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# Marginal Economic Value of Streamflow: A Case Study for the Colorado River Basin

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The marginal economic value of streamflow leaving forested areas in the Colorado River Basin was estimated by determining the impact on water use of a small change in streamflow and then applying economic value estimates to the water use changes. The effect on water use of a change in streamflow was estimated with a network flow model that simulated salinity levels and the routing of flow to consumptive uses and hydroelectric dams throughout the Basin. The results show that, under current water management institutions, the marginal value of streamflow in the Colorado River Basin is largely determined by nonconsumptive water uses, principally energy production, rather than by consumptive agricultural or municipal uses. The analysis demonstrates the importance of a systems framework in estimating the marginal value of streamflow.

## INTRODUCTION

As surface water supplies approach full utilization and competition for existing supplies increases, it becomes increasingly important to know the value of changes in flow. Estimates of the value of flow changes are useful for evaluating water supply augmentation projects, such as alterations in vegetation of upland watersheds, cloud seeding, and transbasin diversions. Such value estimates are also useful in understanding the effect of flow decreases, such as might occur from increasing vegetative cover, climatic changes, or increased upstream consumption.

Perhaps nowhere in the United States is the specter of water scarcity more prominent than in the Colorado River Basin. Efforts to control the Colorado's flow and to allocate its water have long been a focal point of concern among water interests [e.g., *Fradkin*, 1981; *Hundley*, 1975; *Ingram*, 1969]. This highly regulated and much litigated river provides a fitting setting for a study of the marginal value of water.

The specific objective of this study was to estimate the economic value of increases in runoff that could be created by timber harvest in forested areas of the Colorado River Basin. Watershed research has shown that overstory removal in some vegetation types can reduce evapotranspiration and thereby increase streamflow, and much of this research has been carried out at sites in the Colorado River Basin [e.g., *Leaf*, 1975; *Hibbert*, 1979; *Troendle*, 1983]. Although this study focuses on the effects of timber harvest, the analysis has implications for all the aforementioned sources of flow change.

The effect of streamflow change on water use is shown, via a systems approach [*Maass et al.*, 1962], to depend on when the flow increases occur and on all the factors affecting water allocation, including storage and delivery facilities and the institutions affecting water management.



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The analysis incorporates in considerable detail the complex and highly developed water management arrangements that currently determine water allocation in the Basin, including current water laws, major facilities and reservoir operation rules. The sensitivity of the allocation and marginal value of flow to changes in existing management arrangements was investigated by comparing results given the existing arrangements with results given scenarios that incorporate moderate changes to those arrangements. However, major changes in water allocation institutions, such as a change to market allocation of water, were not investigated. The resulting estimates of value, therefore, apply largely to the current institutional setting.

This study builds on two previous studies that investigated the impact of timber harvest on water use and value in the Colorado River Basin. The first [*Bowes et al.*, 1984] compared costs of harvest with several benefits, including increased consumptive water use and hydropower production, but did not adopt a systems approach to determine the effect of streamflow increases on downstream water uses. The other [*Brown et al.*, 1988] used a systems approach to determine the effect of streamflow increases on consumptive uses, but used a much simpler model of the Basin than the current study, ignored hydropower, and did not estimate the monetary value of flow increases. The current study combined economic valuation with the systems approach to water routing, employed a detailed model of the Basin, and estimated the effect of flow changes on river salinity levels in addition to consumptive water use and hydroelectric energy production.

## METHODS

The approach used in this study to estimate the value of streamflow increases was to determine the expected annual effect of the streamflow increases on each water use of interest and then estimate the monetary value of each affected use. Summing the resulting monetary returns of the individual uses and dividing by the mean annual streamflow increase leaving the harvest area yielding an at-the-forest estimate of the unit value of the increase. The value of a flow increase was determined as a sum of quantity and quality effects, as follows:

$$V = Va + Vb \tag{1}$$

given

$$Va = \frac{1}{\Delta Q} \sum_i Pa_i \Delta A_i \tag{2}$$

$$Vb = \frac{1}{\Delta Q} \sum_i Pb_i \Delta B p_i \tag{3}$$

where

- $V$ value per acre foot (1 acre foot equals $1.234 \times 10^3$ $m^3$) of streamflow change;
- $Va$ value per acre foot from quantity changes;
- $Vb$ value per acre foot from quality changes;
- $Pa_i$ marginal value per acre foot of water in use $i$;
- $Pb_i$ marginal value per mg/L change in total dissolved solids (TDS) of water used by use $i$;
- $\Delta Q$ mean annual streamflow change (acre feet);
- $\Delta A_i$ mean annual change in quantity of water applied to use $i$ caused by streamflow change (acre feet);
- $\Delta B$ mean annual change in mg/L of TDS of Colorado River water caused by streamflow change;
- $p_i$ proportion of water in use $i$ originating from Colorado River; and
- $i$ a specific use type in a specific location.

The hydrologic model is described in this section. Determination of economic values of specific uses is described is a subsequent section.

Streamflow increases cause both positive and negative effects. Positive effects in the Colorado River Basin resulting from quantity changes include increases in consumptive use; increases in hydroelectric energy production; increases in deliveries to Mexico; enlargements in the surface area of reservoirs used for recreation; and increases in instream flows used for recreation or fish habitat. The principal positive effect of streamflow increases resulting from water quality changes is the dilution of TDS, which damage pipes and water-using appliances and lower agricultural yields, particularly in the Lower Basin. The main negative effect of streamflow increase is an increased potential for flooding damage.

We only estimated the value of streamflow increases in terms of consumptive use, hydroelectric energy production, and water quality improvements. Additional deliveries to Mexico were not valued because we adopted a national accounting stance. No attempt was made to estimate the value of recreation affected by changes in reservoir surface area or instream flow. Reservoir recreation is unlikely to be very sensitive to the small changes in storage caused by the increases, and instream flow changes would generally be too small and poorly timed to significantly improve river recreation or fish habitat.

The effects of streamflow increases on individual water uses were determined by simulating water flow, storage, use, evaporation, and salinity levels in the Colorado River Basin both with and without the flow increases, and computing the difference in water use caused by the flow increases. To perform the "without" simulations, estimates of Basin flows that could be expected to occur in the absence of timber harvest were needed. The "with" simulations were then done with postulated flow increases added to the preincrease flows at the appropriate Basin locations.

Use of the with-minus-without approach is based on the assumption that the flow change would not be managed as a separate entity, i.e., that the same laws, reservoir operating rules, and delivery guidelines would apply with or without the flow change. This assumption is appropriate in light of two facts. First, streamflow increases from timber harvest would be relatively small and difficult to distinguish from normal flows at major downstream reservoirs. Second, courts have held in several cases that water saved by vegetation changes are tributary to the stream and subject to call by prior appropriators [*Brown and Fogel*, 1987].

We simulated water allocation given discrete scenarios, each with fixed institutional parameters (e.g., storage and delivery facilities, operating rules, water request level). Even with fixed institutional parameters, the value of runoff increases would be expected to vary over time depending on hydrologic conditions. For example, the runoff increases of one or even several consecutive years may remain in storage in the first downstream reservoir, contributing little to hydropower production and none to consumptive use, until some later year when the accumulated increases would all be released to downstream users. Our emphasis was not on these year-by-year fluctuations in the value of runoff changes. Rather, we focused on the expected value, which is estimated as the long-run mean in a world where hydrologic conditions vary naturally but demand, facilities, and institutional arrangements remain constant.

Some mechanism was needed to account for uncertainty about streamflow. Perhaps the preferred approach would have been to generate alternative sets of synthetic traces, perform simulations with each set, and average over the alternative simulations to determine the expected effects of the flow increases. Because incorporation of synthetic flows for the entire Basin was beyond the scope of this study, the simulations were performed using alternative orderings derived from a 78-year historical trace of reconstructed virgin flows for the Basin. Mean annual results from each simulation provided an estimate of the mean annual disposition of flows under the demand, institutional, and timber harvest assumptions of the simulation. Averaging across the results of simulations based on alternative orderings of the flow data gave the expected effects of the flow increases. Thus, the mean annual quantity effects of the streamflow increases on the individual uses were determined as follows:

$$\Delta A_i = \frac{1}{t}\frac{1}{y} \sum_m^t \sum_j^y \sum_k^{12} (\mathrm{A1}_{imjk} - \mathrm{A2}_{imjk}) \tag{4}$$

where

- $\Delta A_i$ mean annual change in quantity of water applied to use $i$;
- $A1_{imjk}$ water applied to use $i$, given flow trace $m$, in year $j$, month $k$, with flow increases;
- $A2_{imjk}$ water applied to use $i$, given flow trace $m$, in year $j$, month $k$, without flow increases;
- $t$ number of alternative flow traces; and
- $y$ number of years simulated.

Averaging the results of alternative orderings of an historical trace is a pragmatic approach to dealing with uncertainty about the timing of flows. It assumes that each alternative ordering of the flows is an equally likely future occurrence. We used four orderings (1906–1983, 1926–1983 then 1906–1925, 1946–1983 then 1906–1945, and 1966–1983 then 1906–1965). Little change in the mean was obtained by averaging results of more than four orderings.

Each multiyear pair of with and without simulations produced mean annual estimates of the disposition of a flow increase, plus estimates of the effect of the increase on electricity production, TDS levels, reservoir storage levels, etc. The four categories of disposition were consumptive use, evaporation, outflow to Mexico, and an estimate of the net change in reservoir storage (end-of-simulation minus start-of-simulation storage). We did not place a value on the net change in storage. A net increase in storage would have value to the extent that it would allow additional "future" water use. The error introduced by this omission is small because, as reported in the results section, the amount of the flow increases that remained in storage at the end of the simulations was generally small compared with the total volume of the increase that evaporated or was applied to immediate use during the study period.

Water quality in the Lower Basin is a major concern, with TDS being the principal component of the problem [*Miller et al.*, 1986]. Significant quantities of salts enter the Colorado River and its tributaries from natural sources, and large quantities also enter in return flows of agricultural diversions. These salts have been estimated to cause very high costs on Lower Basin municipal and agricultural users [*Kleinman and Brown*, 1980]. Because runoff increases are expected to be of high quality, they would dilute the salts in the river, and thus lower the costs to Lower Basin water users.

The effect on Lower Basin salt concentrations of both changes in flow and changes in salt quantities entering the system are not well understood, principally because of inadequate knowledge about the complex process of salt mixing in the major Basin reservoirs (Lakes Powell and Mean) [*Gardner*, 1983]. Because of this lack of knowledge, we chose to estimate only mean annual Lower Basin TDS over a multiyear simulation, based on the assumption of complete mixing of salts in the reservoirs. This assumption implies that the runoff increases completely mix with all other flow in diluting the salts. The difference in mean annual TDS ($\Delta B$ of (3)) was computed as mean annual Lower Basin TDS with the flow increases minus a similar quantity estimated without the increases.

Colorado River Basin water quantities were simulated with a linear programming network optimization model. The model uses the out-of-kilter algorithm (OKA) [*Fulkerson*, 1961; *Clasen*, 1968; *Barr et al.*, 1974] to perform a static optimization at each time-step that mimics the system of priorities for water allocation in a river basin network. Other hydrologic adaptations of the OKA include MODSIM [*Shafer*, 1979; *Labadie et al.*, 1983] and its predecessor SIMYLD [*Texas Water Development Board*, 1972].

The OKA solves the network problem using a highly efficient primal-dual technique [*Labadie et al.*, 1984]. It finds the optimal flow in a network of nodes connected by arcs, where each arc is capacitated (i.e., has finite upper and lower bounds on flow) and has a priority associated with moving one unit of flow along it. The problem is stated as follows: Minimize

$$\sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} q_{ij} \tag{5}$$

subject to

$$\sum_{i=1}^{n} q_{ij} - \sum_{i=1} q_{ji} = 0 \qquad j = 1, n \tag{6}$$

$$l_{ij} \le q_{ij} \le u_{ij} \qquad \text{all } i, j \tag{7}$$

where

$q_{ij}$ flow along $\text{arc}_{ij}$ (i.e., from node $i$ to node $j$);
$c_{ij}$ priority associated with flow along $\text{arc}_{ij}$;
$l_{ij}$ lower bound on flow along $\text{arc}_{ij}$;
$u_{ij}$ upper bound on flow along $\text{arc}_{ij}$; and
$n$ number of network nodes.

Condition (5) expresses the criterion for optimality; (6) specifies that mass balance must be maintained at every node; and condition (7) constrains the flow along any arc to be within lower and upper bounds.

The arcs of the model represent inflows, river reaches, diversions, carryover storage, reservoir releases, system outflow, and evaporation. Constraints on these arcs are set to simulate inflow quantities, storage capacities, consumptive use requests, and turbine capacities. As used in this study, the arc priorities were required to simply reflect the ordering of priorities that determine water allocation under the appropriation doctrine that is universally used in the states, or parts of states, that comprise the Colorado River Basin. The optimal set of flows will be such that the diversion or reservoir with the highest priority will be supplied water until its capacity has been reached, subject to available flow, before any flow will be allocated to features with lower priorities. (For recent applications of the OKA to hydrologic problems, see *Brown et al.* [1988] and *Cheng et al.* [1989].)

## COLORADO RIVER BASIN NETWORK

Management of Colorado River Basin (Figure 1) storage and delivery facilities was assumed to proceed according to existing legal arrangements. That is, intrastate water allocation was assumed to follow the doctrine of prior appropriation, and interstate allocation to follow existing compacts, treaties, and court decisions. Existing administrative decisions regarding reservoir operating rules were assumed for the base scenario, but changed for others. The existing legal and administrative institutions are described briefly here and in more detail by *Hundley* [1986], *Nathanson* [1978], and *Bureau and Reclamation* (*BOR*) [1987].

To model water movement and disposition in the Colorado River Basin, all major river reaches and reservoirs were included; inflow, flow gains, and flow losses were modeled at 29 points of natural flow change; and a great number of individual consumptive use points were recognized. This detail required that the model network contain about 160 nodes and 480 acres.

### *Reservoir Management*

The 14 reservoirs of the model contain a total active capacity of 61.4 million acre feet (MAF) ($7.574 \times 10^{10}$ m$^3$).

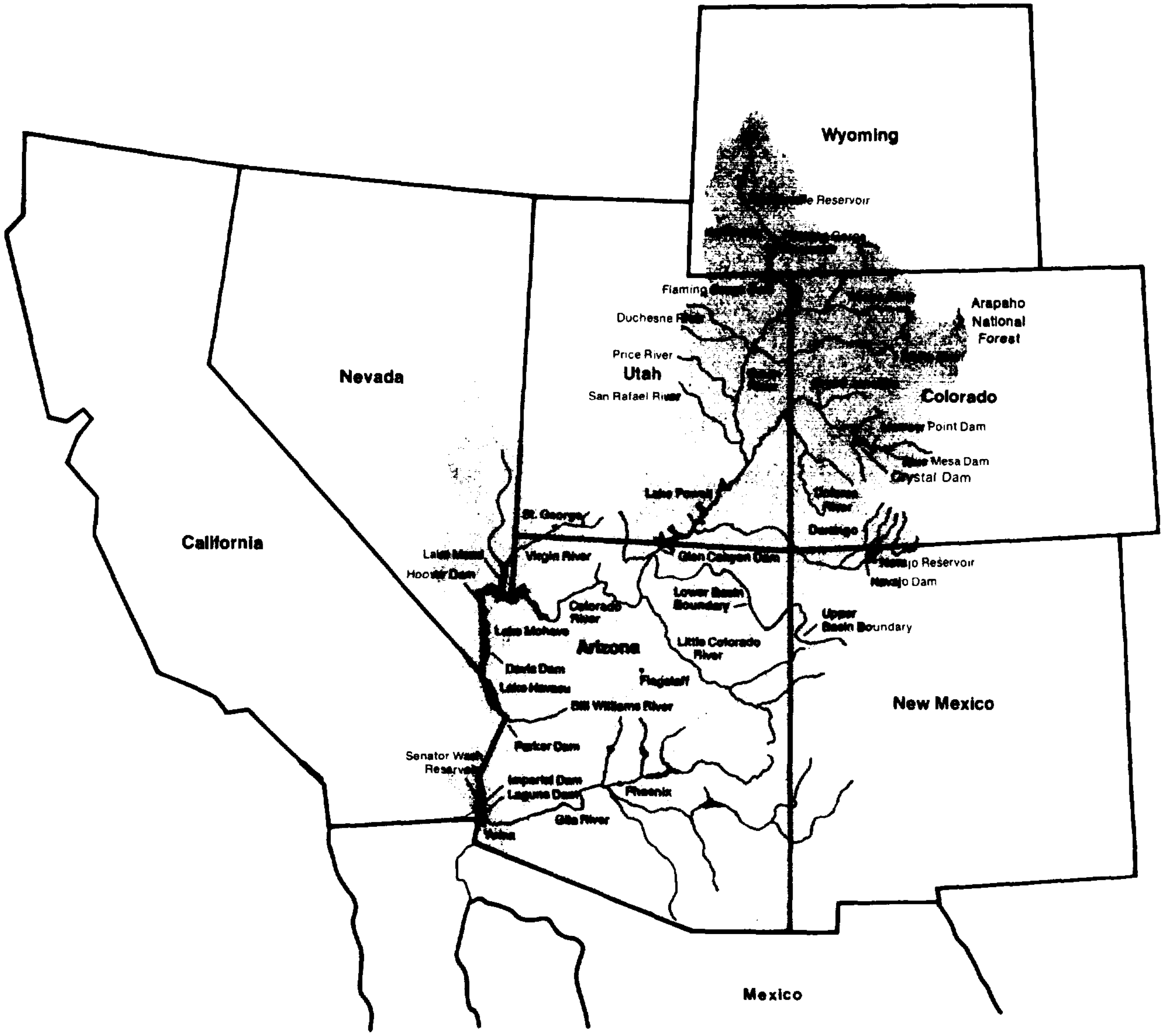


Fig. 1. Colorado River Basin.

Eleven of these reservoirs have electric power facilities, containing a total generating capacity of 3375 MW (Table 1).

Reservoir storage capacity was modeled by breaking the capacity at a reservoir into two or more parts, and representing each part by an arc in the model. One arc represented target storage, the level of storage that the BOR attempts to maintain for power production and other purposes [*BOR*, 1987]. The other arc represented surplus (above target) storage. For some reservoirs, target storage was constant, while for others it varied monthly (Table 1).

Releases from Lakes Powell and Mead are based on a complex set of laws and operating criteria. Releases from Lake Powell were set to a minimum of 8.23 MAF ($1.02 \times 10^{10}$ m$^3$) per year, based on the reservoir operation criteria established pursuant to the Colorado River Basin Project Act of 1968 (reflecting the apportionment established in the Colorado River Compact of 1922, and assuming that the Upper Basin contributes half of the Mexican delivery committment of 1.5 MAF ($1.9 \times 10^9$ m$^3$) per year). Releases in excess of this minimum were made when spills occurred or when additional releases were indicated by the rules governing "equalization" of storage between Lakes Powell and Mead. The equalization, or "parity," rules, required by the Colorado River Basin Project Act of 1968 (Public Law 90-537), essentially allow additional releases from Lake Powell if end of water year storage in Lake Powell is expected to exceed Lake Mead storage and if the Upper Basin is quite confident that it can meet its future required deliveries to the Lower Basin without shorting Upper Basin users. Releases from Lake Mead were based on forecasted inflows and requests for consumptive use deliveries, subject to flood control objectives. Modeling Powell and Mead releases required forecasting future flows, and was accomplished with an application-specific subroutine to the OKA model. For more detail on Powell and Mead release rules, see *Nathanson* [1978] or *BOR* [1987].

Reservoir evaporation was computed at the end of each month from surface area/volume relationships and unit evaporation rates adopted from *BOR* [1985].

Energy production was modeled as a function of (1) the amount of water that passed through the turbines, (2) the feet of effective head that the water dropped, and (3) power plant

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## INTRODUCTION

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## METHODS

The approach used in this study to estimate the value of streamflow increases was to determine the expected annual effect of the streamflow increases on each water use of interest and then estimate the monetary value of each affected use. Summing the resulting monetary returns of the individual uses and dividing by the mean annual streamflow increase leaving the harvest area yielding an at-the-forest estimate of the unit value of the increase. The value of a flow increase was determined as a sum of quantity and quality effects, as follows:

$$V = Va + Vb \tag{1}$$

given

$$Va = \frac{1}{\Delta Q} \sum_i Pa_i \Delta A_i \tag{2}$$

$$Vb = \frac{1}{\Delta Q} \sum_i Pb_i \Delta B p_i \tag{3}$$

where

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Each multiyear pair of with and without simulations produced mean annual estimates of the disposition of a flow increase, plus estimates of the effect of the increase on electricity production, TDS levels, reservoir storage levels, etc. The four categories of disposition were consumptive use, evaporation, outflow to Mexico, and an estimate of the net change in reservoir storage (end-of-simulation minus start-of-simulation storage). We did not place a value on the net change in storage. A net increase in storage would have value to the extent that it would allow additional "future" water use. The error introduced by this omission is small because, as reported in the results section, the amount of the flow increases that remained in storage at the end of the simulations was generally small compared with the total volume of the increase that evaporated or was applied to immediate use during the study period.

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The OKA solves the network problem using a highly efficient primal-dual technique [*Labadie et al.*, 1984]. It finds the optimal flow in a network of nodes connected by arcs, where each arc is capacitated (i.e., has finite upper and lower bounds on flow) and has a priority associated with moving one unit of flow along it. The problem is stated as follows: Minimize

$$\sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} q_{ij} \tag{5}$$

subject to

$$\sum_{i=1}^{n} q_{ij} - \sum_{i=1} q_{ji} = 0 \qquad j = 1, n \tag{6}$$

$$l_{ij} \le q_{ij} \le u_{ij} \qquad \text{all } i, j \tag{7}$$

where

$q_{ij}$ flow along $\text{arc}_{ij}$ (i.e., from node $i$ to node $j$);
$c_{ij}$ priority associated with flow along $\text{arc}_{ij}$;
$l_{ij}$ lower bound on flow along $\text{arc}_{ij}$;
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Condition (5) expresses the criterion for optimality; (6) specifies that mass balance must be maintained at every node; and condition (7) constrains the flow along any arc to be within lower and upper bounds.

The arcs of the model represent inflows, river reaches, diversions, carryover storage, reservoir releases, system outflow, and evaporation. Constraints on these arcs are set to simulate inflow quantities, storage capacities, consumptive use requests, and turbine capacities. As used in this study, the arc priorities were required to simply reflect the ordering of priorities that determine water allocation under the appropriation doctrine that is universally used in the states, or parts of states, that comprise the Colorado River Basin. The optimal set of flows will be such that the diversion or reservoir with the highest priority will be supplied water until its capacity has been reached, subject to available flow, before any flow will be allocated to features with lower priorities. (For recent applications of the OKA to hydrologic problems, see *Brown et al.* [1988] and *Cheng et al.* [1989].)

## COLORADO RIVER BASIN NETWORK

Management of Colorado River Basin (Figure 1) storage and delivery facilities was assumed to proceed according to existing legal arrangements. That is, intrastate water allocation was assumed to follow the doctrine of prior appropriation, and interstate allocation to follow existing compacts, treaties, and court decisions. Existing administrative decisions regarding reservoir operating rules were assumed for the base scenario, but changed for others. The existing legal and administrative institutions are described briefly here and in more detail by *Hundley* [1986], *Nathanson* [1978], and *Bureau and Reclamation* (*BOR*) [1987].

To model water movement and disposition in the Colorado River Basin, all major river reaches and reservoirs were included; inflow, flow gains, and flow losses were modeled at 29 points of natural flow change; and a great number of individual consumptive use points were recognized. This detail required that the model network contain about 160 nodes and 480 acres.

### *Reservoir Management*

The 14 reservoirs of the model contain a total active capacity of 61.4 million acre feet (MAF) ($7.574 \times 10^{10}$ m$^3$).

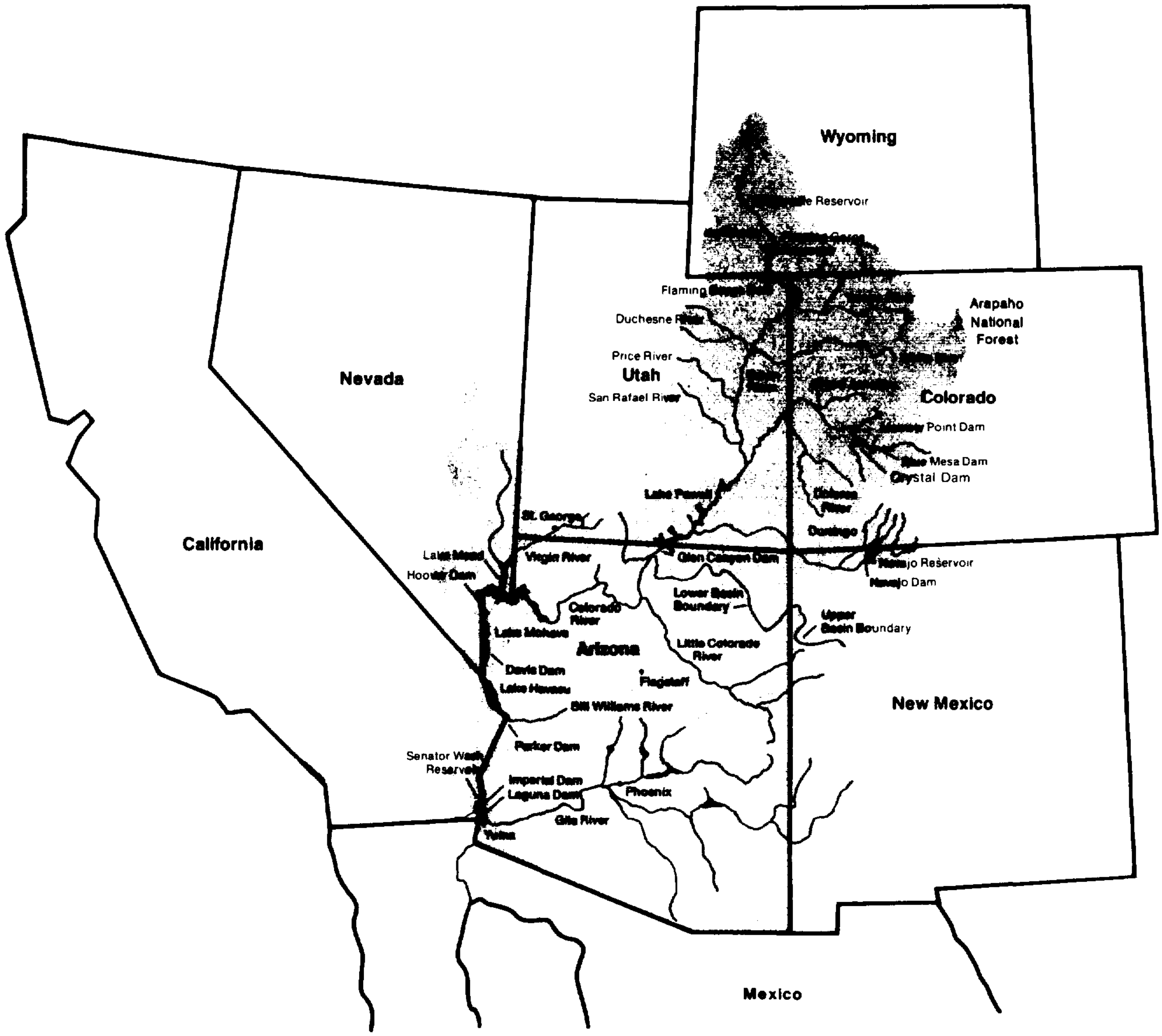


Fig. 1. Colorado River Basin.

Eleven of these reservoirs have electric power facilities, containing a total generating capacity of 3375 MW (Table 1).

Reservoir storage capacity was modeled by breaking the capacity at a reservoir into two or more parts, and representing each part by an arc in the model. One arc represented target storage, the level of storage that the BOR attempts to maintain for power production and other purposes [*BOR*, 1987]. The other arc represented surplus (above target) storage. For some reservoirs, target storage was constant, while for others it varied monthly (Table 1).

Releases from Lakes Powell and Mead are based on a complex set of laws and operating criteria. Releases from Lake Powell were set to a minimum of 8.23 MAF ($1.02 \times 10^{10}$ m$^3$) per year, based on the reservoir operation criteria established pursuant to the Colorado River Basin Project Act of 1968 (reflecting the apportionment established in the Colorado River Compact of 1922, and assuming that the Upper Basin contributes half of the Mexican delivery committment of 1.5 MAF ($1.9 \times 10^9$ m$^3$) per year). Releases in excess of this minimum were made when spills occurred or when additional releases were indicated by the rules governing "equalization" of storage between Lakes Powell and Mead. The equalization, or "parity," rules, required by the Colorado River Basin Project Act of 1968 (Public Law 90-537), essentially allow additional releases from Lake Powell if end of water year storage in Lake Powell is expected to exceed Lake Mead storage and if the Upper Basin is quite confident that it can meet its future required deliveries to the Lower Basin without shorting Upper Basin users. Releases from Lake Mead were based on forecasted inflows and requests for consumptive use deliveries, subject to flood control objectives. Modeling Powell and Mead releases required forecasting future flows, and was accomplished with an application-specific subroutine to the OKA model. For more detail on Powell and Mead release rules, see *Nathanson* [1978] or *BOR* [1987].

Reservoir evaporation was computed at the end of each month from surface area/volume relationships and unit evaporation rates adopted from *BOR* [1985].

Energy production was modeled as a function of (1) the amount of water that passed through the turbines, (2) the feet of effective head that the water dropped, and (3) power plant

TABLE 1. Reservoir Storage and Hydroelectric Power Facilities in the Colorado River Basin

| Reservoir | Live Storage Capacity,[a] KAF[c] | Generator Capacity,[b] 1000 W | Turbine Discharge Capacity[a], 1000 cfs | Minimum Head[a], feet | Maximum Head[a], feet | Tailwater Elevation[a], feet | Target Storage[a], KAF |
|---|---|---|---|---|---|---|---|
| Upper Basin | | | | | | | |
| Fontenelle | 345 | 10 | 1.7 | 80 | 110 | 6,396 | 165–345[d] |
| Flaming Gorge | 3,724 | 108 | 4.3 | 260 | 440 | 5,740 | 1,041 |
| Starvation[e] | 255 | ... | ... | ... | ... | ... | 255 |
| Taylor Park | 106 | ... | ... | ... | ... | ... | 50–106 |
| Blue Mesa | 830 | 60 | 3.0 | 236 | 360 | 7,161 | 249 |
| Morrow Point | 117 | 120 | 5.0 | 353 | 430 | 6,770 | 115[f] |
| Crystal | 18 | 28 | 1.7 | 166 | 224 | 6,533 | 14 |
| Ridgway | 55 | ... | ... | ... | ... | ... | 41 |
| McPhee[g] | 381 | 1.35 | 0.1 | 190 | 260 | 6,660 | 229 |
| Navajo[g] | 1,642 | 30 | 1.4 | 270 | 365 | 5,270 | 947–1,641 |
| Powell | 24,454 | 1206 | 31.5 | 358 | 568 | 3,145 | 24,454 |
| Lower Basin | | | | | | | |
| Mead | 27,019 | 1452 | 38.0 | 420 | 585 | 645 | 21,669–25,519[h] |
| Mohave | 1,810 | 240 | 26.5 | 89 | 136 | 512 | 1,371–1,754 |
| Havasu | 619 | 120 | 20.0 | 60 | 80 | 370 | 539–611 |
| Total | 61,375 | | | | | | |

1 foot equals 0.3048 m.
[a]Sources: Input parameters for the CRSS model [*BOR*, 1985, also personal communication, 1988].
[b]Sources: *Western Area Power Administration* (*WAPA*) [1985]. BOR (personal communication, 1988).
[c]KAF denotes 1000 acre feet, equal to $1.2335 \times 10^6$ m$^3$.
[d]Ranges indicate the range in monthly values.
[e]An aggregation of eight small reservoirs.
[f]Morrow Point target storage different from the BOR's CRSS model, in order to adequately simulate hydropower production.
[g]Hydropower plants currently under construction, but were assumed to be in operation.
[h]Mead target storage from August to December depends on storage space among Mead and four Upper Basin reservoirs.

efficiency (0.9), generator capacity, and turbine capacity (Table 1). Electric energy produced at each plant each month was apportioned to peaking and base load categories based on the relationship of production to capacity. Peaking power was produced when possible because of its greater value (it replaces energy otherwise typically produced at relatively expensive combustion turbine plants). However, a substantial proportion of the energy produced at the plants was base load (otherwise typically produced at coal-fired plants).

### *Requests for Consumptive Use*

Consumptive use (i.e., depletion, or diversion minus return flow) was modeled directly in this study, thereby avoiding the need to model both diversion and return flow. This simplification was based on the determination that most return flows enter the channel upstream of the next downstream node.

Two levels of consumptive water use were modeled, corresponding to predictions for years 1990 and 2000 of consumptive use requests for Basin water. Except for the "excess" requests, described below, the consumptive use estimates were taken from the depletion schedules developed by *BOR* [1986]. The requests are based on historical use and expected future use in light of legal entitlement, current and expected delivery capacity, and expected development of water-using projects. They do not reflect econometric predictions of demand.

For the 1990 use level, Basin consumptive use requests were modeled as 164 separate depletions, totaling a request of 14.2 MAF ($1.75 \times 10^{10}$ m$^3$) per year. The individual depletions differentiate diversion locations and use types. Their distribution among the nine major Upper Basin reaches and the Lower Basin states is shown in Table 2. For year 2000, 183 depletions were included, totaling a request of 14.9 MAF ($1.84 \times 10^{10}$ m$^3$) per year, 5% increase over 1990.

The Boulder Canyon Project Act of 1928, as reinforced by the 1963 U.S. Supreme Court decision in *California versus Arizona*, authorized the following allocation of the Lower Basin's 7.5 MAF ($9.25 \times 10^9$ m$^3$) per year: 2.8 MAF ($3.45 \times 10^9$ m$^3$) to Arizona, 4.4 MAF ($5.43 \times 10^9$ m$^3$) to California, and 0.3 MAF ($0.37 \times 10^9$ m$^3$) to Nevada. Both the 1990 and 2000 consumptive use request levels assume that Arizona and California request their full entitlements. Nevada is assumed to request 178 KAF ($2.20 \times 10^8$ m$^3$) and 250 KAF ($3.08 \times 10^8$ m$^3$) in years 1990 and 2000, respectively. Additional use is expected, largely by native vegetation along the river channel, of 436 and 455 KAF (5.38 and $5.61 \times 10^8$ m$^3$) in years 1990 and 2000, respectively (Table 2). This additional use is not assigned to specific Lower Basin states, and is in addition to the Lower Basin's 7.5 MAF ($9.25 \times 10^9$ m$^3$) allocation.

California's authorized depletion of 4.4 MAF ($5.43 \times 10^9$ m$^3$) per year includes 497 KAF ($6.13 \times 10^8$ m$^3$) that is delivered to the Metropolitan Water District (MWD), an agency that supplies water along the southern coastal region including the Los Angeles area. In addition to this authorized depletion, we assumed an "excess" MWD request of 729 KAF ($8.99 \times 10^8$ m$^3$) per year, which is the difference between the highest historical annual delivery to MWD (1.226 MAF ($1.512 \times 10^9$ m$^3$)) and MWD's authorized delivery. The maximum delivery is limited by the capacity of the Colorado River Aqueduct. The excess request brings California's total request to 5.129 MAF ($6.327 \times 10^9$ m$^3$) per year. The excess request of 729 KAF ($8.99 \times 10^8$ m$^3$) is an

TABLE 2. Annual Requested Consumptive Use Depletions

| Use Area | Number of Diversions | | Requested Depletion, 1000 acre feet[a] | |
|---|---|---|---|---|
| | 1990 | 2000 | 1990 | 2000 |
| Upper Basin | | | | |
| Green | 24 | 30 | 565 | 641 |
| Yampa | 8 | 9 | 137 | 186 |
| Duchesne | 8 | 10 | 553 | 664 |
| San Rafael | 6 | 6 | 94 | 94 |
| White | 4 | 6 | 45 | 78 |
| Gunnison | 10 | 11 | 482 | 493 |
| Colorado | 30 | 32 | 1,233 | 1,302 |
| Dolores | 8 | 8 | 48 | 48 |
| San Juan | 25 | 29 | 736 | 947 |
| Total | 123 | 141 | 3,893 | 4,453 |
| Lower Basin | | | | |
| Arizona[b] | | | | |
| Mainstem | 13 | 14 | 1,285 | 1,312 |
| CAP high priority | 1 | 1 | 345 | 415 |
| CAP low priority | 1 | 1 | 1,170 | 1,037 |
| CAP excess[c] | 1 | 1 | 285 | 312 |
| California | | | | |
| Mainstem | 9 | 9 | 530 | 530 |
| Imperial/Coachella | 2 | 2 | 3,373 | 3,373 |
| MWD authorized | 1 | 1 | 497 | 497 |
| MWD excess[d] | 1 | 1 | 729 | 729 |
| Nevada | 5 | 5 | 178 | 250 |
| Unassigned | 6 | 6 | 436 | 455 |
| Total | 40 | 41 | 8,828 | 8,946 |
| Mexico | 1 | 1 | 1,515 | 1,515 |
| Total | 164 | 183 | 14,236 | 14,914 |

Source: *BOR* [1986], except for excess requests.
[a]1000 acre feet equal $1.2335 \times 10^6$ m$^3$.
[b]Assumes completion of the Tucson Aqueduct of the CAP, which is expected in 1991.
[c]Assumes a maximum CAP diversion of 1.8 MAF ($2.22 \times 10^9$ m$^3$) per year.
[d]Assumes a maximum MWD request of 1.226 MAF ($1.512 \times 10^9$ m$^3$) per year.

upper bound, for two reasons. First, even before the Central Arizona Project (CAP) began diverting water, the typical MWD delivery was considerably below the capacity of the Colorado River Aqueduct. Second, future water transfers may lower the maximum request. Proposed transfers from agriculture to MWD [*Holburt et al.*, 1988] would increase MWD's authorized depletion, concomitantly lowering the maximum excess MWD depletion because the total depletion is limited by the capacity of the aqueduct.

Arizona's authorized depletion of 2.8 MAF ($3.45 \times 10^9$ m$^3$) per year includes 1.285 MAF ($1.59 \times 10^9$ m$^3$) (in 1990) for uses along the mainstream. The residual, 1.515 MAF ($1.87 \times 10^9$ m$^3$), was allocated to CAP, which, when completed, will deliver water to south central Arizona, including Phoenix and Tucson. The CAP allocation in year 1990 was separated into high and low priority requests (Table 2). The high priority request (345 KAF ($4.26 \times 10^8$ m$^3$) in 1990) corresponds to the expected delivery to municipal and industrial users. Agricultural users are assumed to request the remainder of the authorized CAP diversion (1.170 MAF ($1.444 \times 10^9$ m$^3$) in 1990). In addition to this authorized depletion, we assumed an "excess" CAP request of 285 KAF ($3.52 \times 10^8$ m$^3$) (in 1990), which is the difference between 1.8 MAF ($2.2 \times 10^9$ m$^3$), the amount that we assume the CAP could utilize on a regular basis if sufficient water were available, and CAP's authorized delivery. This excess delivery would go directly to agriculture or be used to recharge the groundwater basin. In light of recent difficulties in finding buyers for all available CAP water, this excess CAP request must, like the MWD excess request, be considered an upper bound. The sensitivity of the results to the upper bounds on CAP and MWD requests is examined in the results section.

*Priorities*

In the model, the Mexico delivery obligation had first priority. In the Upper Basin, the Lee Ferry delivery, required by the Compact, the Powell-Mead equalization criteria, and the Mexico delivery obligation, was satisfied first. Upper Basin consumptive use requests, which were all given equal priority, were satisfied next, followed by the filling of Upper Basin reservoirs to the target storage levels. Note that assigning highest priority to the Mexico delivery is not strictly correct since, according to the Mexican water treaty of 1944, deliveries to Mexico can be curtailed in times of "extraordinary drought." This simplification in the model is of little consequence, however, because such "extraordinary" conditions were not encountered.

In the Lower Basin, first priority was given to consumptive uses except MWD excess and CAP. Mohave and Havasu target storage was satisfied next, followed by CAP high priority requests. CAP use was considered of lower priority than other use authorized under the Compact allocations, based on the stipulation of the Colorado River Basin Project Act of 1968, which authorized construction of the CAP, that withdrawals to CAP would not interfere with California's full 4.4 MAF ($5.43 \times 10^9$ m$^3$) of authorized depletions. "Shortage" storage in Mead, set at 10.762 MAF ($1.328 \times 10^{10}$ m$^3$), held the next priority, followed by CAP low priority requests. The CAP low priority request, of about 1 MAF ($1.233 \times 10^9$ m$^3$), was held subordinate to Mead "shortage" storage in order to protect future consumptive uses of higher priority (e.g., California and mainstream uses) from shortages. This subordination of low priority CAP requests reflects one interpretation of the 1963 Supreme Court decision in *Arizona versus California* and the Colorado River Basin Project Act [*BOR*, 1987, p. 73].

The next priority was to satisfy a portion of the 1.014 MAF ($1.251 \times 10^9$ m$^3$) (in 1990) of excess CAP and MWD requests, followed by Mead storage above the "shortage" level and below the flood control pool. This priority of some of the MWD and CAP excess requests over Mead storage in excess of the "shortage" level approximates the "surplus strategy" in the BOR's Colorado River Simulation System (CRSS) model, whereby some water may be released to out-of-Compact uses in anticipation of spring runoff in excess of Compact-authorized demands and available storage space [*BOR*, 1987, p. 71]. Lowest priority was assigned to the rest of the MWD and CAP excess requests. Thus, only Lower Basin spills, flood control releases from Mead, and storage above the target levels of Mohave and Havasu were available to meet the last portion of the MWD and CAP excess requests. Deliveries to the excess requests were divided equally between these two depletions (following Article II (B) (2) of the Supreme Court decree in *Arizona versus California*).

To summarize, the priorities are as follows: (1) Mexico delivery (1.5 MAF ($1.9 \times 10^9$ m$^3$)); (2) Lee Ferry delivery (8.23 MAF ($1.02 \times 10^{10}$ m$^3$); (3) Upper Basin consumptive use (3.893 MAF ($4.804 \times 10^9$ m$^3$) in 1990, Table 2); (4) Upper Basin target storage (Table 1); (5) Lower Basin consumptive use except MWD excess and CAP (6.299 MAF ($7.770 \times 10^9$ m$^3$) in 1990, Table 2); (6) Mohave and Havasu target storage (Table 1); (7) CAP high priority use (345 KAF ($4.26 \times 10^8$ m$^3$) in 1990); (8) Mead "shortage" storage (10.762 MAF ($1.328 \times 10^{10}$ m$^3$); (9) CAP low priority use (1.170 MAF ($1.443 \times 10^9$ m$^3$) in 1990); (10) "surplus strategy" excess MWD and CAP use (365 KAF ($4.50 \times 10^8$ m$^3$)); (11) Mead storage above the "shortage" level and below the target level; (12) remainder of CAP and MWD excess use (649 KAF ($8.01 \times 10^8$ m$^3$) in 1990); (13) storage above the target storage levels of each reservoir.

In keeping with current reservoir management in the Basin, specific requests for water for hydroelectric energy production and salt dilution were not included in the network. However, note that BOR's target storage levels emphasize maintaining hydraulic head for power production.

### *Water Quality*

Mean annual Lower Basin salt concentrations, or total dissolved solids (TDS) levels, were computed by tracking salt mass and water volume entering the Lower Basin, and comparing these quantities at a specific Lower Basin mainstem location (below Mead and above Havasu). The average quantity of salt entering the river was computed as the sum of salt entering from natural sources plus quantities in return flows of each diversion. The natural salt level, assumed to be 6.474 million tons ($5.873 \times 10^9$ kg) per year, was computed by routing BOR's estimates of natural contribution from each of the 29 inflow points throughout the network. The TDS of return flows depended on the amount of consumptive use at each withdrawal point, the proportion of the associated withdrawal that returns to the river, and the TDS concentration level of the return flow. Water consumption at each diversion was predicted by the model. Return flow proportion and TDS concentrations for each diversion were taken from the CRSS depletion schedule [*BOR*, 1986]. For a typical 1990 simulation, return flows were estimated to contribute an average of 3.833 million tons ($3.477 \times 10^9$ kg) of salt per year. Finally, we assumed that TDS of the streamflow increases was 50 mg/L [*Stottlemyer and Troendle*, 1987].

### *Flows*

"Normal" flows, those without the postulated flow increases, were based on a 78-year period (1906–1983) of monthly reconstructed virgin flows developed by BOR for 29 stations throughout the Basin that account for inflows and mainstem flow gains and losses.

The postulated mean annual increase was assumed to be static over the 78-year simulation. However, the increase that occurred in any one year was assumed to vary roughly proportionally to the normal flow at the inflow point downstream of the treatment area where the increase was assumed to enter the network. This assumption was based on research at Fraser Experimental Forest, which has demonstrated the correspondence of annual flow increases to annual precipitation [*Troendle*, 1983], and the assumption that the same precipitation that would affect flow from from the treatment areas would affect flow from areas contributing to the downstream inflow point. Finally, based on experience at Fraser Experimental Forest [*Troendle*, 1983], the increases were assumed to occur entirely during the heavy runoff season. The monthly distribution was 5%, 70%, and 25% in April, May, and June, respectively.

The source of streamflow increase postulated to become available as a result of timber harvest was the Arapaho National Forest, located at the upper reaches of the Colorado River mainstem (Figure 1). A nominal mean annual increase of 40 KAF ($4.9 \times 10^7$ m$^3$) was assumed, which is half of the increase postulated by *Brown et al.* [1988] as a maximum potential increase from vegetation management. Annual increases varied from about 20 KAF ($2.5 \times 10^7$ m$^3$) associated with normal flow in year 1977 to about 50 KAF ($6.2 \times 10^7$ m$^3$) for year 1957. The 40 KAF ($4.9 \times 10^7$ m$^3$) mean annual streamflow increase is equivalent to 0.27% of mean annual virgin flow at Lee Ferry over the historical flow record.

## MARGINAL ECONOMIC VALUES OF AFFECTED WATER USES

The change in water use, multiplied by the appropriate estimate of willingness to pay for the change, indicates the economic value of the change. Willingness to pay for changes in water use was estimated assuming the objective of economic efficiency from a national accounting stance. Current technology was taken as given. Because the changes in flow and consequent changes in water use postulated here are relatively small, the changes were assumed to leave commodity and factor prices unaffected. Values were adjusted to 1985 using the GNP deflator.

The number of water uses for which estimates of value were needed was limited for two reasons. First, the analysis was limited to consumptive uses, hydroelectric energy production, and salt dilution, thus ignoring impacts on recreation and flooding. Second, only values for water uses that were affected by the streamflow increases are needed for this analysis. As described in the next section, few Upper Basin consumptive uses, and no Lower Basin users except MWD and CAP, were affected by the flow increases.

Secondary sources were consulted to determine the economic values. Agricultural use values were derived using residual imputation, hydroelectric and some municipal and industrial (M & I) values were derived using the alternative cost method, other M & I values were estimated based on market price observation, and the value of salt dilution was estimated based on the cost savings to water users (see *Young and Gray* [1972] or *U.S. Water Resources Council* [1979] for more detail on these methods). Values for the uses that are affected by streamflow increases are described here and summarized in Table 3.

### *Upper Basin Agriculture*

*Narayanan et al.* [1979] divided the Upper Basin into eight subbasin areas, and derived the net return in each area to numerous crops. Their approach is based on data for each subbasin on crop values, variable input costs, yields, and consumptive water use. *Howe and Ahrens* [1988] updated Narayanan et al.'s work, and added annualized fixed costs to

TABLE 3. Water Values for Water Uses Affected by Changes in Streamflow

| Use | Marginal Value | Effect of Change in Marginal Value[a] |
|---|---|---|
| | *Consumptive Use, per acre foot*[b] | |
| Upper Basin agriculture[c] | 21–48 | NA |
| Upper Basin transmountain diversion[d] | 98 | 0.011/$ |
| MWD extra[e] | 110 | 0.054/$ |
| CAP | 0 | 0.054/$ |
| | *Hydropower, per kWh* | |
| Peaking | 0.05 | 0.362/mill |
| Base load | 0.018 | 1.137/mill |
| | *Salt Dilution, per mg/L* | |
| Municipal and industrial | 200,668 | 0.000057/$ |

Values are in 1985 dollars. NA denotes not applicable.

[a]Change in value of flow increase per unit change in marginal value of specified use given scenario A.

[b]Valued at point of diversion from river. 1 acre foot equals 1233.5 $m^3$.

[c]Value depends on location within Upper Basin [*Narayanan et al.*, 1979].

[d]Value depends on location of diversion. A value of up to $216 per acre foot is possible in some locations.

[e]Value assumes unused capacity in the Colorado River Aqueduct.

the cost estimates, to derive the return to water. The values ignore costs to Lower Basin Colorado River water users from the increase in Lower Basin TDS levels caused by Upper Basin agricultural users (these costs are estimated separately in this study, as described below).

We focused only on production of alfalfa and pasture, which, according to agricultural extension reports, account for from 71% to 97% of the total irrigated acreage of the eight subbasins, and are the most likely crops to be affected by a change in water availability. The weighted (by crop acreage) average return per acre foot of the eight subbasins varies from $21 to $48. We assigned the appropriate subbasin value to each Upper Basin agricultural water use. The values apply to a scenario where a change in water availability would cause a change in acres planted and no change in technology. The values overestimate the marginal value of water if farmers would react to increased water supply by increasing water application per acre rather than irrigating additional acreage. The values underestimate the marginal value of water if additional water could be utilized without increasing fixed (e.g., management) costs. We did not attempt more accurate estimates of the marginal value because they have little impact on the final estimates of the value of streamflow changes (as seen below, the streamflow changes rarely affect Upper Basin agricultural uses).

### *Upper Basin Transmountain Diversion*

Colorado River water is diverted via numerous tunnels and canals to cities and farms along the Colorado Front Range. Diversions to northern Colorado and the Denver area are sometimes affected by the streamflow increases. There is an active market for shares of Colorado–Big Thompson (CBT) project water, which is delivered to shareholders in the Northern Colorado Water Conservancy District [*Howe*, 1986]. Over the period 1965–1985, the price per acre foot of CBT shares has varied, in 1985 dollars, from $1,451 in 1965, to a high of $4,684 in 1980, to a low of $1,080 in 1985 [*Saliba et al.*, 1987]. The mean price over this 21-year period is $2,454, which is equivalent to a capitalized value of $98 per acre foot assuming a 4% interest rate.

Denver and its suburbs lie south of the Northern Colorado Water Conservancy District, and are generally perceived to be in greater need of additional water supplies. A proposed water development project, Two Forks, received the support of the governor of Colorado and the Denver Water Board. Two Forks was expected to cost approximately $460 million for construction and mitigation, and to yield about 100 KAF ($1.23 \times 10^8$ $m^3$) per year. Assuming a useful life of 50 years and a 4% interest rate, the annualized cost is $216 per acre foot, over twice the mean annual CBT price. We use this alternative cost of $216 per acre foot as an upper bound on the value of transmountain diversions. Note that delivery costs to the Front Range are positive in some locations and negative in others where power is generated as the water drops; in any case they are minimal and were ignored.

### *Central Arizona Project*

Only lower priority and excess CAP deliveries are affected by the flow increases. This water may be used directly in agriculture or recharged into the aquifer for later use. We used the imputed value approach under the assumption that the additional water would be used in agriculture in Pinal County, the agricultural area expected to be most dependent on CAP water, to grow the crops that currently occupy the most acreage. Upland cotton, Pima cotton, Durham wheat, and barley occupied a total of 89% of the agricultural acreage in Pinal County in 1985 (additional acreage was mainly in high-value vegetables and fruits, and not likely to be affected by variations in water supply) [*Arizona Agricultural Statistics Service*, 1986]. Based on *Hathorn et al.*'s [1985] crop budgets for Pinal County, the weighted (by acreage planted) annual return to water for these four crops is $27 per acre foot applied. As with the Upper Basin value estimates, these estimates apply to a scenario of increasing acreage with additional water availability.

From this estimate we must subtract the cost of applying

CAP water, which consists largely of pumping the water from the Colorado River to Pinal County and installing the surface water delivery system from the CAP canal to the farms. The lift required to reach the Pinal County farms includes 1212 feet (369.4 m) of head in the Granite Reef Aqueduct from Lake Havasu to Phoenix and an additional 84 feet (25.6 m) along the Salt-Gila Aqueduct to Pinal County. Pumping along these two stretches is estimated to require 1657 and 121 kWh per acre foot, respectively. This power is expected to be produced at a coal-fired plant. Given that the opportunity cost of the necessary power is 18 mills per kilowatt hour (see below), the total variable cost of pumping CAP water to Pinal County is about $32 per acre foot. Subtracting this $32 cost from the returns to water from farming leaves a negative balance, without even considering the cost of the necessary local delivery system. Thus, we assume no value to society of additional deliveries of CAP water for agricultural use.

### *Metropolitan Water District*

*Wahl and Davis* [1985] reported that MWD's least expensive alternative source of water was via water transfers from the Imperial Valley. Although it was unclear in 1985 whether the institutional mechanisms were available for such a transfer, there was the possibility that MWD could pay for capital improvements to the agricultural water delivery system in the Imperial Valley and then divert the conserved water via the Colorado River Aqueduct to the MWD service area. The institutional mechanisms appear to now be in place, for MWD currently has a tentative agreement to obtain 100 KAF ($1.23 \times 10^8$ m$^3$) per year from the Imperial Valley at an annualized cost estimated at $110 per acre foot [*Quinn*, 1989; *Holburn et al.*, 1988]. The cost includes the capital cost of the conservation measures, as well as costs for environmental mitigation, legal services, operating expenses, and other elements.

This agreement indicates that MWD is willing to pay at least $110 per acre foot for additional Colorado River water (the delivery cost, which is the same for all water delivered via the Colorado River Aqueduct, can be ignored here). Of course, this willingness to pay applies only if there is unused capacity in the Colorado River Aqueduct to deliver the water to the MWD. Once that capacity no longer exists, the marginal value of Colorado River water to MWD will drop considerably, because the value would then have to reflect the very high cost of new delivery capability. Thus, if MWD continues to obtain Colorado River water from other users, via additional conservation measures or just paying farmers to plant fewer acres, the $110 marginal value will only be temporary. At the point when the aqueduct is no longer available for additional deliveries from the Colorado River, the marginal user in California is likely to become the agricultural sector along the Colorado River or in the Imperial Valley, and the value of additional Colorado River water in California is likely to be similar to the above mentioned value in Arizona of $27 per acre foot. We use the $110 per acre foot value, recognizing that it may underestimate MWD's current willingness to pay but considerably overestimate the value in the long run.

### *Hydropower*

Hydropower is used to replace more expensive power produced at thermal plants. The marginal cost of the thermally produced power that is replaced by hydropower, minus the marginal cost of operating the hydropower plant, is an approximation of the marginal value of the hydropower. The marginal cost of hydroelectric plants was found to be very small, and not worth including in the calculation. The marginal costs of thermal plants were estimated by the costs of fuel at such plants, which are about 90% of total variable costs. Fuel prices at combustion turbine plants, used to produce peaking power, were about $0.05 per kWh nationwide. Fuel prices at coal-fired plants, used to produce base load power, were about $0.018 per kWh nationwide [*Energy Information Administration*, 1985; *Gibbons*, 1986]. The $0.05 and $0.018 costs were used to value peaking and base load hydropower, respectively.

### *Total Dissolved Solids*

Because flow increases from harvest are low in TDS, the increases would dilute the salts of water delivered to Lower Basin users. The value of such dilution was computed as the reduction in the costs that TDS impose on water users. There is some controversy about the adequacy of existing estimates of the costs of TDS on Lower Basin Colorado River water users, and certainly the definitive work on the subject has yet to be written. We based our estimates on work reported by *Anderson and Kleinman* [1978], *Kleinman and Brown*, [1980], and *d'Arge and Eubanks* [1978].

The total cost per mg/L change in TDS of Colorado River water is estimated to be $200,668 per year, based largely on more frequent replacement of pipes and appliances. This estimate may be conservative. For example, *Maas* [1986] reports reduction in production of some crops at TDS levels well below the 800 mg/L minimum assumed by Anderson and Kleinman for agricultural impacts. Furthermore, a recent study by *Lohman et al.* [1988], issued by BOR, estimated a 1986 cost of TDS in Colorado River water to Lower Basin users of nearly three times the *Kleinman and Brown* [1980] estimate.

## DISPOSITION AND VALUE OF FLOW CHANGE

Comparison of simulations with and without flow increases, all else equal, indicated the effect of the flow increases. Comparisons were performed for a base scenario (A) and three other scenarios (B–D). "Shortages" refer to the difference between authorized requests (all but the "excess" requests, Table 2) and depletions. Thus, in the Lower Basin, if depletions fall short of total requests, the shortfall can consist of shortages as well as unmet excess requests.

### *Base Scenario*

Scenario A reflects current demand, facilities, and institutional constraints. The characteristics of scenario A are as follows: (1) consumptive use requests at the 1990 level (Table 2); (2) normal flow trace of 78 years (1906–1983); (3) operating rules based on current practice and priorities, as described above; (4) streamflow increase average annual of 40 KAF ($4.9 \times 10^7$ m$^3$) from Arapahoe National Forest; (5) reservoir storage initially three-fourths of capacity.

*Consumptive use.* With just normal flows, mean annual requests exceeded deliveries to consumptive uses by 597 KAF ($7.36 \times 10^8$ m$^3$). Upper Basin shortages accounted for

TABLE 4. Projected Mean Annual Water Disposition, Unmet Requests, Hydroelectric Energy Production, and Lower Basin TDS Level for Scenario A

| | Normal Flows | Enhanced Flows[a] | Difference |
|---|---|---|---|
| Water disposition, KAF[b] | | | |
| Upper Basin | | | |
| Consumptive use | 3821.7 | 3822.1 | 0.4 |
| Evaporation | 645.1 | 647.5 | 2.4 |
| Lower Basin | | | |
| Consumptive use | 8302.5 | 8306.7 | 4.3 |
| Evaporation | 1209.6 | 1213.5 | 3.9 |
| Outflow to Mexico | 2556.6 | 2580.1 | 23.5 |
| Net change in storage | 2.4 | 7.5 | 5.1 |
| Unmet requests, KAF | | | |
| Upper Basin | 71.3 | 70.9 | −0.4 |
| Lower Basin | 525.6 | 522.2 | −4.3 |
| Hydropower production, kWh/$10^6$ | | | |
| Peaking power | 2973.0 | 2974.3 | 1.3 |
| Base load | 10473.3 | 10518.3 | 45.0 |
| Lower Basin TDS, mg/L[c] | 712.55 | 710.31 | −2.24 |

Scenario A is based on year 1990 consumptive use requests; current reservoir operating rules; 1906–1983 hydrologic record; reservoirs initially 75% full.

[a]Mean annual flow increase of 40 KAF from vegetation treatment on Arapaho National Forest.

[b]KAF denotes 1000 acre feet, equal to $1.2335 \times 10^6$ m$^3$.

[c]TDS in mainstem between Lakes Mead and Mohave.

only 71 KAF ($8.8 \times 10^7$ m$^3$) of this total (Table 4), and were shared by numerous diversions along four different river reaches. The majority of the Upper Basin shortages were concentrated in the years of the simulations corresponding to the more recent years of the 1906–1983 record, when flows were generally below average. In no case were shortages to Upper Basin requests caused by a Compact call from the Lower Basin. Rather, the observed shortages were caused by requests in excess of local water availability.

With just normal flows, Lower Basin requests exceeded deliveries by 526 KAF ($6.49 \times 10^8$ m$^3$) per year (Table 4) (the annual shortfall in deliveries ranged from 140 to 650 KAF (1.73–8.02 $\times 10^8$ m$^3$) over the typical 78-year simulation). The CAP and MWD excess requests accounted for almost all of this shortfall, averaging 40 and 484 KAF (4.9 and 59.7 $\times 10^7$ m$^3$) per year, respectively. Thus, there was almost always sufficient water to meet all Lower Basin requests except these two requests in excess of Compact requirements.

About 491 KAF ($6.06 \times 10^8$ m$^3$) per year on average were delivered to the MWD and CAP excess requests. This delivery resulted from Mead releases because of the "surplus strategy" (priority 10) and Mead flood control releases and spills (priority 12). The full 365 KAF ($4.50 \times 10^8$ m$^3$) potentially made available from Mead because of the surplus strategy were delivered every year, but deliveries to the excess accounts resulting from Mead flood control releases and spills were intermittent, and averaged 126 KAF ($1.55 \times 10^8$ m$^3$) per year.

During most months when flood control releases were made, the releases were greater than the needs of the two excess requests, resulting in deliveries to Mexico in addition to the 1.5 MAF ($1.85 \times 10^9$ m$^3$) obligation. Additional deliveries to Mexico occurred during most of the high-flow years, and during a few other years, for a total of about 30 of the 78 years, and averaged 1.042 MAF ($1.285 \times 10^9$ m$^3$) per year.

Over both Upper and Lower Basins, streamflow increases averaging 40 KAF ($4.9 \times 10^7$ m$^3$) per year from the Arapaho National Forest alleviated 4.7 KAF ($5.8 \times 10^6$ m$^3$) of the consumptive use request shortfall. Upper Basin shortages were alleviated during about five of the 78 years simulated, for an average annual shortage reduction of 0.43 KAF ($5.3 \times 10^5$ m$^3$) (Table 4). This water was diverted from the Upper Colorado mainstem to users in the Front Range. In the Lower Basin, shortfalls were alleviated during about 15 of the 78 years by deliveries to the "remainder" CAP and MWD excess accounts (priority 12). The mean annual decrease in shortfall was 4.3 KAF ($5.3 \times 10^6$ m$^3$).

The streamflow increase that was not consumptively used either evaporated, flowed on to Mexico, or was in storage at the end of the simulations. On an average annual basis, 6.3 KAF ($7.8 \times 10^6$ m$^3$) evaporated, 23.5 KAF ($2.90 \times 10^7$ m$^3$) flowed to Mexico, and 5.1 KAF ($6.3 \times 10^6$ m$^3$) contributed to end-of-simulation storage (Table 4).

The streamflow increases did little to enhance deliveries to the Lower Basin excess requests, for two reasons. First, the stochastic nature of flow, compare with the timing of requests for consumptive use, limits the proportion of marginal flows that can be delivered for consumptive use. This is probably true for all river basins [*Brown*, 1987; *Brown and Fogel*, 1987]. Second, the specific rules followed in the Basin hinder delivery at the margin because they emphasize (1) saving water in storage to meet future high priority uses at the expense of current requests by lower priority uses and (2) hydroelectric energy production. The increases tended to accumulate in Lakes Powell and Mead, increasing the surface area of the reservoirs and thereby increasing evaporation. The increases accumulated in Lake Powell because Powell storage was sufficient to meet required releases to the Lower Basin without the flow increases. Generally they were only released from Powell when Powell spilled or when releases were made to enhance "equalization" of storage in Lakes Powell and Mead. The increases then accumulated in Lake Mead until Mead spilled or releases were made for flood control purposes. Because Mead spills and flood control releases were available to meet CAP and MWD excess requests, the increases that were included in the spills and flood control releases sometimes alleviated shortages to these two requests.

However, in most months the increases in spills and flood control releases that were caused by the increased streamflow were not needed, because the releases in absence of the streamflow increases were sufficient to meet the requests of the CAP and MWD excess accounts. That is, the increases tended to be released from Mead during months when there was sufficient flow in the Lower Basin mainstem to satisfy the CAP and MWD excess requests, so that the increases flowed on to the Gulf of California. Occasionally, however, the streamflow increases were released from Mead for flood control reasons during a month when the excess requests were short.

*Hydropower.* With just normal flows, average annual energy production at the 11 hydropower plants included in the model (Table 1) totaled 13,446 million kWh (Table 4). Twenty-two percent of this was peaking power. The streamflow increases enhanced energy production by 46 million kWh. Some additional energy was produced during every year of the simulations. The annual increase in additional energy produced varied from a low of 10 million to a high of 175 million kWh. The increased energy production with the additional inflow is attributable both to the additional releases and to the increased head caused by additional storage. About half of the increase in energy was produced at Glen Canyon (Lake Powell), and the remainder was produced at the three Lower Basin plants. Only 3% of the increase was peaking power. Little of the additional flow produced peaking power because the power plants were typically operating at capacity during peak demand times without the additional flows. Thus, the additional flows tended to be released during nonpeak times.

*Total dissolved solids.* With just normal flows, TDS averaged 712.6 mg/L below Lake Mead. The streamflow increases decreased mean annual TDS by 2.24 mg/L (Table 4).

*Value of streamflow increases.* As specified in equations (2) and (3), monetary values (Table 3) were multiplied by the appropriate mean annual quantities of use of the flow increase to determine the value of each category of use. For example, 0.43 KAF ($5.3 \times 10^5$ $m^3$) of the 40 KAF ($4.9 \times 10^7$ $m^3$) annual streamflow increase was delivered to Upper Basin consumptive users via transmountain diversion. When valued at \$98 per acre foot, this delivery contributed \$1.05 to the per acre foot value of the flow increase ($(0.43 \times 98)/40 = 1.05$). The values of the separate use categories were summed to yield a value of about \$40 per acre foot of streamflow increase (Table 5). Over the four hydrologic traces, this value ranged from \$39 to \$43 per acre foot. Consumptive use, hydropower, and salt dilution contribute \$7, \$22, and \$11, respectively, to this total (Table 5).

*Bowes et al.* [1984] estimated a gross marginal value of water from vegetation management of roughly \$65 per acre foot per year, which does not differ greatly from our estimates of about \$40 per acre foot given current institutions and demand. However, the similarly is largely fortuitous. While the hydroelectric power component of the Bowes et al. estimate of value is almost identical to ours (about \$22 per acre foot), there are major differences in other components. Consumptive use contributes 65% of the Bowes et al. value, but less than 20% of ours. This difference is due more to the difference in methods for determining the allocation of flow increases than to the differences in value of water applied to individual uses. Bowes et al. simply assumed that all flow increases would be delivered to consumptive uses. Finally, Bowes et al. did not include the value of flow increases in salt dilution, which contributed almost 30% of our value estimate.

TABLE 5. Effect and Value of Streamflow Increase With Alternative Scenarios

| | Scenarios[a] | | | |
|---|---|---|---|---|
| | A | B | C | D |
| *Physical Effect of Increase* | | | | |
| Water disposition, KAF[b] | | | | |
| Consumptive use | | | | |
| Upper Basin | 0.4 | 0.5 | 0.4 | 0.5 |
| Lower Basin | 4.3 | 0.5 | 12.1 | 9.4 |
| Evaporation | 6.3 | 7.4 | 6.9 | 6.8 |
| Flow to Mexico | 23.5 | 16.5 | 16.5 | 13.6 |
| Net change in storage | 5.1 | 4.7 | 3.7 | 9.3 |
| Total | 39.6 | 39.6 | 39.6 | 39.6 |
| Hydropower, kWh/$10^6$ | 46.3 | 75.2 | 73.4 | 56.2 |
| Reduction in Lower Basin TDS, mg/L | 2.24 | 2.31 | 2.13 | 2.16 |
| *Value of Increase, dollars per acre foot*[c] | | | | |
| Consumptive use | 6.96 | 15.86 | 17.86 | 14.29 |
| Hydropower | 22.05 | 41.09 | 39.32 | 28.62 |
| Salt Dilution | 11.36 | 11.72 | 10.79 | 10.95 |
| Total | 40.38 | 68.67 | 67.97 | 53.85 |

[a]Scenario A: consumptive use at year 1990 level; current reservoir operating rules; 1906–1983 hydrologic record; mean annual streamflow increase from Arapaho National Forest of 40 KAF ($4.9 \times 10^7$ $m^3$). Scenario B: same as scenario A except consumptive use requests for year 2000. Scenario C: same as scenario A except flexibility in releasing from Lake Mead to meet excess demands. Scenario D: same as scenario A except lower target storage levels.

[b]KAF denotes 1000 acre feet, equal to $1.2335 \times 10^6$ $m^3$.

[c]Values are in 1985 dollars; marginal values from Table 3.

## Sensitivity Analysis

Two levels of sensitivity analysis were performed. The first examined the importance of the following aspects of scenario A: initial storage levels, hydrologic record, amount of streamflow increase, location of streamflow increase, quantity of Lower Basin excess request, and marginal economic values of specific water uses. The second, more fundamental, level of analysis examined three alternative scenarios, focusing on the general level of consumptive use requests and reservoir operating rules. Each of these changes from scenario A was evaluated assuming all other aspects of scenario A remained unchanged.

*Initial storage level.* Initial reservoir storage affected water allocation during the first years of a simulation, but did not significantly affect simulation average results. The value of streamflow increases was \$40 per acre foot whether reservoirs were initially three-fourths full, as in scenario A, or only one-quarter full.

*Hydrologic record.* The first 30 years of this century experienced what, according to tree ring studies [*Stockton and Jacoby*, 1976], were unusually high flows. To avoid these high flows, the analysis was performed based on the flow records for the 54 years from 1930 to 1983. Mean annual virgin flow at Lee Ferry was 13.7 MAF ($1.69 \times 10^{10}$ $m^3$) during this period, compared with 14.9 MAF ($1.84 \times 10^{10}$ $m^3$) for 1906–1983.

The change in hydrologic record had a significant effect on use of normal flows. Volume of Upper Basin shortages increased by 39%, volume of Lower Basin unmet requests increased by 13%, hydroelectric energy production decreased by 39%, and outflow to Mexico dropped almost to the minimum of 1.5 MAF ($1.85 \times 10^9$ $m^3$) per year.

The increase in Upper Basin shortages allowed more of the streamflow increase to be delivered to Upper Basin consumptive uses. However, the lower flows resulted in fewer excess releases from Lake Mead, thereby lowering delivery of the flow increases to Lower Basin consumptive uses, increasing evaporation of the flow increases, lowering release to Mexico of the increases, and decreasing total additional kWh of energy. The value of the streamflow increases was $41 per acre foot, slightly higher than with scenario A. Thus, while the reduction in normal flows with this scenario caused large changes in the use and value of normal flows, compared with scenario A, it had little effect on the disposition and value of the flow increases.

*Amount of streamflow increase.* The mean annual streamflow increase was increased from 40 to 80 KAF (4.9 to $9.9 \times 10^7$ $m^3$). The value of the streamflow increases decreased only slightly as a result, to $39 per acre foot. This insensitivity of the value of flow increase to the amount of the increase suggests a roughly linear value function within the range from 40 to 80 KAF (4.9 to $9.9 \times 10^7$ $m^3$) of increase.

*Location of flow increase.* Two alternative sources of streamflow increase from timber harvest were hypothesized. First, the increase was assumed to occur on the Grand Mesa, Uncompaghre, and Gunnison (GMUG) National Forests of western Colorado, to contribute additional flows at five separate model nodes, one on the upper mainstream, three along the Gunnison River, and one on the Dolores River. This change increased the value of the streamflow increase, compared with scenario A, to $44 per acre foot. Second, the flow increases were hypothesized to occur on the San Juan National Forest of southwestern Colorado, to contribute additional flows at three model nodes, two on the San Juan River and one on the Dolores River. This change in location caused a small increase in the value, to $41 per acre foot. The increases in value occurred mainly because of additional power produced along the Gunnison and San Juan Rivers.

*Excess requests.* Purchase of Colorado River water from agricultural users by MWD could eventually fill the Colorado River Aqueduct, eliminating MWD's ability to accept additional flow and in essence eliminating MWD's excess demand. If such transfers happened, the value of streamflow increases would drop to $34 per acre foot.

There is some indication that CAP requests will be lower than the requests assumed for scenario A. One possibility is that CAP excess requests would not exist. Eliminating CAP excess requests dropped the value of flow increases from $40 to $39 per acre foot. This slight drop in value resulted from reduced deliveries of the flow increases to the MWD excess account, which occurred because the lack of the CAP excess request allowed slightly more of the normal flow to be delivered to MWD, leaving less of a deficit to be potentially met by the flow increases.

Eliminating the CAP excess request changed deliveries to the MWD excess request only slightly; similarly, eliminating the MWD excess request changed deliveries to the CAP excess request only slightly. These effects were small because the reduction in each request was not sufficient to substantially increase Mead spills or flood control releases during months when the remaining excess request was not already being met.

TABLE 6. Projected Mean Annual Water Disposition, Unmet Requests, Hydropower Production, and Lower Basin TDS Levels for Alternative Scenarios Given Normal Flows

| | Scenarios[a] | | | |
|---|---|---|---|---|
| | A | B | C | D |
| Water disposition, KAF[b] | | | | |
| Upper Basin | | | | |
| Consumptive use | 3821.7 | 4297.3 | 3821.3 | 3829.2 |
| Evaporation | 645.1 | 594.7 | 596.8 | 614.9 |
| Lower Basin | | | | |
| Consumptive use | 8302.5 | 8330.0 | 8754.4 | 8537.6 |
| Evaporation | 1209.6 | 1129.5 | 1120.6 | 1170.2 |
| Outflow to Mexico | 2556.6 | 2270.1 | 2334.9 | 2391.0 |
| Net change in storage | 2.4 | −93.5 | −90.4 | −5.4 |
| Unmet requests, KAF | | | | |
| Upper Basin | 71.3 | 155.7 | 71.7 | 63.8 |
| Lower Basin | 525.6 | 616.0 | 73.3 | 290.4 |
| Hydropower production, million kWh | 13446.3 | 12629.2 | 13139.6 | 13039.2 |
| Lower Basin TDS, mg/L[c] | 712.6 | 741.0 | 703.3 | 709.3 |

[a]Scenario A: year 1990 consumptive use requests; current reservoir operating rules; 1906–1983 hydrologic record; reservoirs initially 75% full. Scenario B: same as scenario A except consumptive use requests for year 2000. Scenario C: same as scenario A except flexibility in releasing from Lake Mead to meet excess requests. Scenario D: same as scenario A except lower target storage levels.
[b]KAF denotes 1000 acre feet, equal to $1.234 \times 10^6$ $m^3$.
[c]TDS in mainstem between Lakes Mead and Mohave.

*Economic values.* Because the value of streamflow increases, as computed here, is simply an additive function of the unit values of the different uses to which the increases are put (equations (1)–(3)), the effect of changes in the unit values is easily calculated. The dollar changes in the value of the streamflow increase, given changes in the marginal values of specific uses, are listed for scenario A in the right-hand column of Table 3. For example, the value of the flow increase changes $0.011 per dollar change in the value of Upper Basin transmountain diversion. Thus, if the value of such diversions were $216 rather than $98 per acre foot (a possibility suggested above), the value of the flow increases would increase by $1.30 per acre foot (suggesting that the value of flow changes is not very sensitive to variations in the value of transmountain diversions). Similarly, a doubling of the MWD value would increase the value of flow increases by $5.94 per acre foot.

*Scenario B: Year 2000 consumptive use requests.* This scenario substitutes the year 2000 consumptive use request level (Table 2) for the year 1990 request level of scenario A. Given only normal flows, both consumptive use deliveries and unmet requests were greater than with the year 1990 requests (Table 6). Upper Basin shortages more than doubled, to 156 KAF ($1.92 \times 10^8$ $m^3$) per year, and Lower Basin unmet requests increased by 17% to average 616 KAF ($7.60 \times 10^8$ $m^3$) per year. Also, because the largest increases in consumptive use occurred in the Upper Basin, less of the normal flow reached the major hydroelectric plants, and hydroelectric energy production consequently decreased, by 6%, compared with scenario A.

Deliveries of the flow increases to consumptive uses more than doubled with this scenario, compared with the year 1990 consumptive use request level of scenario A, reaching 10 KAF ($1.2 \times 10^7$ $m^3$) per year, or about one-fourth of the flow increase (Table 5). Most of the deliveries of the flow increases went to Lower Basin "surplus strategy" excess CAP and MWD uses (priority 10), plus in some cases CAP low priority uses (priority 9). Because these accounts were of higher priority than Lake Mead storage above the "shortage" level, any flow increases in storage above that level were available to meet these requests. Furthermore, the increase in energy production caused by the streamflow increases was considerably greater given the year 2000 requests than it was given the 1990 requests, principally because more of the flow increase eventually reached the major Lower Basin diversions, thereby passing through Glen Canyon, Hoover, and Davis dams.

The value of the flow increases is $69 per acre foot given the year 2000 consumptive use requests, $29 more than given the 1990 requests (Table 5). The increase in value occurred mainly because of the increase in hydroelectric energy production.

*Scenario C: More flexibility in Mead releases to excess requests.* This scenario incorporates a change in priorities to allow additional releases from Lake Mead to meet Lower Basin requests in excess of those authorized by interstate compact. With scenario A, only 36% of the CAP and MWD excess requests (priority 10) were subject to deliveries from Lake Mead storage above the "shortage" level. With this scenario, storage in Lake Mead above the "shortage" level was assumed to be available for all the excess requests.

The primary effects of this change, given just normal flows, were to lower mean annual end-of-year storage in the Basin from 45.7 MAF ($5.64 \times 10^{10}$ $m^3$) with scenario A to 40.1 MAF ($4.95 \times 10^{10}$ $m^3$), reduce Lower Basin unmet requests by 86%, and decrease hydroelectric energy production by 2% (Table 6). The flow increases under this scenario were more effectively delivered to Lower Basin users, and produced considerably more energy, compared with scenario A (Table 5). The large increase in energy occurred because of the increased releases of the flow increase from Lakes Powell and Mead, and the enhanced effect of the flow increases on hydraulic head because the reservoirs were lower in storage. The value of the flow increase was $68 per acre foot with this scenario (Table 5). This value rises to $90 per acre foot assuming consumptive use requests at the year 2000 level.

*Scenario D: lower target storage levels.* In this scenario, the target storage levels of all reservoirs were set at the lesser of (1) 75% of reservoir capacity (of capacity minus 1.5 MAF ($1.85 \times 10^9$ $m^3$) of flood control space in the case of Lake Mead), and (2) target storage of scenario A (see Table 1). By far the largest changes from scenario A caused by this rule were in target storage levels of Lakes Powell and Mead, which were reduced to 18.3 and 19.1 MAF (2.26 and $2.36 \times 10^{10}$ $m^3$) respectively. Because storage above the target level has lower priority than any consumptive use, lowering the target storage levels makes more water available for low priority consumptive uses such as the CAP and MWD excess requests.

The primary effects of this change on disposition of normal flows were to lower Basin storage levels (mean end of year storage dropped to 43.7 MAF ($5.39 \times 10^{10}$ $m^3$) from 45.7 MAF ($5.64 \times 10^{10}$ $m^3$) with scenario A), reduce Lower Basin unmet requests by 45%, and reduce hydroelectric energy production by 3% (Table 6). The flow increases were more effectively delivered to Lower Basin users, compared with scenario A, with almost 25% of the increase being delivered to consumptive uses (Table 5). However, energy production remained the principal component of the value of the flow increase, which totaled $54 per acre foot.

## SUMMARY AND CONCLUSIONS

Modeling river basin water storage, loss, and routing is an important step in understanding the disposition of streamflow increases. The timing of such increases, as well as the facilities and institutions that control their allocation, can play important roles in utilization of the increase. In the Colorado River Basin, such modeling indicates that given current consumptive use requests and institutional arrangements, only about 12% of the flow increases would be consumptively used. This percentage increases to 28% given year 2000 requests, and to 32% given a change in reservoir operating rules at Lake Mead to facilitate deliveries to the excess requests.

If reservoir storage is lacking, delivery of streamflow increases to consumptive users is dependent on the timing of those increases. Lack of storage on the Upper Basin mainstem above Lake Mead sometimes limited ability to deliver flow increases to Upper Basin consumptive users, but this limitation was of relatively minor consequence because of the general lack of Upper Basin shortages. Far more important in limiting delivery of the flow increases to Basin consumptive users were the reservoir operating rules for Lakes Powell and Mead, which are of course a reflection of important institutional constraints. Clearly, ample reservoir storage and consumptive use demand, as found in the Lower Basin, do not guarantee that a high proportion of flow increases will be consumptively used if reservoir operating rules favor other objectives.

The consumptive use rates found here can be compared with those of two other studies that evaluated delivery of flow increases to consumptive use. *Brown et al.* [1988] found for the Colorado River Basin that at a future demand level and assuming that water was allocated to consumptive uses according to the marginal economic value of each use type, about 50% of streamflow increases were consumptively used. And, in the Salt Verde Basin of Arizona, where delivery to consumptive users is less constrained by institutional arrangements than in the Colorado River system, *Brown and Fogel* [1987] found that from 40% to perhaps 60% of streamflow increases would be delivered to consumptive uses.

Given current institutions, the year 1990 consumptive use request level, and reasonable variations in assumed parameters, the expected value of flow increases from timber harvest on national forest land varied from $34 to $46 per acre foot. Consumptive use of the flow increases contributed less than 20% of this value, while hydroelectric energy production contributed close to 50% and salt dilution contributed the remainder. The value was relatively insensitive to changes in initial storage, the amount of normal flow, the amount of flow increase, the location of the flow increase, and the value of Upper Basin consumptive use. The value was somewhat more sensitive to reasonable alterations in the MWD excess request and to values of Lower Basin consumptive use, hydroelectric energy, and salt dilution.

The value of the flow increase was very sensitive to changes in consumptive use request level (scenario B) and changes in reservoir operation criteria designed to enhance consumptive use deliveries (scenarios C and D). The value of the flow increase given these scenarios varied from $54 to $69 per acre foot (Table 5). Most of the increases in value with these three scenarios, compared with scenario A, are attributable to increases in hydroelectric energy production.

The purpose of this paper was to estimate the economic value of streamflow increases, and understand the sensitivity of that value to changes in location of the increases, consumptive use requests, reservoir operating rules, and other factors. In the course of investigating that sensitivity, we found that the impacts of flow increases on water use are dwarfed by the impacts of changes in reservoir operating rules (scenarios C and D). For example, the changes in target storage of scenario D lowered shortfall in delivery to Lower Basin excess requests by 45%, compared with scenario A, while the flow increases caused less than a 3% change in these shortfalls under either scenario. Clearly, flow increase from vegetation management is not the only option for addressing expected water requests in the Colorado River Basin. Even if a complete analysis of forest management, one that also evaluated the impact on flooding, timber yields, and other aspects ignored here, showed that the benefits of timber harvest exceeded the costs, there may be more efficient, largely institutional, approaches to reaching the same goals. Such institutional mechanisms for dealing with expected water shortages in the Colorado River Basin should certainly receive additional exploration.

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