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HYDROLOGIC AND ECONOMIC IMPACTS OF DROUGHT UNDER ALTERNATIVE POLICY RESPONSES[1]

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ABSTRACT: A severe sustained drought in the Colorado River Basin would cause economic damages throughout the Basin. An integrated hydrologic-economic-institutional model introduced here shows that consumptive water users in headwaters states are particularly vulnerable to very large shortfalls and hence large damages because their rights are effectively junior to downstream users. Chronic shortfalls to consumptive users relying on diversions in excess of rights under the Colorado River Compact are also possible. Nonconsumptive water uses (for hydropower and recreation) are severely affected during the worst drought years as instream flows are reduced and reservoirs are depleted. Damages to these uses exceeds those to consumptive uses, with the value of lost hydropower production the single largest economic impact of a severe sustained drought. Modeling of alternative policy responses to drought suggests three general policy approaches with particular promise for reducing damages. Consumptive use damages can be reduced by over 90 percent through reallocation from low to high valued uses and through reservoir storage strategies which minimize evaporation losses. Reservoir management to preserve minimum power pool levels for hydropower production (and to maintain reservoir recreation) may reduce damages to these nonconsumptive uses by over 30 percent, but it may increase consumptive use shortfalls.
(KEY TERMS: economic impacts; drought; water policy; reservoir management; institutions; modeling.)

INTRODUCTION

Seven states in the southwestern United States utilize Colorado River Basin water resources. The region's agriculture is totally dependent on irrigation, with Basin water typically the sole irrigation supply. Water from the Colorado River mainstem and its Colorado tributaries accounts for nearly 40 percent of the water supply for the largest population center in each of four western states, including California (Booker and Colby, 1995). Las Vegas, the largest city near the river, is almost wholly dependent on river supplies and has few viable alternatives. Regional energy production utilizes instream flows directly for hydropower generation and requires Basin water for cooling at thermal plants. These same instream flows, and water stored in Basin reservoirs, provide recreational opportunities throughout the year to regional, national, and international visitors.

While alternatives to Colorado River supplies exist, they are limited or prohibitively costly, or both. The Colorado River and its tributaries are the critical resource enabling residents of the Southwest to transform an arid landscape. An extreme drought extending over several decades could be expected to result in exceptional impacts to a system so dependent on a single water supply. One purpose of this work is to develop detailed, quantitative estimates of the economic damages of a specific, hypothetical drought (more severe than any from the historical record) on consumptive and nonconsumptive users of Basin water resources. Damages are estimated here by modeling the existing system of reservoirs and the water allocation institutions governing reservoir management and water deliveries. No additional water storage facilities and no water transfers from low to high valued uses during drought are included under this baseline scenario, severely restricting possible responses to drought.

While little can be done to prevent the occurrence of drought, policies for managing Basin water resources might greatly influence the consequences of drought. Water users have long recognized the risks in depending on a highly variable resource such as the Colorado River. One response in the Colorado River Basin has been the construction of a number of

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storage reservoirs; capacity in Basin reservoirs is now four times the mean annual inflow, sufficient to provide carryover storage for many years. Recognizing that values in consumptive uses may vary by factors of ten or more within the Basin (Booker and Colby, 1995), advocates of water markets have pointed to potential gains from trade as an additional or alternative approach to dealing with Basin water scarcity. In response, some Basin states (e.g., California, in response to drought) have introduced limited water "banks," or markets to more efficiently distribute limited supplies. Griffin and Hsu (1993) point out, however, that in the absence of institutions representing instream flow values, water markets will likely fail to maximize economic benefits from trade.

Our second purpose is to investigate potential benefits from relaxing the assumption that drought would be managed under existing rules. In addition to suggested management, alternatives consistent with the current general policy framework known as the Law of the River (e.g., MacDonnell *et al.*, 1995), policies altering traditional water rights structures, those which reserve water for instream uses, or those allowing interstate consumptive use markets are investigated.

An integrated hydrologic-economic-institutional model (CRIM, the Colorado River Institutional Model) for estimating the economic and hydrologic impacts of drought is first introduced. Second, model results are used to develop a detailed assessment of economic impacts of the severe sustained drought under the existing operating rules and policy (the Law of the River). The economic and hydrologic impacts reported are derived directly from the use of CRIM to model the severe sustained drought under this existing River management. Eight alternative policy responses to drought are then modeled. Drought impacts under each policy are critically examined, and several recommendations are provided.

MODEL DESCRIPTION

An integrated economic-hydrologic-legal model was developed for this study to estimate economic impacts of alternative water allocations and to investigate impacts of policy responses to drought. Termed the Colorado River Institutional Model (CRIM), it expands on an earlier Basin model reported by Booker and Young (1994) by adding more realistic hydrology, utilizing less aggregated economic data, and modeling with a richer set of institutional choices. While numerous recent modeling efforts examine economic impacts of variable flow levels in the Basin [see Brown *et al.* (1990), Oamek (1990), Lee *et al.* (1993), Brookshire *et al.* (1993), and Henderson and Lord (1995)], CRIM focuses on modeling the water allocation problem under a range of non-market and market-based institutions.

CRIM model components include 24 river nodes, seven reservoirs (including active and dead storage, evaporation, hydropower production and benefits, and flatwater recreation benefits), 32 consumptive use locations, two instream flow uses (Glen Canyon and Grand Canyon), and 14 inflow points. Figure 1 summarizes the model design.

Water allocation and economic benefits of water use are determined on an annual basis. Reservoir storage levels, including salinity loads, are carried from one annual time step to the next. The model is not forward looking, except to the extent that institutional allocation rules may include trigger points for water use reductions when reservoir storage or elevations decline below set levels. The sequential decision making followed by CRIM facilitates the modeling of existing Basin institutions and comparison with other Basin models. Hurd, Callaway, and Smith (RCG, Inc., Boulder, Colorado, 1995) have prepared a dynamic formulation of CRIM. Decision variables are generally limited to water use at all Basin locations, and reservoir releases. Flow and salinity levels, reservoir storage, and economic impacts are the state variables which describe the resulting system. CRIM is written in GAMS (Brooke *et al.*, 1988) and solved using its MINOS nonlinear solver. A typical simulation of a 38-year drought sequence requires 30 minutes using a Gateway 486 DX-33.

Nine alternative policy responses to drought were developed within CRIM, including, as the base case, the existing "Law of the River." Each individual policy response could generally be instituted at any time; several are independent and could be utilized in combination. In the work described below, policy responses are investigated when hydrologic conditions reach predetermined trigger points.

CRIM Under the Law of the River

CRIM is formulated as an optimization problem, nonlinear in the objective function and constraints. Hydrologic and economic factors are included as constraints, while institutional factors are primarily (though not exclusively) simulated in the objective function. Colorado River Basin water resources are allocated under a complex set of interstate compacts, federal laws, court decisions, administrative rules, and a treaty between the United States and Mexico, known collectively as the Law of the River. The set of allocation rules can be interpreted as determining a priority system for the use of Basin water resources.

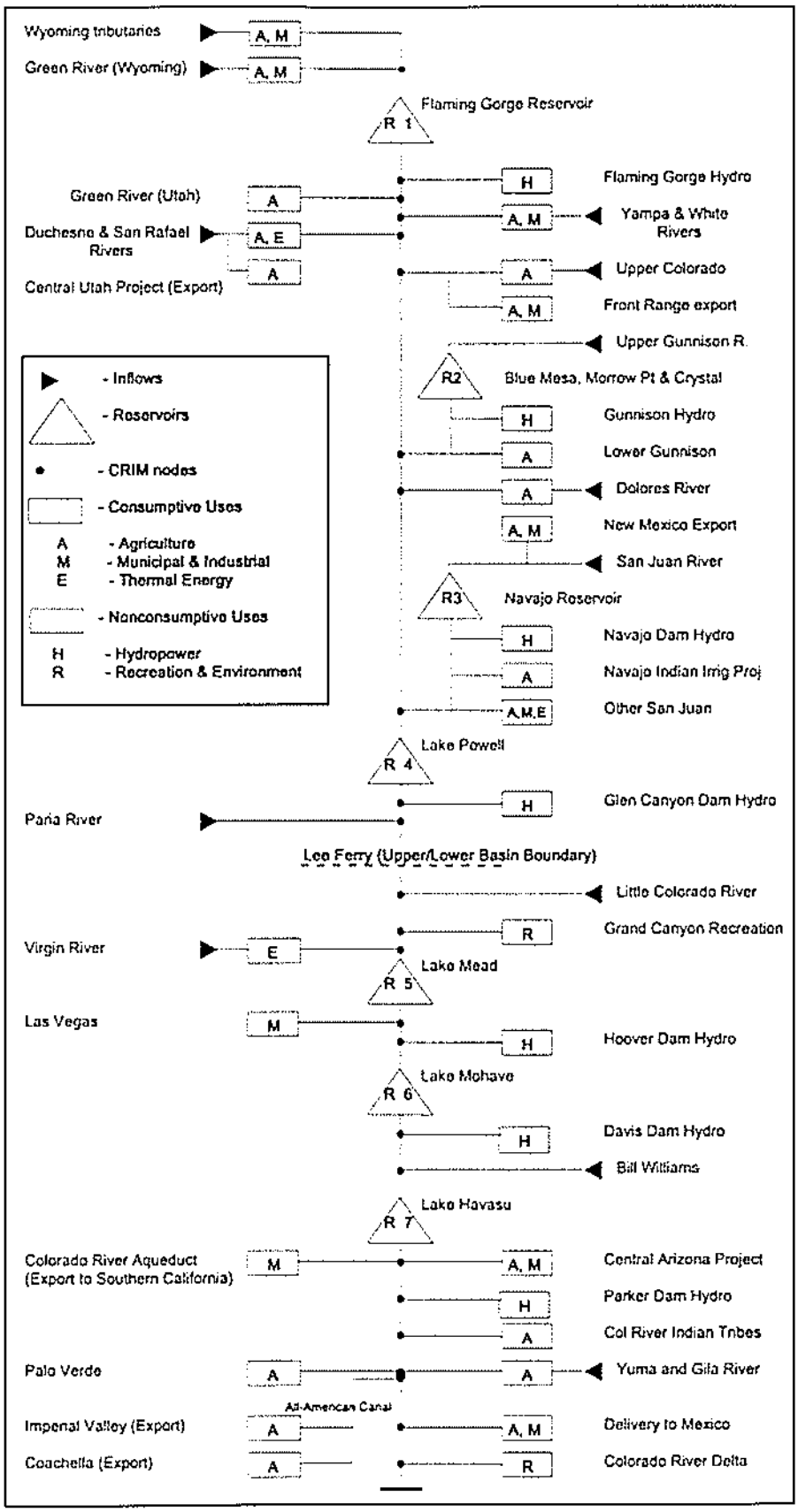

Figure 1. Colorado River Basin as Represented by the Colorado River Institutional Model (CRIM).

The set of priorities utilized by CRIM can be summarized as follows, from highest to lowest priority:

1. Mexican delivery obligation.
2. Upper Basin consumptive use rights perfected prior to the 1922 Colorado River Compact.
3. Lee Ferry delivery ("annual objective release");
4. Remaining Upper Basin consumptive use.
5. Lower Basin consumptive use, exclusive of priorities (6) and (8) below.
6. Metropolitan Water District (MWD) surplus diversions.
7. Storage in Lake Mohave and Lake Havasu.
8. Central Arizona Project (CAP) normal diversions (surplus diversions are not modeled).
9. Upper Basin storage.

Objective Function. The priorities for use of Colorado River water resources under the Law of the River policy lead directly to one form of the objective function $V(X_p, X_u)$ used by CRIM:

$$V(X_p, X_u) = \sum_p \alpha_p X_p - \beta T_u \left[\left(\sum_s (X_s - \rho_s X_u)^2 \right) \right]^{1/2} \tag{1}$$

where X_p is the annual "use" (consumptive use, instream flow, or addition to storage) associated with priority p, X_s is the annual consumptive use level for each Upper Basin state s, X_u is the total annual consumptive use by all Upper Basin states, ρ_s is the percentage allocation to each under the 1948 Upper Colorado River Basin Compact (Upper Basin Compact), and T_u is the total annual shortfall to Upper Basin consumptive users. Arizona's Upper Basin uses of up to 50 thousand acre-feet (kaf) per year are not included, given the seniority of such use under the Upper Basin Compact. The weighting constants α_p and β, are based on the priorities p listed in the previous section. The constants are ordered such that $\beta > \alpha_p$ and $\alpha_p > \alpha_{p+1}$, where priority (seniority) decreases with increasing p. The square root of the last term in Equation (1) is taken to facilitate convergence of the solution algorithm. Changes utilized under specific alternative policy responses are described below.

If Upper Basin consumptive uses cannot be fully satisfied, then $T_u > 0$ and consumptive use in each state is based on its share under the Upper Basin Compact. Arizona's Upper Basin annual use is the smaller of 50 kaf or its full request for Basin water. Proportional reductions across all uses within each state are required when requests for Basin water cannot be fully satisfied. So-called "prior perfected rights" existing prior to the full Basin Colorado River Compact are protected by placing a constraint on Upper Basin use $X_u \geq \bar{X}_u$ where $\bar{X}_u$ is set at the estimated annual level of such rights of 2,000 kaf. Water use in southern California by the MWD above its existing water rights (including transfers from the Imperial Irrigation District and the Palo Verde Irrigation District) is not permitted unless surplus conditions (total storage above 25.0 maf) prevail in Lake Mead. Similarly, annual deliveries to Arizona's Central Arizona Project (CAP) are limited to 450 kaf when the elevation at Lake Mead is less than 1095 feet (shortage conditions).

Annual reservoir releases for consumptive use or storage at downstream reservoirs are determined by the so-called equalization rule. This is implemented by a set of constraints which give priority to Lower Basin storage, while requiring equal proportional drawdown of Upper Basin reservoirs.

Hydrologic Constraints. Water and salt flows as well as reservoir water and salt levels are dependent on water and salt inflows, and on water use and reservoir levels, the decision variables. Mass balance constraints give annual water flows Q_i (kaf/year) leaving node i

$$Q_i = Q_{i-1} + q_i + R_i - X_i \tag{2}$$

where q_i and R_i are net inflows and reservoir releases between i and i-1, respectively, and X_i is the total consumptive use (including exports) from i. Mainstem withdrawals and return flows are not explicitly modeled using this framework; this is a reasonable approximation here, where withdrawals are small relative to total flow levels and return flows occur near the point of withdrawal. Net reservoir releases R_i are the difference between the initial active storage levels minus evaporation, and final active storage levels in each annual time step.

Salt flows (thousand tons/year) are estimated using a similar mass balance approach assuming constant salt inflows over time. Consumptive uses within the Basin thus neither contribute to nor diminish salt loading, although salinity concentrations increase with consumptive use as dilution decreases. While unrealistic, there is little systematic data on the relationship between water use (or withdrawals) and salt loading for the full Basin. For an illustration of the relationship between water use practices and resulting salt loading for one specific Basin location, the Grand Valley in Colorado see Gardner and Young (1988). Full mixing of salts in Basin reservoirs is assumed during any given year.

Intertemporal Model Operation. The storage capacity of Basin reservoirs is approximately 60 maf, four times the total average annual inflow to the Basin. Carryover storage from one year to the next is the critical reservoir function in the context of this study. Intertemporal reservoir accounting is maintained by calculations outside the optimization model to reduce model nonlinearities. Reservoir active and dead storage levels are utilized prior to each annual optimization to calculate elevations and areas. Elevation and area are in turn used to estimate annual evaporation and average hydropower heads, respectively. The optimization model is then solved using fixed evaporation and heads, together with the inflow and depletion requests for the particular year. Reservoir water and salt levels given by the model solution are then used to determine the new inputs for the following year's optimization problem.

Reservoir Area and Elevation Calculations. Reservoir areas and elevations are calculated before each optimization using formulas derived from those used in the USBR (1986) Colorado River Simulation Model (CRSM). A simplified piecewise approach was utilized for both area and elevation calculations. Above dead storage contents, a single quadratic approximation to the piecewise cubic fits used by CRSM was made. A single linear approximation was used below dead storage levels. Critical reservoir elevations and contents (dead storage, minimum power pool, maximum power, and maximum storage) reported by the Upper Colorado River Commission (1992) were used.

Use of Existing Basin Databases. Three Basin databases are utilized by CRIM. Depletion requests initially developed by USBR (1991) and discussed in detail by Booker and Colby (1995), drought inflows to 29 Basin locations (Tarboton, 1995), and historic salt levels at 20 Basin locations reported under the Colorado River Basin Salinity Control Program comprise the hydrologic data.

Depletion Requests. Present and future requests for consumptive use depletions by Basin users follow the USBR's CRSM water demand and inflow data sets (USBR, 1991), adjusted to reflect reasonable future conditions (Booker and Colby, 1995). High, medium, and low projections of future depletion requests were made based on assumptions of Basin population growth, agricultural water use, and demand for energy products. The medium scenario used for the simulations reported here reflects the USBR depletion projections with three major exceptions. Requests for agricultural water depletions are projected to remain constant at present levels. Central Arizona Project annual diversions are limited to 450 kaf under Lower Basin shortage conditions. Las Vegas requests for diversions are assumed to grow without institutional bounds based on projected population levels.

Depletion requests in the basic data set are given for 256 distinct depletion points. These points are aggregated to a total of 32 consumptive use locations for use in CRIM. Attributes associated with each use are Upper or Lower Basin, state, Basin use or export, type of use (agricultural, municipal, energy), and economic demand function. The demand function is specified on a consumptive use basis. CRIM scales the total benefit function associated with each economic demand function to a depletion schedule as described by Booker and Colby (1995). Table 1 summarizes the consumptive use depletion points and their attributes.

TABLE 1. Attributes of Colorado River Consumptive Use Locations in the Colorado River Institutional Model (CRIM).

Depletion	Primary Use[1]	Location[2]	Economic Demand Function
WYa1	A	UB	Wyoming Agric
WYa2	A	UB	Wyoming Agric
WYm2	E	UB	Energy
UTa1	A	UB	Utah Agric
WYa3	A	UB	Wyoming Agric
COa1	A	UB	Colorado Agric
COe1	E	UB	Energy
UTa2	A	UB	Utah Agric
UTa3	A	UB	Utah Agric
UTe1	E	UB	Energy
COa2	A, X	UB	Front Range Agric
COm2	M, X	UB	Front Range Muni
COa3	A	UB	Colorado Agric
COa4	A	UB	Colorado Agric
COa5	A	UB	Colorado Agric
COa6	A	UB	Colorado Agric
AZub	A	UB	New Mexico Agric
NMa1	A, X	UB	San Juan-Chama Agric
NMm1	M, X	UB	San Juan-Chama Muni
NMa2	A	UB	NIIP Agric
NMe1	E	UB	Energy
NMa3	A	UB	New Mexico Agric
VNe1	E	LB	Energy[3]
NVm1	M	LB	Las Vegas Muni
CAm1	M, X	LB	MWD Muni
AZa1	A, X	LB	CAP Agric
AZm1	A, X	LB	CAP Muni
AZa2	A	LB	Col River Indian Tribe Agric
CAa1	A	LB	California Agric
CAa2	A, X	LB	California Agric
CAa3	A, X	LB	California Agric
AZa3	A, X	LB	Yuma Agric

[1]A=agriculture, M=municipal and industrial, E=thermal energy, X=export from the Basin.
[2]Use is located in the Upper Basin (UB) or the Lower Basin (LB).
[3]Virgin River use, primarily in Utah.

Water and Salt Inflows. The 29 water inflow points used by CRSM (USBR, 1991), aggregated to 14 inflow locations, are used by CRIM. A drought sequence developed by Tarboton (1995) and described below was utilized. Basin salt inflows were estimated from the average historical salt loads at 20 Basin locations reported by U.S. Department of Interior (1989). Salt loads are converted to inflows for use by CRIM and then aggregated to the 14 source locations utilized for water inflows. Variation of salt inflows with water level was not investigated.

Model Verification

CRIM provides annual estimates of water use and benefits, flows, storage, and evaporation which closely match those of Hydrosphere's Colorado River Model (Harding *et al.*, 1995), which in turn follow those of USBR's CRSM model. Reservoir storage is a sensitive measure of overall model performance because systematic differences in consumptive use estimates or aggregate Basin evaporation are integrated over time. Figure 2 compares CRIM and Colorado River Model (CRM) estimates of total storage in the major Basin reservoirs (Lake Powell and Lake Mead) when hydrologic inputs and requests for consumptive use depletions are identical, using the 38-year drought sequence described below. The CRIM estimate of increasing reservoir depletion lead those of CRM by less than one half year at year 20. In the final year of the modeled drought (year 38), the CRIM estimate of Basin storage is within 6 percent of the CRM estimate. The small differences which occur are related to differing interpretations of CAP deliveries under shortage conditions.

IMPACTS UNDER THE LAW OF THE RIVER

Drought impacts under the Law of the River are presented in this section. Three distinct drought periods are identified, with specific impacts characterizing each period. Hydrologic impacts are summarized to provide a context for interpreting economic impact estimates. Damages to consumptive uses from the severe and sustained drought and total drought damages, including hydropower production losses, recreation losses, and salinity damages, are presented.

Severe and Sustained Drought Impacts Under the Law of the River

The single drought utilized in this study is embedded in the 38-year flow sequence discussed in detail by Tarboton (1995). The sequence represents one estimate of the worst extended drought occurring during the past 500 years. The average annual

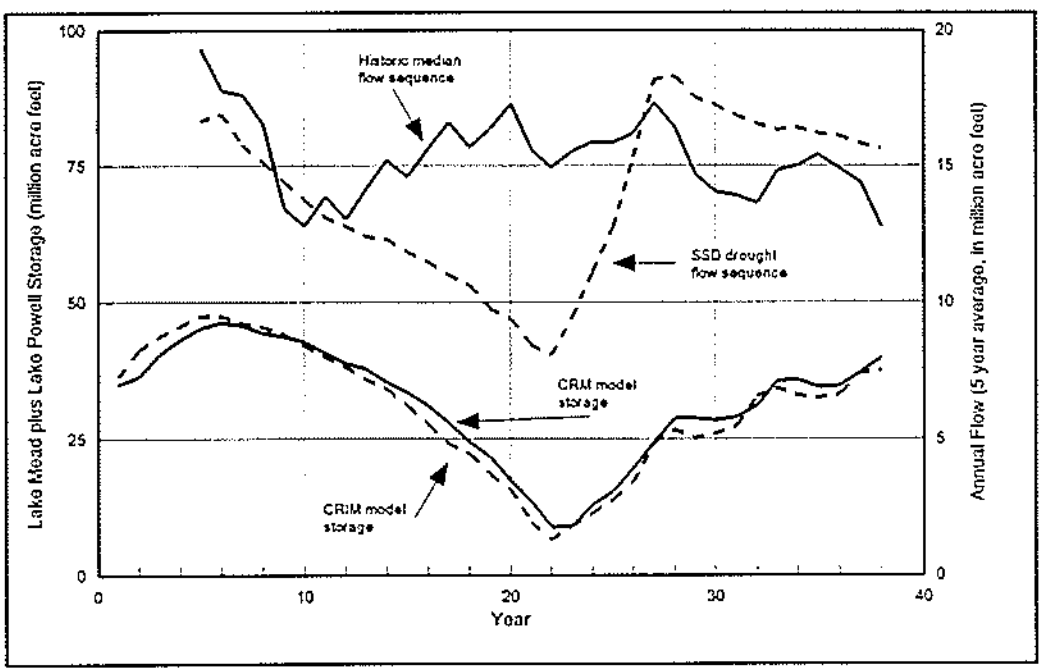

Figure 2. Severe and Sustained Drought (SSD) Flow Sequence (top, right scale) and the Resulting Combined Lake Powell and Lake Mead Contents from CRIM and CRM (Harding *et al.*, 1995).

naturalized flow over the full sequence is 14.2 maf/year, compared to 15.4 maf/year for the median 38 years from the historical record (Figure 2). However, Basin inflows average only 9.3 maf/year in the driest 10 years of the drought sequence. Economic impacts are summarized in Figure 3.

Baseline: Years 1 through 9

The initial nine years of the full 38-year drought sequence serve as a base period for establishing typical hydropower and recreation benefits and salinity damages. Basin inflows average 15.5 maf/year, while storage in Basin reservoirs increases from 46 maf to 52 maf, with a peak of over 56 maf in year 6. Benefits of hydropower production average roughly $600 million per year during this period, while recreation benefits average $500 million. Damages to consumptive water users (agricultural and municipal) from salinity average $250 million per year. These levels give representative benefits and damages from nonconsumptive use of Colorado River water resources under typical river conditions and establish a base level of benefits and costs for use in measuring

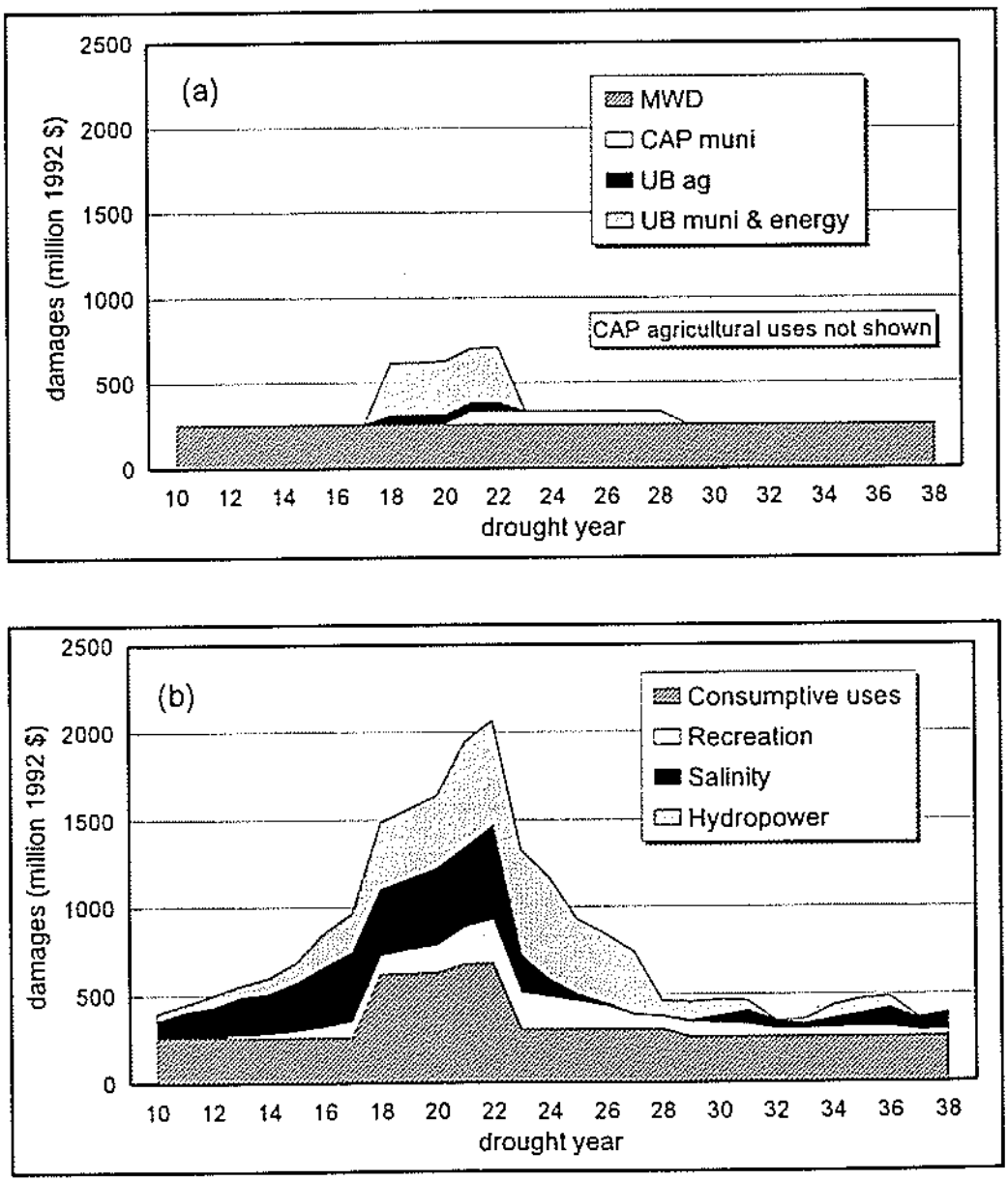

Figure 3. Consumptive Use (a) and Total Economic Damages (b) Under the Law of the River.

actual drought damages during years 10 through 38 of the drought sequence.

Consumptive uses are generally satisfied in full during years 1 through 9. The single exception is consumptive use by southern California municipal users served by the Metropolitan Water District (MWD). At no time during the period are surplus conditions present in Lake Mead; as a result, deliveries to MWD are limited to senior rights only. The total shortfall to MWD gradually decreases from year 1 to year 9 as water made available from Imperial Irrigation District irrigation efficiency improvements and from the All-American canal lining project become available. By year 9 these projects are fully implemented, leaving a chronic shortfall to MWD of 636 kaf per year and resulting in damages estimated at $258 million annually.

Early Drought: Years 10 through 16

Basin inflows average only 11.8 maf per year during this initial phase of the drought. Basin storage is reduced from 50 maf in year 10 to 29 maf by year 16, with 87 percent of the storage loss occurring in the Upper Basin. Strikingly, active storage in Lake Powell is nearly exhausted (reduced to 4 maf, 15 percent of capacity) at the end of year 16. This loss of storage is a critical factor in shortfalls to Upper Basin users in subsequent years.

Consumptive Uses. Despite the dramatic loss of Upper Basin storage, the only shortfall to Basin consumptive uses remains the chronic shortfall to MWD. All other lower and Upper Basin depletions are satisfied in full.

Hydropower. With decreasing reservoir elevations and reduced flows, hydropower production falls throughout the period. The loss of hydropower heads results in a decrease from year 10 to year 16 in the marginal value of Upper Basin water for hydropower production. Total Basin hydropower production is reduced 29 percent by year 16 compared to base levels (Table 2).

Recreation. Damages to recreational users, primarily flatwater boaters at Upper Basin reservoirs, become significant by year 16 as Upper Basin storage is largely exhausted. Total Basin recreation benefits are reduced by 12 percent ($60 million) in year 16 relative to the base period, but these damages are unevenly distributed: benefits to boaters on Lake Powell are reduced 49 percent.

Salinity. Salinity concentrations slowly rise over the drought period as reduced flows concentrate salt loads. While reservoir storage buffers increases in any given year, a seven-year period of low flows results in both elevated river and reservoir salinity levels by year 16. Concentrations would likely exceed the Basin salinity standards adopted in 1976 of 723 mg/l below Hoover Dam and 879 mg/l below Imperial Dam. By year 16 damages to consumptive users from elevated salinity could exceed $300 million per year relative to the base level.

Critical Drought: Years 17-22

During the critical, severe period of the drought, Basin inflows average only 8.4 maf per year, never exceeding 10 maf in a given year. The Upper Basin is poorly prepared for these dramatic flow reductions, as

TABLE 2. Hydropower Production at Basin Reservoirs During Severe Sustained Drought Sequence (1992 dollars).

	Value of Power Generation (million $)			Marginal Value of Instream Flow ($/af)		
Hydropower Plant	Base Period	Year 16	Year 19	Base Period	Year 16	Year 19
Flaming Gorge	28	24	0	20.6	16.6	0
Curecanti Unit*	97	0	0	46.9	0	0
Navajo	32	0	0	17.7	0	0
Glen Canyon	239	172	0	27.1	20.9	0
Hoover Dam	204	210	197	24.7	24.0	23.0
Parker Dam	48	50	49	5.9	5.9	5.9
Davis Dam	24	24	24	3.4	3.4	3.4

*Composite of Morrow Point, Blue Mesa, and Crystal Dams.

storage was greatly reduced during the previous period of below normal flows. The Lower Basin retains significant storage to meet most of its requests for consumptive use. Instream uses are severely affected as very low flows occur and reservoir levels continue to decline.

Remaining Upper Basin active storage is exhausted in the first year of this critical phase. With insufficient inflows to satisfy consumptive users and meet the annual objective release of 8.23 maf from Glen Canyon Dam, Upper Basin uses are severely curtailed starting in year 18. In year 21, deliveries to CAP are reduced in a futile effort to protect power production at Lake Mead. By the end of year 22, storage in Lake Mead is nearly exhausted. Hydropower production is reduced to exceptionally low levels by year 21 as most power plants are rendered inactive by low reservoir levels. Table 3 summarizes drought damages to Basin consumptive users in year 21.

Consumptive Uses. Upper Basin consumptive uses lose up to 55 percent of requested depletions starting in year 18. Marginal damages are $630/af for thermal energy users with limited alternative supplies and $1,200/af for Colorado Front Range cities (e.g., Denver). Marginal damages suffered by agricultural users range from $58/af in Colorado for users with no alternative supplies to $23/af for New Mexico exports where Colorado River water is a supplemental supply source.

Lower Basin consumptive users are remarkably well protected from drought damages. CAP use is reduced by 665 kaf/year starting in year 21, a 60 percent reduction. Damages to CAP municipal uses (after inclusion of reduced CAP pumping costs) are estimated at $76 million annually starting in year 21. CAP agricultural users are also assumed to suffer reductions in CAP deliveries. From a national economic perspective, such reductions result in a net benefit of

TABLE 3. Consumptive Use Damages, Year 21 of the Severe Sustained Drought (1992 dollars).

Depletion Label	Consumptive Use (thousand af)	Proportion of Full Request)	Total Drought Damage ($ million)	Marginal Benefits ($/af)	Average Damages ($/af)
WYA1	51	0.49	1	37	21
WYA2	116	0.49	3	37	21
WYM2	55	0.49	16	483	271
UTA1	29	0.47	1	40	22
WYA3	53	0.49	1	37	21
COA1	45	0.41	2	59	26
COE1	18	0.41	8	640	311
UTA2	104	0.47	3	40	22
UTA3	248	0.47	6	40	22
UTE1	59	0.47	19	521	281
COA2	98	0.41	3	31	21
COM2	217	0.41	230	1234	727
COA3	218	0.41	8	59	26
COA4	206	0.41	8	59	26
COA5	91	0.41	4	59	26
COA6	118	0.41	5	59	26
AZUB	50	1.00	0	12	NA
NMA1	19	0.45	0	23	17
NMM1	31	0.45	32	1543	846
NMA2	63	0.45	4	47	46
NME1	41	0.45	14	545	288
NMA3	69	0.45	2	49	24
VNE1	11	0.47	4	521	281
NVM1	258	1.00	0	367	NA
CAM1	703	0.53	258	720	406
AZA1	153	0.25	–26	–53	–57
AZM1	297	0.59	72	549	349
AZA2	565	1.00	0	14	NA
CAA1	831	1.00	0	27	NA
CAA2	2840	1.00	0	27	NA
CAA3	394	1.00	0	27	NA
AZA3	715	1.00	0	20	NA

NA = Not Applicable.

$26 million annually because costs of pumping CAP water exceed the income produced by CAP agriculture.

Hydropower. By year 19, hydropower production is significantly reduced following the loss of the Flaming Gorge and Glen Canyon power plants to declining reservoir levels (Table 2). By year 21, Lake Mead also falls below the minimum power pool level necessary for power production, and total Basin production is reduced to only 10 percent of typical levels. The economic damage from lost production in the full Basin is estimated at just over $600 million annually.

Recreation. Damages to recreation users increase throughout the period as reservoir levels decline. The total loss of benefits relative to the base period reaches over $250 million by year 22 as most reservoirs are nearly depleted. Significantly, Lake Mohave and Lake Havasu maintain storage levels at capacity, preserving benefits to flatwater boaters of over $140 million in year 22.

Reduced instream flows decrease the value of whitewater rafting trips in the Basin. At the single site included in our model, the Grand Canyon, rafting benefits are reduced 75 percent to $2.4 million per year in year 21, as flows through the Grand Canyon are reduced from a typical 9 maf per year to only 2.5 maf/year. Grand Canyon fishing is less affected, with benefits reduced 30 percent to $0.4 million per year.

Salinity. Damages to consumptive users from salinity continue to increase as salinity levels rise throughout the critical drought phase. Levels up to 50 percent above the Basin salinity standards below Hoover and Imperial Dams are likely. Salinity levels in water delivered to Mexico would likely exceed 1400 mg/l. Damages to U.S. consumptive users could approach $500 million per year.

Recovery: Years 23-38

Basin inflows of 16.8 maf/year during the recovery period are almost exactly double those during the critical drought years 17 through 22. Reservoir storage levels are slowly rebuilt starting in year 23, while consumptive use returns quickly to near normal levels. With little high salinity water in storage, Basin salinity levels are also projected to return quickly to normal levels.

Consumptive Uses. With inflows exceeding 16 maf per year in years 23 through 28, Upper Basin use returns immediately to the full level of requested depletions while still allowing an annual release at Glen Canyon Dam of 8.23 maf, and additional water to rebuild storage levels. Additional Upper Basin releases to compensate the Lower Basin for reduced deliveries during the critical phase are not required by CRIM. Such releases might be required under the 1922 Compact, in which case damages to Upper Basin consumptive users would persist for several additional years. Diversions by CAP remain at low levels until year 28 due to low storage levels at Lake Mead.

Hydropower. Hydropower production returns to normal after 10 years of the recovery. The initial high flows do little to immediately restore production, however, as most plants remain inoperative due to low reservoir levels.

Recreation. Recreation benefits similarly return slowly to normal levels, with damages of nearly $200 million per year persisting for several years. Refilling of Basin reservoirs is the critical factor in returning flatwater recreation benefits to normal levels. With consumptive uses at high levels, reservoirs remain depleted for a number of years despite the higher than average inflows to the Basin.

Salinity. Basin salinity levels dramatically decrease in the first year of high flows. Because little (high salinity) water remains in storage, the dilution effects of the high flows are particularly strong. Further, depleted Basin reservoirs refill with low salinity water. By year 27, five years into the recovery, salinity concentrations return to levels typical of the base period.

Summary of Drought Impacts Under the Law of the River

A severe sustained drought of the type which might occur in the Colorado River Basin every 500 years would result in the following under the existing institutions allocating use of Basin water resources:

1. Exhaust virtually all Upper Basin water storage.
2. Greatly reduce hydropower production at Upper Basin power plants and reduce opportunities for Upper Basin flatwater recreation. Total impact: nearly $500 million in direct economic damages annually for up to seven years.
3. Leave Upper Basin consumptive users vulnerable to severe supply shortfalls. Such shortfalls could result in direct economic damages of $400 million annually for several years.
4. Potentially deplete Lower Basin storage, with further hydropower and recreation losses of $300 million annually for up to six years.

5. Result in salinity levels in Lower Basin drinking and irrigation water significantly above any experienced since construction of Hoover Dam, and which exceed existing Colorado River standards.

Sensitivity to Model Assumptions

A large number of specific assumptions are necessary in a modeling effort of this scale. Some assumptions may directly affect model results, while others may be relatively innocuous. The sensitivity of the results presented in the previous section to several specific model assumptions are discussed here.

Choice of Model. Three modeling systems were utilized in the study of the severe sustained drought reported in this issue. While each model provided particular advantages, consistent predictions of the effect of a severe sustained drought on the Basin were found across models. For example, Figure 2 compares reservoir storage when the CRIM and CRM models (Harding *et al.*, 1995) use identical depletion data. The CRIM model is particularly useful for comparing the performance of alternative policy responses to drought. Because CRIM is a partial equilibrium model, its direct damage estimates should be treated with caution. More importantly, uncertainty in the underlying benefit functions for various uses, particularly at large reductions from full supply levels (e.g., ≥ 50 percent) where damages are not well understood implies that CRIM damage estimates should be treated as provisional.

Drought Definition. The drought utilized in this study is precisely defined by a 38-year hydrologic inflow sequence, together with initial reservoir conditions. One major result is the virtual emptying of Upper and Lower Basin reservoirs. Upper Basin reservoirs are depleted first, followed by the drawdown of Lake Mead. Hydropower and recreation losses occur throughout the period of lowered reservoir levels, while consumptive use shortfalls are limited to the period (and immediate aftermath) of extremely low flows. The precise magnitude and timing of hydropower and recreation damages are sensitive to the inflow levels used in the drought sequence, and to reservoir initial conditions. Upper Basin hydropower and recreation damages discussed above would occur even with initial storage at capacity given this study's drought sequence. Similarly, damages of similar magnitude would occur if our initial reservoir conditions and a somewhat less severe though similarly sustained drought sequence were used. One robust conclusion is that the first and inevitable drought impact under the Law of the River is a reduction in Upper Basin storage.

The duration of consumptive use shortfalls (and to a lesser extent their magnitude) and the minimum Lower Basin reservoir levels reached during the drought are highly sensitive to the precise drought inflows and initial reservoir storage. The sequence of low flows is less important, though reductions in Upper Basin use when Upper Basin storage is exhausted are greatly reduced as inflows approach normal levels.

Consumptive Use Levels. Just as small changes to inflow levels impact consumptive use shortfalls, such shortfalls are highly sensitive to total consumptive use levels. For example, if actual Upper Basin consumptive use were just 10 percent below that given by our depletion request data, Upper Basin shortfalls would be delayed by two to three years, and the total period of critical shortfalls would be reduced from five years to perhaps two years. Economic damage estimates assume that consumptive use shortfalls within Upper Basin states occur across all uses. To the extent that this does not hold and higher valued uses have relatively senior (junior) rights, drought damages are overstated (understated).

Salinity. Modeling Basin salt levels includes numerous uncertainties. Quantitative estimates of future salinity levels under drought may contain large errors. Water stored in Basin water clearly buffers salinity increases during low inflow periods and would tend to slow reductions in salinity levels during high inflow periods. In the extended drought presented here, little stored water remains when high inflows return to the Basin. The estimated rapid recovery from high salinity levels is a direct consequence of such low storage levels; if minimum storage levels were in fact greater, high Basin salinity concentrations would persist over a longer time period. Salt inflows during periods of greatly varying water inflows are not well understood. Further, salt loading from human sources when consumptive use is temporarily reduced is difficult to estimate Basinwide. These uncertainties suggest that Basin salinity estimates should be treated with extreme caution.

One approach to estimating salinity levels when storage is virtually exhausted is to review historical salinity records prior to the closing of Glen Canyon Dam. Such records (U.S. Department of Interior, 1989) suggest that large annual fluctuations in levels would occur, with peak monthly concentrations reaching 1,400 mg/l at Lees Ferry. Because inflows during the most critical years of our study drought are significantly below the historical conditions during which peak salinity concentrations were measured, river

salinity concentrations greater than 1,400 mg/l would be likely.

Economic Valuation. Drought damage estimates rely on model estimates of physical impacts (e.g., consumptive use reductions or loss of hydropower production) together with valuation estimates. The sensitivity of physical impacts to alternative model assumptions is discussed above. Increases or decreases in the estimated marginal value of water uses at full deliveries would result in similar proportional increases or decreases in damage estimates. For example, if Lower Basin hydroelectric power were valued 50 percent above the estimate of 47 mills/kwh (Booker and Colby, 1995) used here, then damages to Lower Basin hydropower users would be 50 percent greater than reported. Increases or decreases in assumed price elasticities of demand could generate much greater differences in estimated damages. Similarly, drought damage estimates are highly sensitive to the availability of non-Colorado River supplies.

DESCRIPTION AND IMPACTS OF ALTERNATIVE POLICY RESPONSES

Damages which result from drought are dependent on the particular water management policies in place during all phases of the drought. The impacts reported above under the existing Law of the River assume static policies throughout the severe sustained drought. This is unrealistic. While the particular policies which would be adopted under such conditions are unknown, a major purpose of this study is to report on the impacts of alternative policies which could plausibly be adopted. We introduce first a number of specific policies which have been proposed as responses to water shortfalls in the Basin. Some policies are potentially complementary: adoption of one would not exclude adoption of a second policy. Others are mutually exclusive and could not be simultaneously implemented. No single ideal policy is identified. Some of the proposed policies were found to be effective in reducing drought impacts, while others (sometimes surprisingly) have little effect or increase damages.

Policy responses to drought can be grouped into three categories based on the general approach: river management, legal environments, and market based. Within each category both state and regional responses may be possible. The specific individual policies investigated for this study are briefly described below, together with a summary of drought damages under each policy response. The objective function used in CRIM remains Equation (1) unless otherwise stated.

River Management Responses

Ten-year Average Delivery at Lees Ferry. Existing operating rules set by the Secretary of the Interior require an "annual objective release" from Glen Canyon Dam of 8.23 maf to satisfy Upper Basin obligations under the Colorado River Compact. During periods of low flows, this required release inevitably leads to the drawdown of Lake Powell, though Lake Mead storage may remain close to capacity. A fixed annual release is not required under the Compact (MacDonnell *et al.*, 1995) and may thus lead to Upper Basin shortfalls during a sustained drought which might otherwise not occur. The requirement for a fixed annual release is changed to a 10-year delivery requirement of 75 maf, consistent with the Compact, plus an additional 7.5 maf per 10 years to satisfy the Upper Basin's Mexican delivery obligation. Equalization of storage in Mead and Powell is also added as a priority when it does not conflict with Compact deliveries. Note that the previous equalization rule could only cause releases from Powell to increase storage in Mead. The changes are implemented for the full 38-year drought sequence.

The impact of these two changes is to allow releases from Powell in a given year of less than 8.23 maf, thus preserving Upper Basin storage when it is below Lower Basin levels. Figure 4 shows this effect starting in year 7; it is important through year 12. After year 12, these lower than normal deliveries must be "paid back," however. This occurs in years 13-17. In years 18-26 the Compact is not satisfied: 10-year average deliveries fall below 8.23 maf/year.

Impacts under this policy response demonstrate an important result: the annual objective release of 8.23 maf does not cause the draining of Lake Powell. Rather, a failure (perhaps inevitable) to reduce Upper Basin use during moderate drought conditions causes the loss of storage. Damage to Upper Basin users inevitably follows when the drought does not end, and the senior rights of the Lower Basin must be satisfied. Indeed, forcing the annual objective release results in a quicker recovery from drought (year 23 of the base policy, though the Lower Basin could argue that the Compact is violated in this case by not requiring higher deliveries) than would this representation of the Compact (where Upper Basin use does not return to full levels until year 26.) Hydropower production is somewhat higher with this policy as reservoir levels are generally slightly higher; this result does not hold in all years, however.

Given a Lower Basin senior right of 7.5 maf/year, plus senior deliveries to Mexico, a loss of all but "present perfected rights" (rights prior to the 1922 Compact) for several years is inevitable in the Upper

Basin. The details of how the Compact is implemented are not particularly important. Only preemptive reductions in Upper Basin use as Powell is depleted would be helpful. Given the severity of the drought, however, no likely policy of early reductions in use could prevent the draining of Powell and hence severe reductions in Upper Basin use.

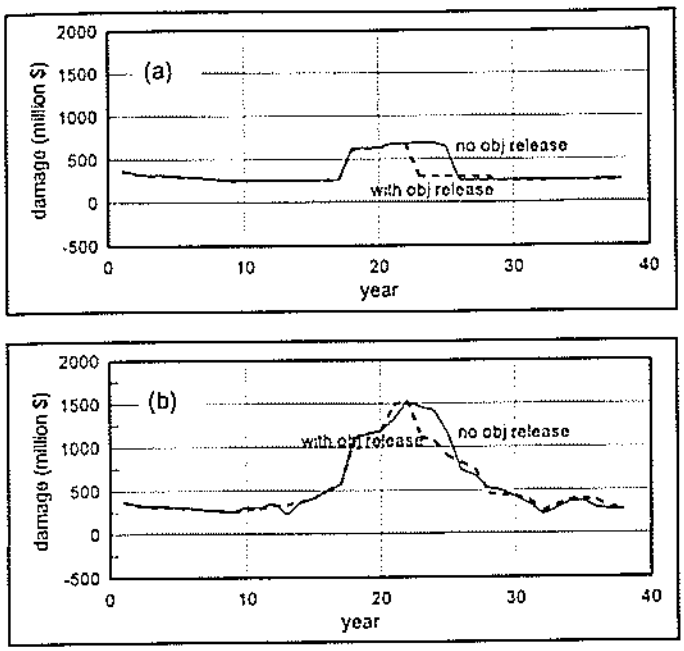

Figure 4. Consumptive Use (a) and Total Economic Damages (Excluding Salinity) (b) with a Ten-year Average Delivery Requirement at Lees Ferry (i.e., no annual objective release).

Basin Reservoir Management. Evaporation losses at Basin reservoirs vary dramatically. Evaporation from mountain reservoirs is little over 1 foot/year, while that from Lake Havasu exceeds 6 feet/year. Because existing reservoir management favors storage at Lower Basin locations, reductions in evaporation losses should be possible through changes in management rules to emphasize storage in Upper Basin locations. Specifically, under this "store high" response, water is preferentially stored at high-elevation reservoirs. Managing Basin reservoirs using this rule would require suspending Compact-related delivery requirements at Lees Ferry. Compact allocations, however, could be maintained through appropriate accounting rules tracking storage for Upper and Lower Basin use, regardless of storage location. The change is implemented for the full 38-year drought sequence.

Reducing evaporation losses through preferential storage in Upper Basin reservoirs eliminates most drought-induced shortfalls to consumptive users (Figure 5). The small annual savings achieved by this policy occurring over the many years of the drought sequence result in several additional years of drought protection. Significant supply shortfalls would occur, however, were the critical phase of the study drought to extend even a single additional year, as total Basin storage falls to 2.3 maf in the final low flow year. The policy is thus highly effective at achieving small annual savings, resulting in a significant increase in the consumptive use drought protection provided by Basin reservoirs. Total damages across all uses (Figure 5) are not as effectively reduced as are consumptive use damages. In all but the critical drought years, total damages under this policy are greater than under the Law of the River, largely because of recreation and hydropower losses as Lower Basin reservoir levels are drawn down. These could be largely mitigated (in non-critical years) by maintaining storage near capacity in Lakes Mohave and Havasu, while limiting Lake Mead drawdown to maintain hydropower production. Such a hybrid policy was not modeled in this study.

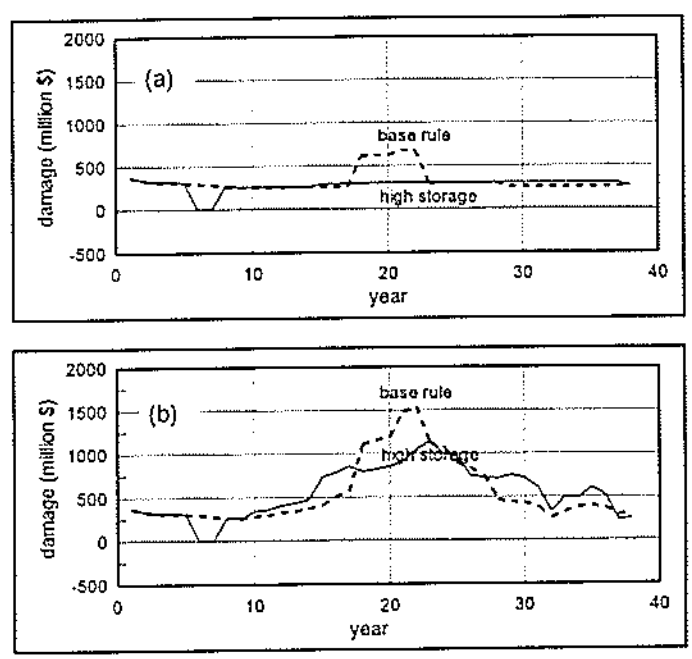

Figure 5. Consumptive Use (a) and Total Economic Damages (excluding salinity) (b) with "Store High" Management of Basin Reservoirs.

Storage for Hydropower Generation. Large losses in hydropower generation result from the severe flow reductions occurring under a severe drought. When the drought is a sustained event and reservoirs are drawn down below minimum power pool levels, hydropower production ceases. Such extreme depletion of reservoir storage occurs under existing reservoir management in the severe sustained drought studied here. Some hydropower generation could be maintained by limiting drawdown of each reservoir to the minimum power pool level. One consequence of such a rule would be a further reduction in consumptive uses, however. A constraint limiting drawdown to minimum power pool is added for the full 38-year drought sequence. An exceptional drawdown to 2 maf below minimum power pool is allowed at Lake Mead when total Basin inflows are less than approximately 8 maf and storage is already at minimum power pool.

Management to maintain minimum power pool levels more than doubled damages to consumptive users during two years of the critical drought phase, with some increased damages occurring over a ten-year period (Figure 6). Small increases in hydropower production over the base policy were found, but large hydropower (and recreation) damages were not avoided (Figure 6). Minimum power pools could not be maintained during several drought years, while the very low flows available during years 17-22 further limited hydropower production. This simple policy was not effective in reducing total drought damages.

Changes to Legal Environments

Proportional Sharing of Shortfalls. Restrictions on water use during shortfalls are presently based on priority systems: intrastate allocations are based on seniority, while the Lower Basin states taken together enjoy highest priority for the great majority of their use of Basin water. The consequence of such systems is uneven patterns of shortfalls. This result is the basis for one major criticism of priority systems. Individual users within states and the Upper Basin states taken together may experience severe shortfalls while others may be fully protected from consequences of drought. The exception to this rule is the proportional sharing of Upper Basin water shortfalls among the Upper Basin states of Colorado, New Mexico, Utah, and Wyoming. Following this example, shortfalls to Colorado River Basin consumptive users in a particular year are distributed among all users. This rule is applied in years where the total shortfall exceeds 1 maf.

Consumptive use damages from drought shortfalls were significantly reduced when shortfalls were proportionally imposed across all uses (Figure 7). Drought damages during years 17 through 22 were reduced to roughly 50 percent of levels estimated under the base policy. This significant reduction in damages occurred because municipal and industrial (M&I) users were better protected from drought than under the base policy. Benefits to M&I users significantly outweighed additional damages to agricultural users. Additional impacts to nonconsumptive users were minimal (Figure 7).

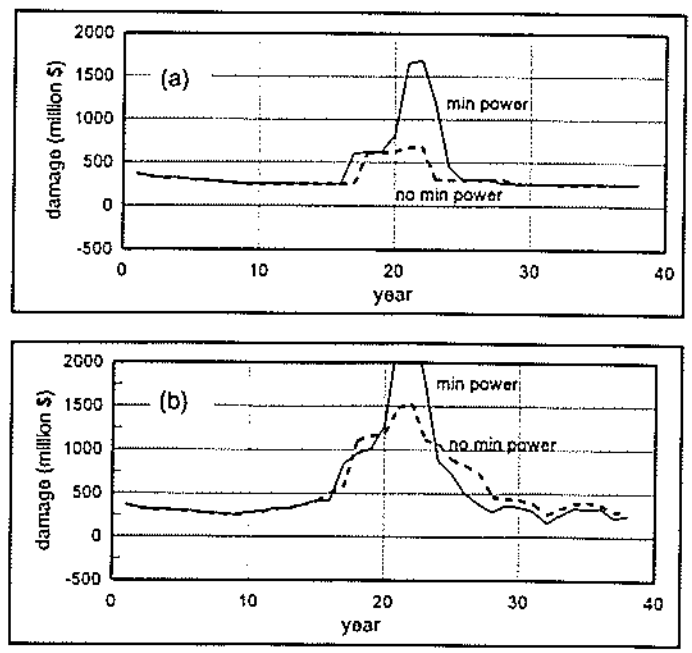

Figure 6. Consumptive Use (a) and Total Economic Damages (excluding salinity) (b) with Maintenance of Minimum Power Pools for Hydropower Generation.

Shifting Shortfalls to Agricultural Sectors. Many believe that water shortfalls are more economically damaging to M&I users than to agricultural users. If this is indeed the case, minimizing drought damages would require some shifting of shortfalls from M&I users to agricultural users. Following this logic and presuming that proportional reductions to agricultural users minimize drought damages, a change to legal rights which protect M&I users from drought while imposing proportional shortfalls on agricultural users is followed. The rule is applied in years where the total shortfall exceeds 1 maf.

If consumptive use shortfalls are shifted entirely to agricultural users (and distributed proportionally between such users), total consumptive use damages in years 17 through 22 are reduced by up to 85 percent (Figure 8). Further, such a policy would

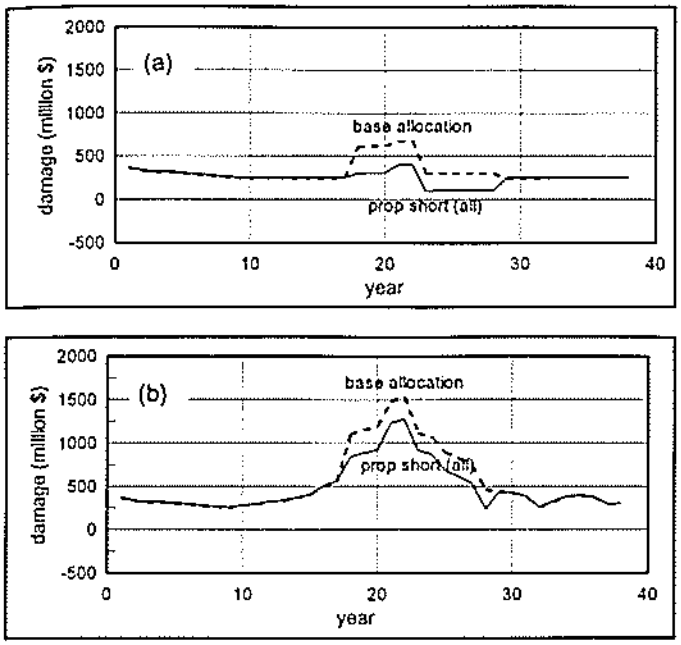

Figure 7. Consumptive Use (a) and Total Economic Damages (excluding salinity) (b) with Proportional Sharing of Shortfalls by All Users.

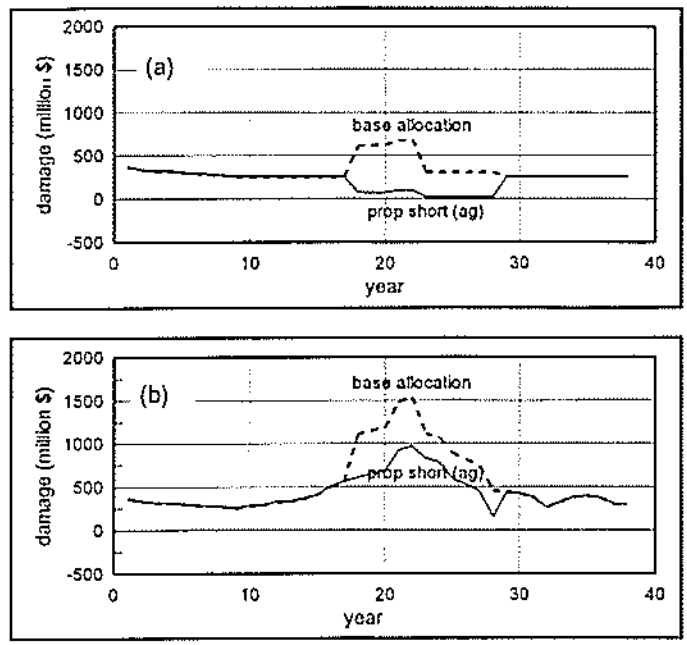

Figure 8. Consumptive Use (a) and Total Economic Damages (excluding salinity) (b) with Shortfalls Shifted to Agricultural Users.

greatly reduce damages from the chronic shortfall to MWD users (see years 21 through 28 where the policy remains in place.) Nonconsumptive use damages are largely unaffected by the policy (Figure 8). For limiting total Basin damages to consumptive users, however, this is a highly effective policy.

Market Based Policy Responses

Intrastate Water Banks. Results from gaming simulations (Henderson and Lord, 1995) suggest that state-level responses can be important in mitigating drought impacts. One approach is to reallocate state water allocations based on intrastate consumptive use values, using state water banks, or direct marketing of water rights between users. Water users are also required to pay full water delivery costs under this policy. Such policies can be implemented unilaterally by states. Intrastate water bank allocations are applied in all years using a second optimization in each time step (see Equation 5 below), with state allocation constrained to those determined by the Law of the River.

Short-term intrastate markets could reduce consumptive use damages in years 17 through 22 by up to 85 percent relative to damages under the base policy (Figure 9). Chronic damages to MWD uses would also be reduced through marketing by California agricultural users. CAP agricultural users would be unable to pay for pumping of CAP water; the result is a net benefit from the national economic perspective. Nonconsumptive use damages are largely unaffected by the policy (Figure 9). For limiting total Basin damages to consumptive users, this is a highly effective policy.

Interstate Consumptive Use Water Bank. Additional benefits from water marketing may remain if state-level transfers do not bring about similarly valued water uses across Basin states. If marginal values in consumptive uses differ greatly, then additional benefits from interstate water marketing are likely. An interstate consumptive use water bank is applied in years where the total shortfall to Basin users exceeds 1 maf. A water bank is simulated by allocating Basin water to maximize consumptive use benefits in each year. The CRIM objective function becomes in this case

$$V = \sum_{p} \left(V_p(x') - C_p(x') \right) \tag{5}$$

where $V_p(x')$ is the total benefit from use of Basin water x' at point p and $C_p(x')$ is the total conveyance and treatment cost at point p.

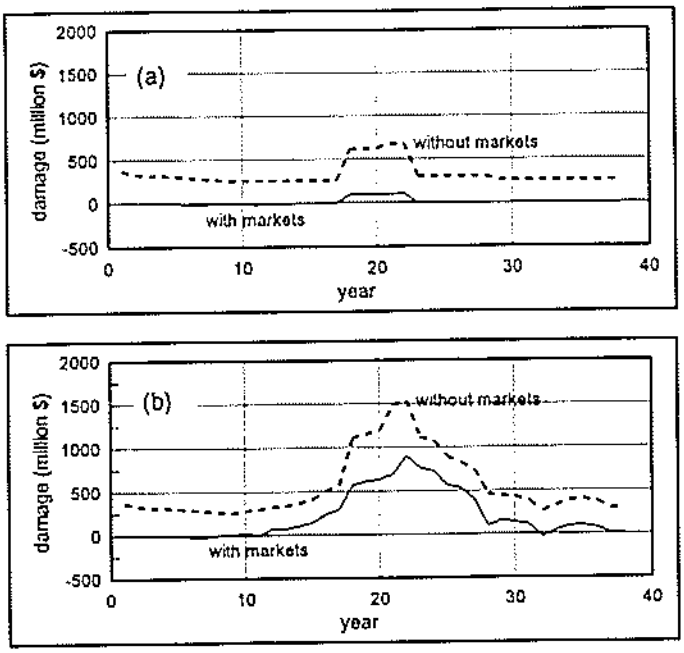

Figure 9. Consumptive Use (a) and Total Economic Damages (excluding salinity) (b) with Intrastate Water Banks (Markets).

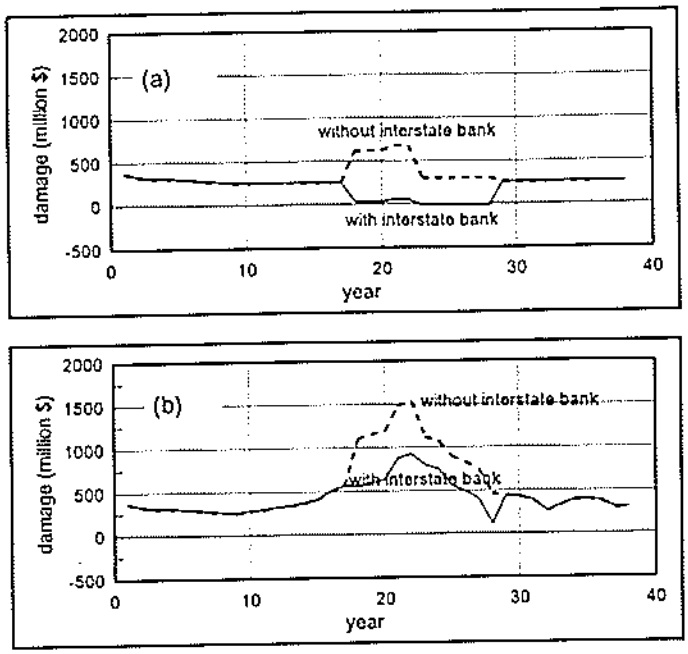

Figure 10. Consumptive Use (a) and Total Economic Damages (excluding salinity) (b) with an Interstate Consumptive Use Water Bank.

An interstate water bank would reduce drought damages to consumptive uses by 85 percent during years 17 through 22, reduce chronic damages to MWD uses, and eliminate CAP agricultural uses (Figure 10). Reductions in consumptive use damages are minor beyond those achievable with intrastate markets or a policy shifting shortfalls to agricultural users. During critical drought years damages to nonconsumptive users increase slightly from those estimated under the base policy (Figure 10) as water is transferred to Upper Basin consumptive uses, further decreasing the remaining hydropower production.

Comparison of Policy Responses

Effective policy responses to drought must address shortfalls to consumptive users and damages from lost hydropower production and recreational opportunities. Salinity damages can also be addressed through policy responses but are not formally treated here [see Booker and Young (1994) for economic impacts of alternative approaches to balancing consumptive and nonconsumptive use benefits, including salinity damages].

Figure 11 summarizes the discounted total damages for years 17 through 28 under the policy responses presented above. The time period chosen is that during which consumptive use shortfalls greater than the chronic MWD shortfall were found under the base Law of the River policy simulation. Nonconsumptive use damages were also greatest in this period. Under the Law of the River policy, the present value of total damages for the 12-year period discounted at a 4 percent annual rate to year 17 is $9.5 billion; if discounted to year 1, the present value of damages is a factor of two less, or roughly $5 billion. The latter figure provides an estimate (in 1992 dollars) of the present value of drought damages (excluding salinity damages) for the 12 years of greatest drought impact, were the full drought sequence to begin this year.

Consumptive use damages (making up 45 percent of the total damages) can be largely mitigated through reallocations from low (primarily agricultural) to high (municipal and industrial) valued uses. Reallocations could occur through changes in legal priorities during drought (the policy shifting shortfalls to agricultural sectors) or through water marketing (e.g., intra- and interstate water banking). Policies providing small annual increases in available supplies (e.g., the "store high" policy to reduce evaporation losses) or those which distribute shortfalls between all users (e.g., the proportional sharing of shortfalls policy) are somewhat effective in reducing total consumptive use damages.

Damages to hydropower production and recreational uses are typically both greater in magnitude than consumptive use damages and more difficult to reduce through policy measures. Maintenance of minimum

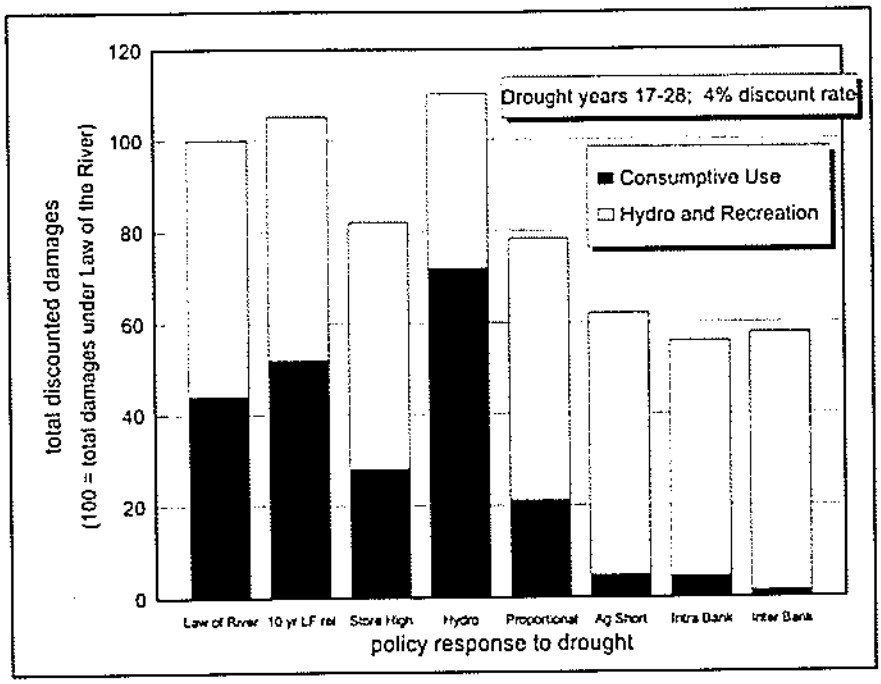

Figure 11. Present Value of Total Drought Damages (excluding salinity) for Years 17 through 28. Were the full drought sequence to begin this year, the present value of Law of the River damages would be $5 billion (1992 dollars).

reservoir levels (primarily for hydropower production but also resulting in recreation benefits) is most effective at reducing such nonconsumptive use damages (31 percent reduction). Damages from large increases in consumptive use shortfalls outweigh these nonconsumptive use benefits, however. Other policies have little effect on nonconsumptive use damages, ranging from an 8 percent reduction (intrastate water banking), to 1 percent to 2 percent increases with proportional distribution of shortfalls and interstate banking.

The modeled shortfall of 636 kaf/year to MWD users obscures damages to other users arising directly from the drought. It is likely that these chronic shortfalls to MWD will be reduced through future transfers from California agricultural users in the Imperial and Palo Verde Irrigation Districts not reflected in the depletion request data used for this study. Focusing only on the purely drought-related damages stresses the significance of nonconsumptive use damages: under the base Law of the River policy, such damages are fully 72 percent of drought-related damages, with consumptive use damages only 28 percent of the total.

Policy Recommendations

Four policy responses are nearly equally effective at reducing drought-related damages. Intra- and interstate water banking reduces such damages by 28 percent and 26 percent, respectively. Shifting consumptive use shortfalls to agricultural users reduces damages by 20 percent, while managing Basin reservoirs to reduce evaporation losses (the "store high" policy) reduces damages by 23 percent. The latter two modeled policies maintain subsidized agricultural uses of CAP water, accounting for the major difference in damages relative to the water-marketing policies which eliminate such use. These results strongly suggest that most gains from water reallocation during drought are possible through intrastate policies. Further, because most agricultural regions include a large proportion of low-valued crops, simple across-the-board reallocations from agricultural to municipal uses during drought is a nearly economically efficient policy. Increasing available supplies through reservoir management is an independent policy with a significant impact in reducing drought damages. Reducing damages to hydropower production and recreation imposes increased consumptive use damages (hydropower protection policy). These increased damages could be greatly reduced, however, through use of one of the four policies identified above.

Together, three policy responses are suggested to reduce damages from drought in the Colorado River Basin:

1. Reallocation from low-valued to high-valued consumptive uses when shortfalls occur.
2. Reservoir management to reduce evaporation losses and increase available supplies.
3. Increased emphasis on maintenance of minimum reservoir levels to support hydropower production and recreational opportunities.

Policies (1) and (2) independently reduce total damages and thus need not be linked. Policy (3) reduces total damages only if a reallocation policy for reducing consumptive-use impacts (1) is also applied. Utilizing all three policy responses together would result in the greatest total reduction in damages from a severe and sustained drought.

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