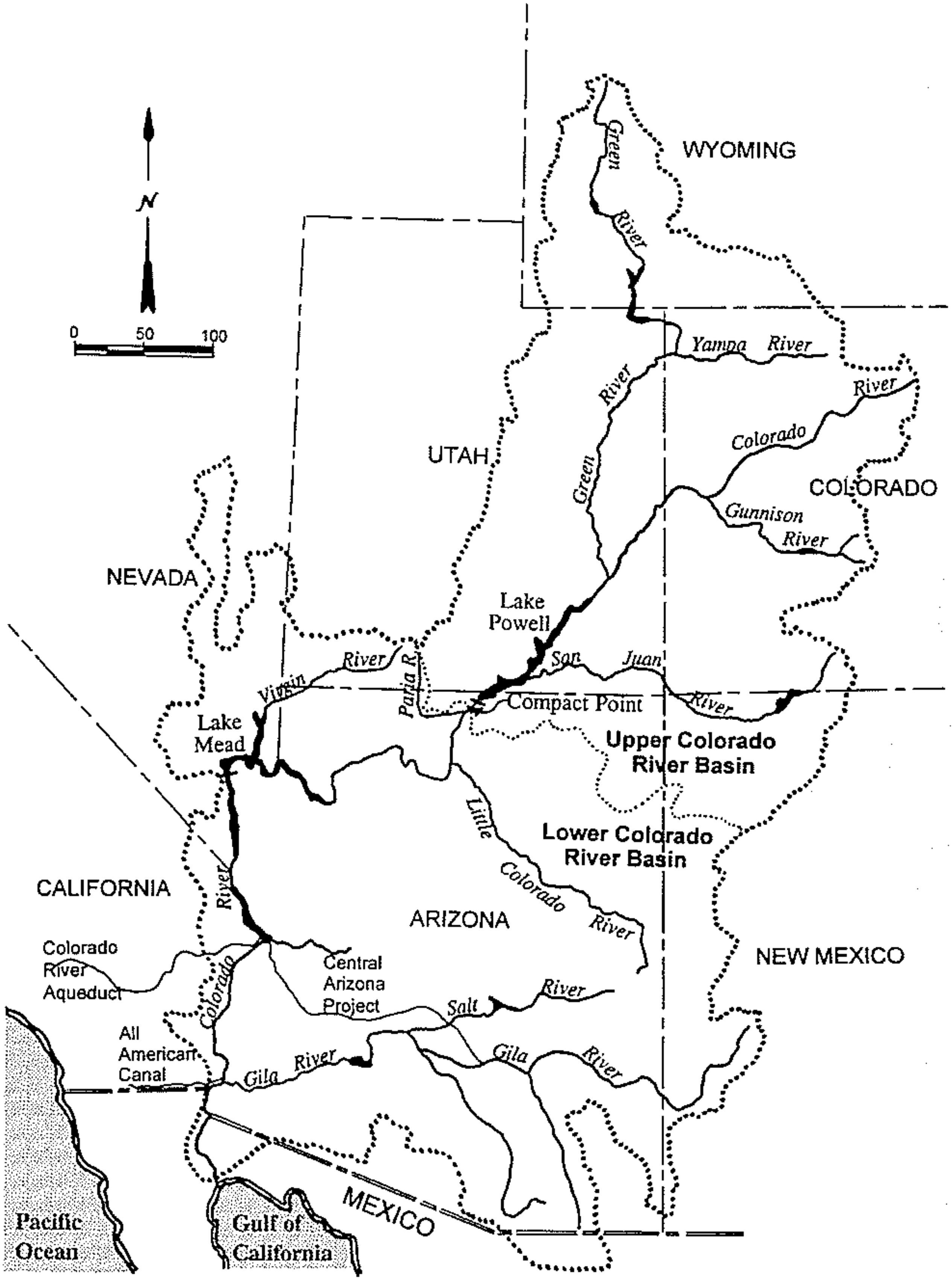

Figure 1. Colorado River Basin.

period, according to a schedule developed in the gaming exercises described by Henderson and Lord (1995).

The USBR depletion estimates on which the depletion data for this analysis are based were developed through model studies that included consideration of water supply, legal entitlement, current and expected delivery capacity, and expected development of water-using projects. Thus, they cannot be considered econometric estimates of demand for water.

DROUGHT-COPING INSTITUTIONAL RESPONSES

The three coping responses considered in this analysis and the manner in which they were implemented in the CRM are described below.

Reverse Equalization

The present equalization rule calls for releases from Lake Powell into Lake Mead to equalize the September 30 contents of the two reservoirs when certain criteria are met. Equalization is applied if: (1) the forecasted end-of-water-year (EOWY) content in Lake Powell is greater than that of Lake Mead; (2) the contents of Upper Basin federal reservoirs are greater than a certain amount – the "602(a) storage;" and (3) the Lake Mead forecasted EOWY vacant space satisfies flood control requirements. The 602(a) storage, according to section 602(a) of the Colorado River Basin Project Act (Public Law 90-537), is that quantity of storage estimated to be necessary to ensure that the Upper Basin can meet its future deliveries to the Lower Basin without impairing Upper Basin consumptive uses. Its determination is at the discretion of the Secretary of the Interior, but in current practice an equation is used (Schuster, 1987; Hydrosphere, 1994).

The reverse equalization rule evaluated here extends the equalization rule to allow for a reduction in the releases from Lake Powell into Lake Mead so as to equalize the September 30 contents of the two reservoirs. As implemented in the CRM for this study, reverse equalization is applied if the following five conditions are met: (1) the forecasted EOWY content in Lake Mead is greater than that of Lake Powell; (2) the forecasted EOWY content of Lake Powell is less than the maximum reservoir capacity; (3) the total contents of Upper Basin federal reservoirs are less than the 602(a) storage; (4) a reverse equalization minimum release equal to 34 thousand acre-feet (kaf) per month from Lake Powell can be made; and (5) the 10-year moving average release from Lake Powell should be more than 7.5 maf to satisfy the CRC delivery obligation at Lee Ferry (the fifth rule is, however, ignored in one scenario where the CRC is temporarily suspended).

Salinity Reduction

Two methods for reducing the system salinity were implemented. The first is irrigation canal lining and reduction of on-farm salt. This was implemented in the CRM by assuming that an annual reduction in salt loading at Upper Basin depletion points totaling in aggregate 1,021 kilo tons would ensue from these measures. The second method is a reduction of salt loading from natural sources. It was assumed in this case that a salt reduction of 180 kilo tons/year from the present loading of 6,474 kilo tons/year would result from measures to reduce the natural salt loading.

Minimum Streamflow Specification

The minimum streamflow levels used in these analyses were defined as the extirpation levels determined by Hardy (1995). These levels were sufficient to prevent extirpation of a population in a given reach. This was implemented in the CRM by specifying minimum flows at this level at eight river reaches within the basin, as shown in Table 1. Priorities assigned to the minimum flows in the CRM are higher than those assigned to any depletion or storage. Monthly distributions for the minimum flows were determined using the long-term average flows at these locations.

TABLE 1. Locations and Magnitudes of Specified Minimum Streamflows at the Extirpation Level.

Location	Annual Minimum Flow (kaf)
Green River Below Fontenelle	62
Green River Below Flaming Gorge	75
Yampa River Above Green Confluence	78
White River Above Green Confluence	26
Gunnison River Below Curecanto	63
San Juan River Above Colorado Confluence	43
Colorado River Above Powell	458
Colorado River Below Mead	501

METHODOLOGY

The drought-coping responses were assessed by comparing three model simulations using: (1) current operating rules for the system (Baseline conditions); (2) operating rules that incorporated the drought-coping responses (Scenario 1); and (3) operating rules that incorporated the drought coping responses but suspended the CRC (Scenario 2). The two scenarios used the same depletion and SSD inflow sets as described earlier, and the same initial starting conditions. The Baseline conditions were the same as those used to simulate the SSD drought in Harding *et. al.* (1995).

Scenario 1 included three of the interstate coping responses identified in the gaming studies of Lord *et. al* (1995). The three options were what we characterize as system-wide responses – i.e., those requiring unanimous agreement among all states. Thus, water banking and marketing arrangements were not evaluated in this study. The three coping responses selected for evaluation were reverse equalization, minimum streamflow specifications, and salinity reduction programs.

The results from Scenario 1 showed that the combination of responses was not effective in mitigating substantial drought impacts in the Upper Basin. Thus, we decided to evaluate an additional coping response, suspension of the delivery requirements of the 1922 CRC. This response would be exceedingly difficult to invoke, for reasons discussed in Henderson and Lord (1995). However, we viewed it as an effective coping response when combined with reverse equalization. An arguable case can be made that article III(e) of the CRC (Meyers, 1966), which prohibits the Lower Basin from calling for water ". . . which cannot reasonably be applied to domestic and agricultural uses . . .," modifies the 75 maf, 10-year basic delivery obligation in article III(d). Under such an interpretation, no CRC call could be made until Lake Mead is empty.

The coping responses have been implemented in the CRM so as to correspond to the gaming model (Henderson and Lord, 1995) as closely as possible in scope and form, including the Central Arizona Project demands which were set to correspond as closely as possible to the amount taken by the player representing the State of Arizona. These amounts fluctuate over the study period and average 519 kaf/year.

System operations were evaluated by examining the streamflows at several locations within the basin, reservoir contents, total annual depletions of Upper and Lower Basin states, salinity, and total system hydropower generation.

In addition to testing the drought-coping responses to the severe and sustained drought hydrology, we also assessed the efficiency of the drought-coping rules when applied to "normal" and "wet" hydrologic conditions. This was done because operating rules developed in response to a drought, particularly a SSD, could be overly conservative and have unanticipated side effects when applied to normal or wet hydrologic conditions.

The Baseline and two coping scenarios were simulated in this case using the 1026-year synthetic streamflow trace divided into 27 38-year traces. The operating rules, initial conditions, and depletions used in the Baseline and two coping scenarios were used to simulate operations of the system for each of the 27 traces. The results from the three simulations using the 1026 years of synthetic streamflows were compared by examining the cumulative frequency distributions of the total annual flows at Lee Ferry and the end-of-water-year contents of Lake Powell and Lake Mead.

RESULTS WITH SSD INFLOWS

Baseline Conditions

The Baseline conditions are the same as in Harding *et al.* (1995).

Streamflows. Statistics of monthly simulated streamflows at the eight locations where minimum streamflows were specified for protecting endangered species (Hardy, 1995) are given in Table 2. A plot of simulated total annual flow at Lee Ferry is shown in Figure 2. Though the simulations were carried out with monthly time-steps, the graphs showing the results have been plotted using annual values, for clarity's sake. The total annual flow at Lee Ferry was below the 8.23 maf/yr minimum objective release required by the Operating Criteria in four consecutive years from year 19 through year 22. The CRC was invoked in year 21, but sufficient releases to comply with it were not achieved until year 26.

Reservoir Contents. Of the 14 reservoirs modeled in CRM, only the results from Lake Powell and Lake Mead are presented. The active storage capacity of these two reservoirs constitute 84 percent of the total active capacity within the system and hence account for most of the storage within the system. In addition, the storage content variation of Lake Powell is typical of the storage contents of other Upper Basin reservoirs.

TABLE 2. Modeled Monthly Streamflow Statistics at Selected Points Within the Colorado River Basin (units in thousands of acre-feet).

Station	Baseline Conditions			Scenario 1			Scenario 2		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Green River Below Fontenelle	8	626	94	8	626	93	8	626	92
Green River Below Flaming Gorge	0	810	104	3	810	103	3	772	99
Yampa River Above Green Confluence	0	773	104	2	773	105	1	773	103
White River Above Green Confluence	0	193	36	2	193	36	2	193	35
Gunnison River Below Curecante	2	719	128	6	899	128	5	899	126
San Juan River Above Colorado Confluence	0	822	101	1	822	100	1	864	97
Colorado River Above Powell	20	3,944	704	27	3,944	702	27	4,567	681
Colorado River Below Mead	245	1,006	661	245	1,006	661	245	1,006	659

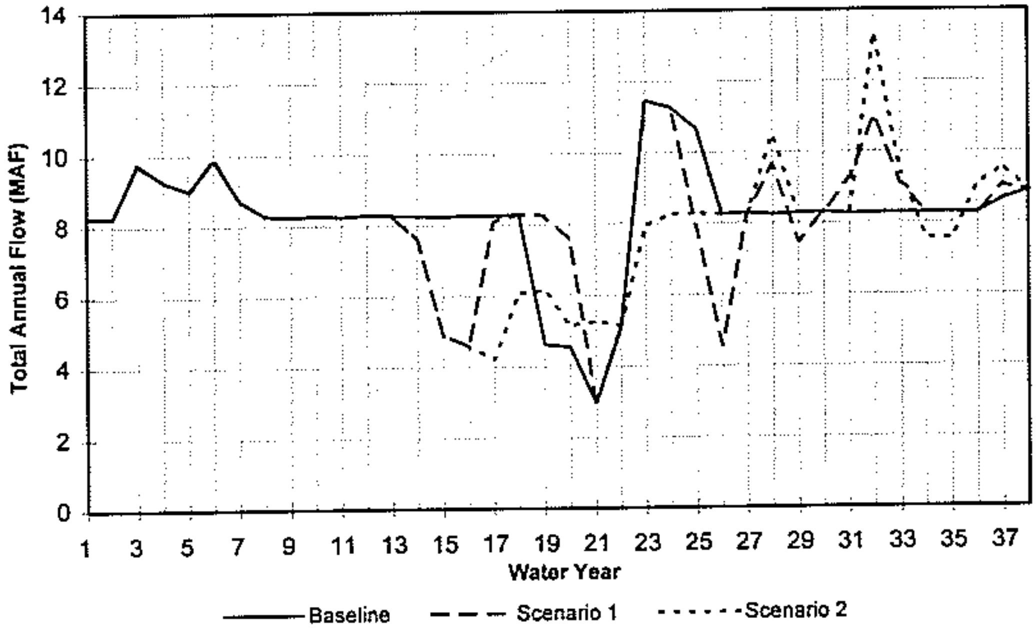

Figure 2. Total Annual Flow at Lee Ferry Under the Baseline, Scenario 1, and Scenario 2, with SSD Inflow Hydrology.

Figure 3 shows that the active storage content of Lake Powell increased to its maximum value at the end of the fifth year and thereafter started to drop as the drought began. The active content of Lake Powell was zero by the end of year 18 and remained at dead storage for eight consecutive years. In contrast, the figure shows that the active content of Lake Mead was affected less. The lowest level at Lake Mead was 7.5 maf at the end of year 22. This sharp difference in storage contents occurred for several reasons: (a) the equalization rule resulted in releases from Lake Powell to Lake Mead above the 8.23 maf/yr minimum objective release in the first few years of the study period; (b) the minimum objective release of 8.23 maf/year from Lake Powell maintained the level of Lake Mead after the content of Lake Powell fell below that of Lake Mead; and (c) obligated deliveries from the Upper Basin through Lake Powell to satisfy the CRC continued during the worst period of the drought.

Depletions. A plot of the total annual depletion for the Upper Basin is shown in Figure 4. The total annual Upper Basin depletion is the sum of the total annual depletions for the states of Colorado, New Mexico, Utah, and Wyoming. Serious shortfalls start to occur

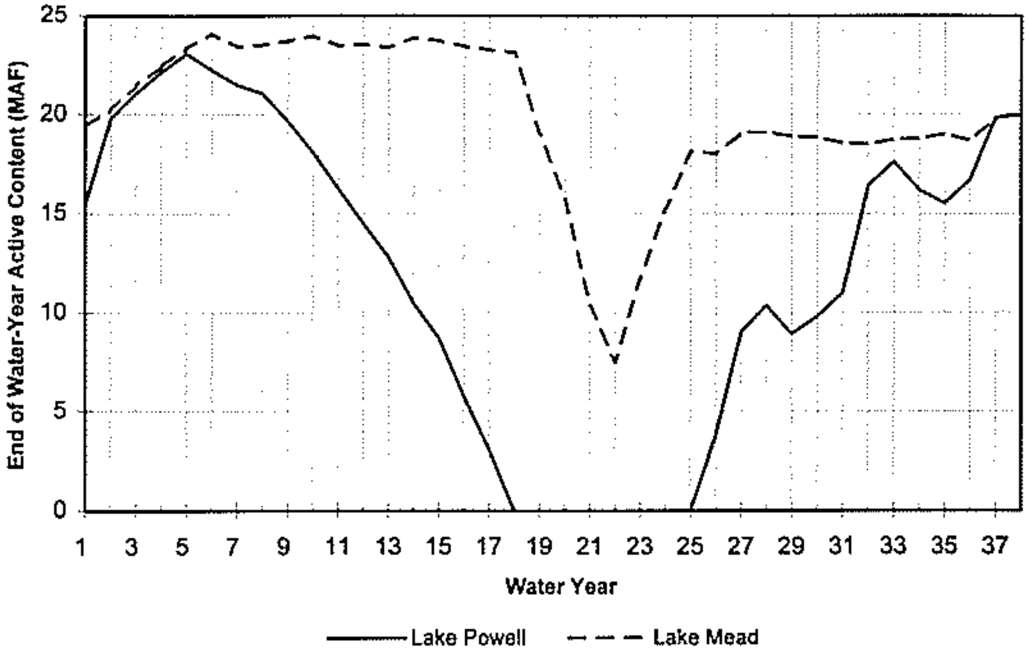

Figure 3. Lake Powell and Lake Mead End of Water-Year Active Contents Under the Baseline, with SSD Inflow Hydrology.

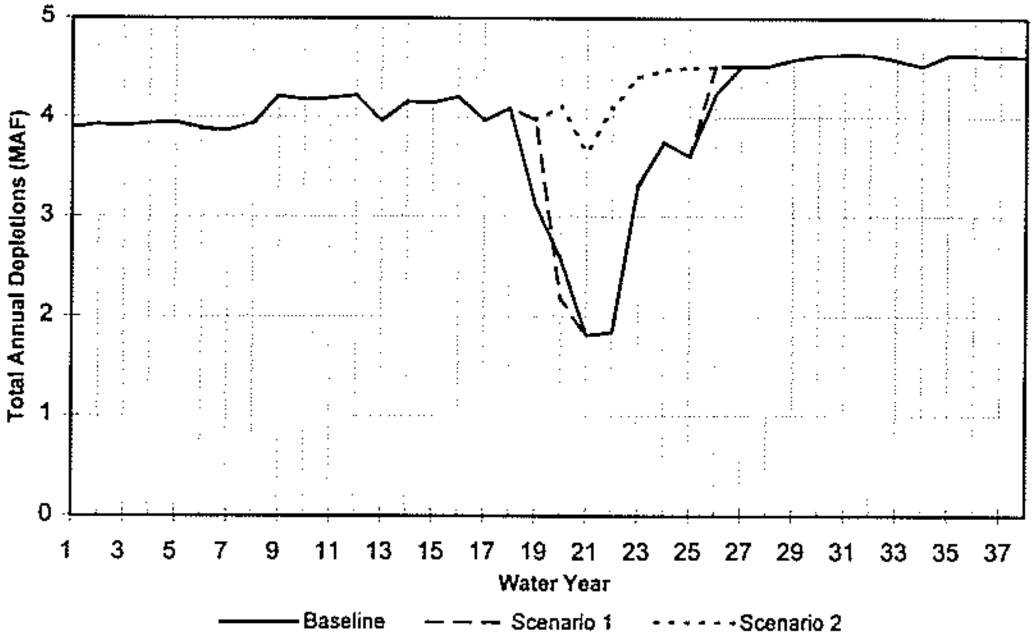

Figure 4. Upper Basin Total Annual Depletions Under the Baseline, Scenario 1, and Scenario 2, with SSD Inflow Hydrology.

in the Upper Basin by the end of year 19 and get progressively worse thereafter. The depletion shortfall in the worst drought year, year 21, is about 59 percent.

Figure 5 shows the Lower Basin total annual depletions. The higher depletions observed in the Lower Basin in years 6 and 7 are due to surplus deliveries to California and Arizona. Slight shortfalls were observed in Lower Basin depletions in two years of the study period affecting Arizona and Nevada. However, the simulated deliveries to Mexico did not experience any delivery shortfall at any time during the study period.

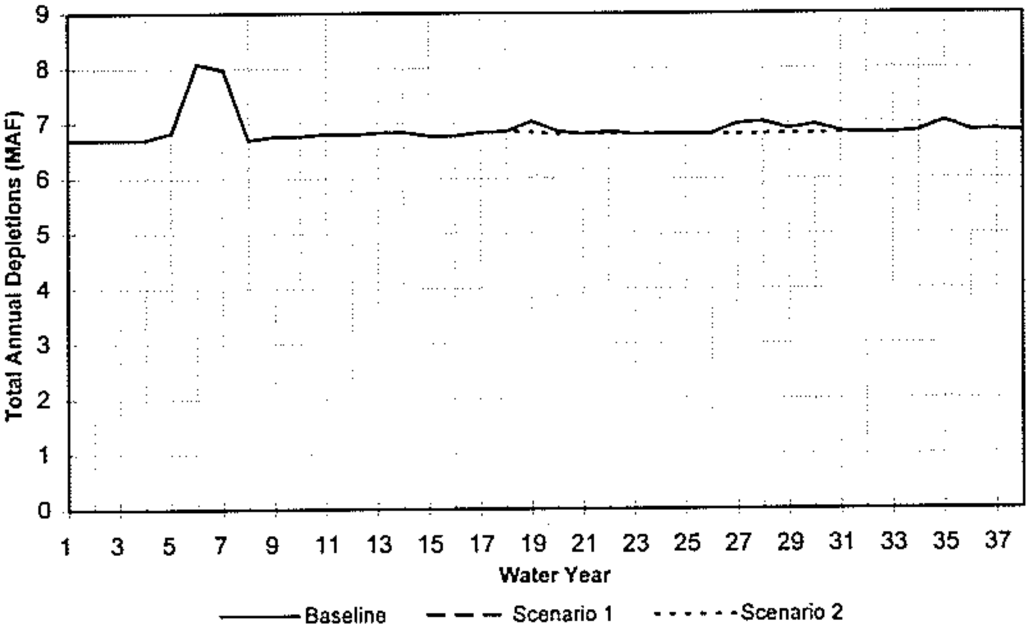

Figure 5. Lower Basin Total Annual Depletions Under the Baseline, Scenario 1, and Scenario 2, with SSD Inflow Hydrology.

Salinity. Figure 6 shows the simulated salt concentration below Lake Mead. The salt concentration below Lake Mead increased as the drought intensified because of the smaller quantity of water available in the system to dilute the salt load. The salt concentration then receded after the drought peaked as more water was available in the system.

Hydropower. Figure 7 shows the generated energy. A rapid drop in the generated energy occurred during the worst drought years as the reservoirs started to drop below their minimum power pools.

Scenario 1

Streamflows. Statistics of simulated monthly flows at locations where the minimum streamflows were specified are given in Table 2. The table shows that the minimum flows specified as part of the drought-coping responses were complied with at all locations. The magnitude of maximum flows are about the same as in the Baseline. This is expected since maximum flows would typically occur in nondrought years where the mitigating effects of the drought-coping responses would be insignificant. The average monthly streamflows were slightly lower in the coping scenarios than in the Baseline. This shows that the drought-coping responses increased the availability of water for consumptive uses or storage.

The total annual flow at Lee Ferry dropped below the 8.23 maf/yr minimum objective release for the first time in year 14 and remained below this level for the next two years due to the effect of the reverse equalization rule (see Figure 2). However, in year 17, the CRC was invoked causing the reverse equalization to be suspended, and a release necessary to meet the CRC requirement was made. Annual releases from the Upper Basin necessary to satisfy the requirement of the CRC were also made in years 18, 19, and 20 even though the drought was intensifying and its effects were starting to become apparent in the Upper Basin. By year 21, the full release required to satisfy the CRC could not be made because of the drought severity in the Upper Basin. A similar situation also occurred in years 22 and 23 even though Upper Basin releases were increased in an effort to meet the CRC requirement. In year 26, reverse equalization was again invoked causing the total annual flow at Lee Ferry to drop to 4.57 maf. The total annual flows were subsequently increased in years 27 and 28 to satisfy the CRC.

Reservoir Contents. The active content of Lake Powell also increased to its maximum value at the end of the fifth year under Scenario 1, as shown in Figure 8, and thereafter started to drop. However, towards the end of year 14, reverse equalization was invoked and less water was released from Lake Powell in an effort to equalize the levels of Lake Powell

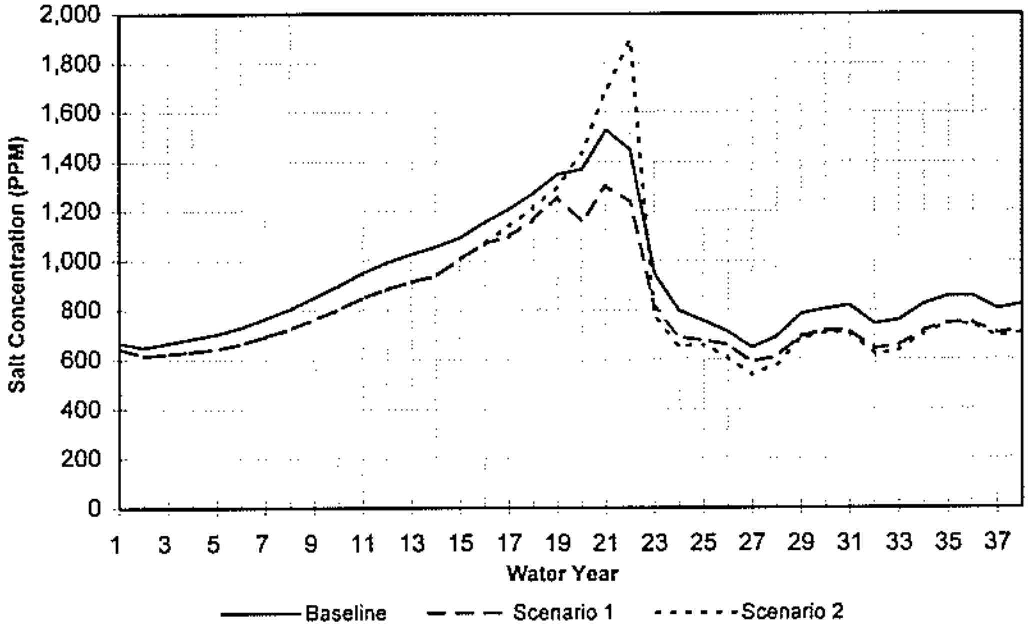

Figure 6. Salt Concentration Below Lake Mead Under the Baseline, Scenario 1, and Scenario 2, with SSD Inflow Hydrology.

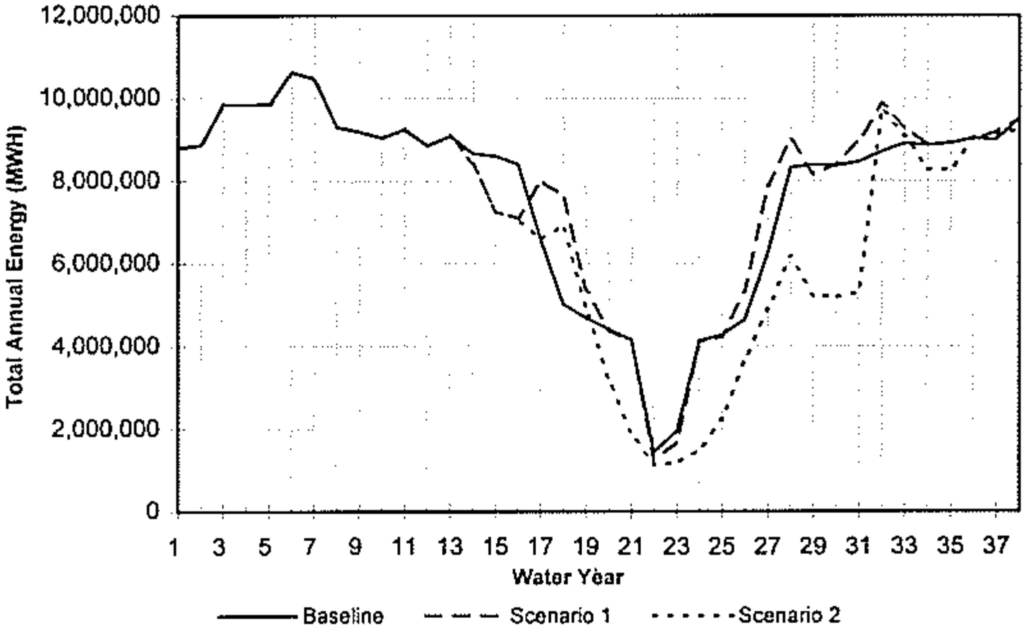

Figure 7. Total Annual System Energy Generated Under the Baseline, Scenario 1, and Scenario 2, with SSD Inflow Hydrology.

and Lake Mead. This reduced the drawdown rate at Lake Powell and resulted in an increased drawdown rate at Lake Mead.

The reverse equalization rule continued to be in effect until year 16. Starting from year 17, reverse equalization was overridden by the CRC. Hence, releases required to achieve the CRC were initiated at Lake Powell. This had the effect of rapidly drawing down the contents of Lake Powell and other Upper Basin Reservoirs while the content of Lake Mead stabilized. By year 20, the level of Lake Powell was down to dead storage and remained there for five

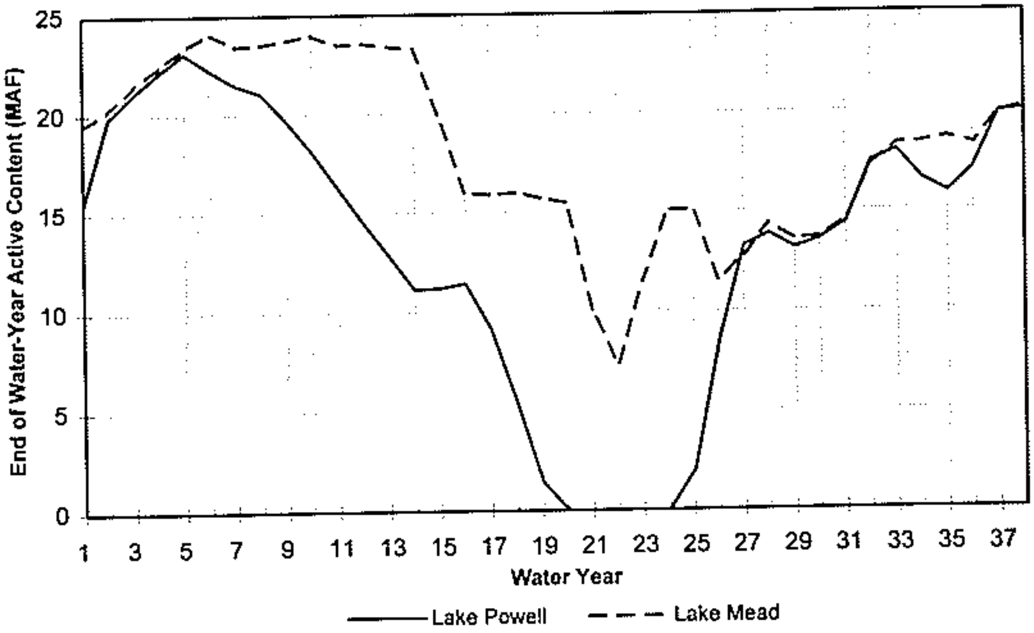

Figure 8. Lake Powell and Lake Mead End of Water-Year Active Content Under Scenario 1 (CRC Call Enforced), with SSD Inflow Hydrology.

consecutive years. The content of Lake Mead dropped sharply in years 21 and 22 because sufficient water was not released from the Upper Basin states to satisfy the CRC call due to the drought severity. Lake Mead dropped to its lowest level of 7.5 maf in year 22, the same as in the Baseline. After year 22, the content of Lake Mead rose rapidly until year 24 because releases necessary to satisfy the CRC were being made from the Upper Basin as the drought started to subside. In years 25 and 26, the reverse equalization rule was again invoked without violating the 7.5 maf 10-year average delivery requirement at Lee Ferry, and the contents of Lake Powell and Lake Mead were equalized by the end of year 27.

Depletions. Figure 4 shows that Upper Basin depletion shortfall was not manifest in Scenario 1 until the end of year 20, at which point it is more severe than the depletion shortfall in the Baseline. The depletion shortfall was delayed for one year because of the implementation of reverse equalization. When it did occur, it was more severe than in the Baseline because of the higher release required to satisfy the CRC after reverse equalization was discontinued. Depletion shortfalls in subsequent years were almost as severe as in the Baseline since the coping response that could mitigate the depletion shortfall (i.e., reverse equalization) had been overridden.

Figure 5, which shows the simulated total annual depletions for the Lower Basin, shows that there were no differences in Lower Basin depletion levels between Scenario 1 and the Baseline. The simulated deliveries to Mexico also did not experience any shortfall at any time during the study period.

Salinity. Figure 6 shows the simulated salt concentration below Lake Mead. The figure shows that the salt concentration below Lake Mead is lower than in the Baseline throughout the study period. This is because of the salinity reduction program implemented as a coping response to reduce salt loading through on-farm efficiencies and natural salt load reductions. The peak of the salt concentration was 15 percent lower than the peak under the Baseline conditions.

Hydropower. Figure 7 shows the energy generated under this scenario. Of the three scenarios, the most energy was generated under Scenario 1 because the amount of the time Lake Powell and Lake Mead were below the minimum power pools was less.

Scenario 2

Streamflows. Statistics of simulated monthly flows at locations where minimum streamflows were specified are given in Table 2. The table shows that the minimum flows specified as part of the drought-coping responses were complied with most of the time at all locations.

The total annual flow at Lee Ferry dropped below the minimum objective release of 8.23 maf/yr for the first time in year 14 (see Figure 2). The drop occurred because of the reverse equalization rule. The total annual flow then remained below the 8.23 maf/yr level for 10 consecutive years starting from year 14. This was allowed to happen because the CRC, which would have required the total annual flows to be increased in order to satisfy the mandated 7.5 maf 10-year delivery requirement, was suspended in this scenario.

Reservoir Contents. There were no differences between the reservoir contents under this scenario and in Scenario 1 for the first 16 years of the study period (see Figure 9; compare to Figure 8). As in Scenario 1, reverse equalization was invoked towards the end of year 14 and was still in place by year 16. However, unlike the Scenario 1, reverse equalization continued to be invoked until year 23.

Because the reverse equalization rule was not overridden in this scenario, its effect in mitigating the drought impact on Upper Basin reservoir contents was more noticeable, as shown in Figure 9. The rule kept the content of Lake Powell to be almost equal to that of Lake Mead throughout the drought period. Reverse equalization resulted in the rapid drawdown of Lake Mead starting towards the end of year 14, such that the content of Mead dropped from 23.24 maf by the end of year 14 to 12.08 maf by the end of year 17, at which point it was almost equal to the content of Lake Powell for the first time. The reverse equalization rule also decreased the drawdown rate of the Upper Basin reservoirs when compared to the Baseline or Scenario 1.

The contents of Lake Powell and Lake Mead continued to fall at about the same rate from year 17, such that by the end of year 22, Lake Powell was empty and Lake Mead was almost empty. The active content of Lake Powell was zero in only one year under this scenario. After the drought peaked, the content of Lake Powell recovered faster than that of Mead, such that by the end of year 27, Lake Powell was much higher than Lake Mead and the total content of Upper Basin reservoirs was more than the 602(a) storage level. This invoked the equalization rule in year 28, causing releases from Lake Powell above the 8.23 maf/yr minimum objective release requirement in order to equalize the contents of Lake Mead and Lake Powell (see Figures 2 and 8). A similar situation also occurred in years 32 and 33. Lake Mead contents were below the elevation of the Southern Nevada intakes (1050 feet msl, corresponding to 7.26 maf) for a period of eight years in Scenario 2.

Depletions. Depletion shortfalls in the Upper Basin under Scenario 2 were substantially reduced compared to the first two scenarios. This is because reverse equalization was implemented throughout the severe drought period and because suspension of the

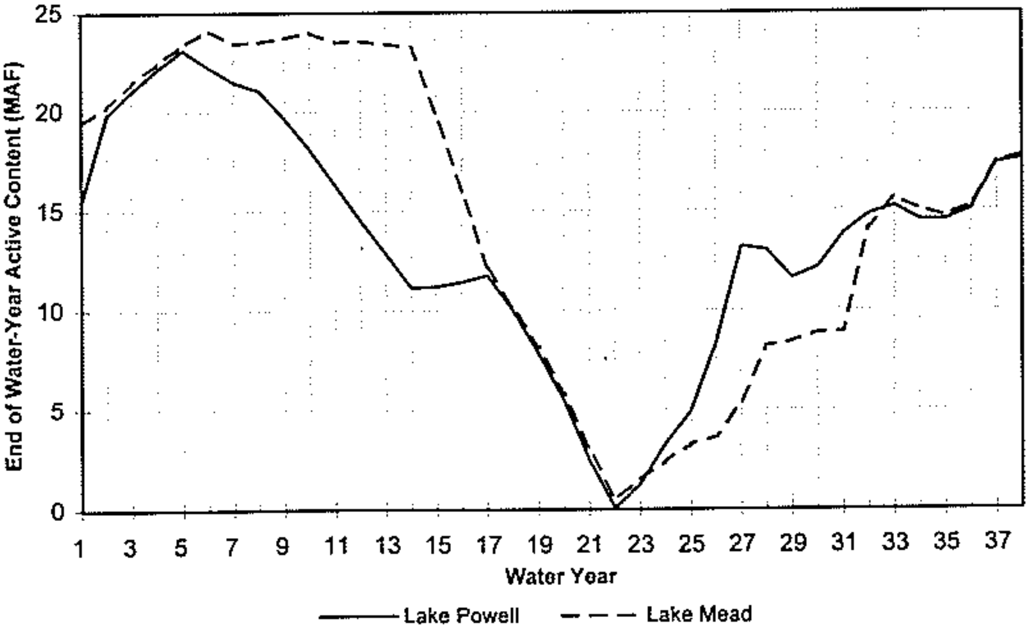

Figure 9. Lake Powell and Lake Mead End of Water-Year Active Content Under Scenario 2 (CRC Call Suspended), with SSD Inflow Hydrology.

CRC eliminated the need to bypass flows when Lake Powell did empty. Hence, more water was kept in Upper Basin reservoirs which were then available for consumptive uses. In the worst year of the drought, year 21, the depletion shortfall in the Upper basin under Scenario 2 was only 18 percent compared to a depletion shortfall of 59 percent under the Baseline and Scenario 1 (see Figure 4).

Lower Basin depletion shortfalls to CAP and Nevada were more under this scenario than in the Baseline and Scenario 1 (see Figure 5). Note that we assumed that Nevada took the necessary measures to continue pumping from Lake Mead after the reservoir level dropped below the existing intake elevation. California depletions were unaffected compared to the Baseline conditions. The shortfalls to CAP and Nevada occurred because reverse equalization, which was in place throughout the drought period, resulted in the drawdown of Lake Mead below its shortage elevation (which corresponds to a reservoir content of 10.762 maf). When the content of Lake Mead falls below the shortage elevation, a shortage is declared, the CAP deliveries are cut back to a minimum annual delivery of 450 kaf/yr, and a shortfall equal to 4 percent of the CAP shortage is imposed on Nevada. The content of Lake Mead dropped below the shortage elevation for the first time in year 19 and remained below the shortage elevation until year 31. Years without depletion shortfalls in this period corresponded to those years when the CAP demand was equal to the minimum 450 kaf/yr. Note that Lake Mead did not empty in this scenario, so it was not necessary to bypass water at Upper Basin diversion locations. Simulated deliveries to Mexico also did not experience any shortfall at any time during the study period.

Salinity. The simulated salt concentration below Lake Mead started off lower compared to the Baseline, at the same level as in Scenario 1 (see Figure 6). However, starting from year 16, the salt concentration increased at a higher rate and was actually higher than in the Baseline in three of the worst drought years in spite of the fact that the salinity reduction program was still being implemented. This is a result of higher depletions in the Upper Basin. The higher depletion rate in the Upper Basin increased the salinity in two ways: (1) by introducing salt into the system from the salt load associated with the depletions; and (2) by decreasing the amount of water in the system available to dilute the salt load. After the worst drought years, the salt concentration below Lake Mead then fell to a level comparable to that under Scenario 1 due to the effect of the salinity reduction programs. The peak of the salt concentration was 24% higher in Scenario 2 than the peak of the salt concentration in the Baseline.

Hydropower. Figure 7 shows the generated energy. A rapid drop in the generated energy also occurred during the worst drought years as the reservoirs started to drop below their minimum power pools. The least amount of energy was generated in this scenario because the reservoirs spent more time below the minimum power pool.

RESULTS UNDER NORMAL HYDROLOGIC CONDITIONS

Drought-coping responses identified as effective in mitigating the effects of an SSD might be overly conservative in normal and wet periods. We examined the cumulative frequency distributions of simulated annual flows at Lee Ferry and reservoir contents of Lake Powell and Lake Mead for the Baseline conditions and two drought-coping scenarios.

The differences between the cumulative frequency distributions of simulated total annual flows at Lee Ferry of the two coping scenarios and that of the Baseline are not significant. Over the middle range flows, between 28 and 70 percent non-exceedence, the frequency distributions of the three simulations are close. The frequency distributions for the coping scenarios are lower than the frequency distributions for the Baseline in the lower flow range (between the 1 and 18 percent non-exceedence values), which is consistent with observations from the simulations where we used the SSD inflows. The cumulative frequency distributions for the coping scenarios are higher in the higher flow ranges, between the 71 and 96 percent exceedence levels. Above the 96 percent exceedence level, the frequency distributions are almost equal. This implies that the coping scenarios induce slightly higher annual flows at Lee Ferry than the Baseline during wet years because Upper Basin reservoir contents are higher, but the there is virtually no difference in the simulated flows at Lee Ferry in extreme flow years since the reservoirs will be spilling in all scenarios.

The cumulative frequency distributions of Lake Powell storage for the coping scenarios are higher than that of the Baseline over the 1 to 64 percent nonexceedence range. Above the 64 percent nonexceedence level, all the curves are quite close. The cumulative frequency distributions for Lake Mead end-of-year storage content for the coping scenarios are lower than that of the Baseline over the 1 to 68 percent nonexceedence range. Above the 68 percent nonexceedence level, all the curves are quite close. These results show that the drought-coping responses tend to keep the reservoirs at higher levels during dry and normal conditions, but the drought-coping responses have very little effect on reservoir storage contents under wet conditions.

SUMMARY AND CONCLUSION

The drought-coping responses evaluated in this study successfully mitigated some of the impacts of the severe and sustained drought on depletions in the Upper Basin, with only slight impacts on consumptive uses in the Lower Basin. Imposition of a minimum streamflow requirement was successful in maintaining specified minimum streamflows throughout the drought, with no apparent effect on consumptive uses. The impacts of the coping responses on other system variables were not as clear cut.

Scenario 1 provided no benefit in terms of depletions, but it improved (over the Baseline conditions) minimum streamflows, energy production and salinity. Reservoir contents were increased modestly in the Upper Basin in Scenario 2 but at the inevitable cost of corresponding reductions in Lower Basin storage. The reverse equalization rule was ineffective in mitigating drought effects because it could only maintain Lake Powell contents temporarily in the face of the CRC delivery obligation. Because of the ten-year scope of the CRC delivery obligation, reduced flows in years 14, 15, and 16 were recaptured in years 19 and 20. These results led us to evaluate the additional coping response of suspension of the delivery obligation of the CRC.

Scenario 2 provided significant benefits in reducing depletion shortfalls in the Upper Basin, with only a slight increase in shortfalls in the Lower Basin. Minimum streamflows were maintained at the specified levels. Salinity conditions and energy production were worse than both the Baseline conditions and Scenario 1 because the coping response allowed additional depletions in the Upper Basin compared to the Baseline and Scenario 1. Reservoir contents were increased in the Upper Basin, but with significant reductions in the Lower Basin. This was the only scenario in which Lake Mead dropped below the elevation of the Southern Nevada Intake.

It is important to note that the accounting of shortfalls reported in the Lower Basin in this study do not include interruption of "surplus" deliveries to California – specifically the Metropolitan Water District (MWD). While these supplies, which have been provided historically, are most commonly referred to as "surplus" deliveries, they can more accurately be described as temporary delivery of unused entitlements. The supplies provided to MWD historically were not "surplus" to fully-developed entitlements, and their expected frequency is greatly reduced now that CAP has begun to take water from the river. Thus, the inability of the system to deliver the so-called surplus supplies to MWD cannot be considered to be a result of the drought. Rather, it is a result of a chronic water shortage and should be addressed as such and not as the object of drought-coping measures.

Assessment of the drought-coping rules under hydrologic conditions representative of long-term conditions indicate that the rules would have relatively inconsequential effects on the operation of the system during normal and wet years.

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