MARKET-BASED OPERATION TO IMPROVE THE EFFICIENCY OF WATER SUPPLIES FROM THE COLORADO RIVER BASIN

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Disposition of water supplies in the Colorado River Basin was simulated under several different allocation systems and two levels of demand. Under the current system of compacts and reservoir operation rules no significant shortfalls were observed at the current demand level. At future demand levels, shortages reached disruptive levels. These shortfalls principally affected the Metropolitan Water District, and their magnitude depended on assumptions regarding surplus release policies at Lake Mead. Under a system of allocation based on economic values, shortages to high-valued M&I users could be dramatically reduced at the expense of modest increases in shortfalls to lower-valued uses (primarily agriculture), but occasional severe shortages to municipal users in both basins persisted . Shortages to municipal users could be eliminated by instituting a reserve policy in mainstem reservoirs, with water purchased from low-valued uses and maintained in storage for use by high-valued uses during drought periods.

This paper reports the quantification of expected relative benefits of alternative management schemes involving transfers of water within the Colorado River Basin. It builds on the results of a study of the disposition of incremental streamflow from forestry practices in the Basin (Brown, et al, in press). The paper first describes the physical and institutional setting of the Colorado River Basin. It then briefly describes the model used to analyze alternative management schemes. Then the estimated effect of management changes is described.

INTRODUCTION

Interest in interstate transfers of water or water rights within the Colorado River Basin has grown in the last decade. Take for example the recent proposal by the Galloway group to transfer water rights from the Yampa river in Colorado for use by the city of San Diego (Bird, 1987) and the current efforts of the Ute Mountain Ute and Southern Ute tribes to obtain Federal legislation to construct the Animas-La Plata project in southwestern Colorado and subsequently lease or sell water from that project to unspecified buyers outside of Colorado. In California, one potential source of supply which the Metropolitan Water District has investigated is the transfer of water from agricultural uses in the Imperial Valley (Wahl and Davis, 1985; Stavins, 1983).

The reason for the interest in transfers is partly due to the geography and hydrology of the basin; part is due to demographics and part is an artifact of the system of institutions which has evolved to manage water within the basin.

The Colorado River Basin drains nearly 250,000 square miles in seven western states before entering Mexico and then the Gulf of California. The Basin is divided politically at Lee Ferry, about 10 miles south of the Arizona-Utah border, into the Upper and Lower Basins. The Upper Basin contains 44% of the land area but contributes 83% of the water yield of the Basin (Hibbert, 1979).

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The natural flows in the Basin are highly irregular in occurrence. While the virgin flow at Lee Ferry has averaged 14.8 million acre feet annually over the study period, annual flows in excess of 23 million acre feet and less than 7 million acre feet have been recorded. Over 70% of the annual virgin flow occurs in the months of May, June, and July.

A formidable array of reservoirs and diversion facilities alters the flow of the Colorado River and its tributaries. The Colorado mainstem's two principal reservoirs, Lake Powell and Lake Mead, provide over 50 million acre feet of storage. Other major reservoirs in the U.S. add over 10 million acre feet of storage, bringing total storage to over 4 times the mean annual flow at Lee Ferry.

Water is diverted from the river at hundreds of relatively small diversion points in the Upper Basin; in the Lower Basin diversions tend to be larger and considerably fewer in number. Major diversion structures in the Lower Basin include the Colorado River Aqueduct that delivers water to the Los Angeles Basin, the Granite Reef Aqueduct supplying the Central Arizona Project (CAP), and the All American Canal System bringing water to the Imperial Valley of California. Below the international boundary, Morelos Dam diverts water for irrigation in the Mexican states of Baja California and Sonora.

Though the vast majority of water in the Basin originates in the Upper Basin, established uses for water in the Lower Basin today are much greater than established uses in the Upper Basin and even exceed any reasonable estimate of fully developed Upper Basin uses; currently 68% of the consumptive use of mainstem water supplies occurs in the Lower Basin.

The institutional setting is principally determined by judicial, statutory, and administrative decisions. Intrastate water allocation largely follows the doctrine of prior appropriation. Although the states differ somewhat in procedures for implementing that doctrine, those differences are of little consequence at the level of detail of this study. Much more important for this study are the interstate water allocation decisions that have resulted from federal legislation and judicial actions to settle interstate disputes. Important aspects of five of those decisions are reviewed here (see also Myers, 1966).

(1) The Colorado River Compact of 1922 apportioned the flow of the river between the Upper and the Lower Basins and required the Upper Basin to deliver to the Lower Basin a ten-year moving average of 7.5 million acre feet, measured at Lee Ferry, plus, if necessary, a share of the Mexican treaty obligation. (2) The Mexican Water Treaty of 1944 set that obligation at 1.5 million acre feet per year. (3) The Upper Colorado River Compact of 1948 allocates among the Upper Basin states any curtailment of use of Colorado River water which might be necessary to meet calls under the 1922 Compact. (4) The U.S. Supreme Court's opinion and decree in <u>Arizona v. California</u> (1963,1964) awarded 2.8 million acre feet of mainstem supplies annually to Arizona, 4.4 million acre feet annually to California, and 300,500 acre feet annually to Nevada. (5) The Colorado River Basin Act of 1968 instructed the Secretary of the Interior to develop and adopt criteria for the operation of the series of federal reservoirs which had been constructed to manage the river's flow. The statutory guidelines provide that the operating rules for Glen Canyon and Hoover Dams, in particular, will assure compliance with the Mexican Treaty, deliver the required 75 million acre-feet per decade to the Lower Basin states, provide carry-over storage to accomplish the first two objectives, and maintain parity in the active storage between Lakes Powell and Mead. The 1968 Act also added another significant operational constraint by making Arizona mainstem diversions under Central Arizona Project (CAP) junior to the first 4.4 million acre feet of California mainstem allocations, as well as to Arizona's non-CAP allocation and Nevada's entitlement.

The net result of the institutional framework is that the right to use water has been vested to entities which cannot now (nor in the foreseeable future) put the water to economical uses, or are currently putting water to low-valued uses. Rights to surplus water are vested to Upper Basin entities and the Central Arizona Project. The marginal values for current uses are generally in agriculture, primarily in the Upper Basin. Entities with current or projected shortfalls are generally municipal users with the most prominent being the Metropolitan Water District (MWD) in southern California.

MWD relies on surplus supplies in excess of California's entitlement of 4.4 million acre feet under Arizona v. California. The CAP has a higher priority entitlement to waters of the Colorado and as uses develop under that project the surplus available to MWD will begin to decline. Further, if additional uses are developed in the Upper Basin, both CAP and MWD would find their supplies diminished. As a result, MWD must plan for a shortfall and has been looking for other sources of supply.

TRANSFERS AS A WATER SUPPLY

Transfers of water or water rights are common within the states of the Colorado River basin. In Colorado, the vast majority of new municipal supplies are transfers of water rights from agricultural users. Intrastate transfers today take place in a market environment which is limited by a regulatory or judicial trustee which assures that non-parties are not injured or are adequately compensated. Proposed interstate transfers of water have met political opposition because they have not met the test of non-injury.

This situation represents something of a "Catch 22". Current institutional frameworks do not recognize interstate transfers of water and thus have no mechanism to insure against non-injury of others. Institutional change is driven, in part, by the political environment which, because of concerns about third party effects, currently opposes necessary institutional change.

If there is to be institutional change, it will come slowly and will be driven by the perception that 1) the benefits of water transfers will substantially outweigh the costs and 2) that those benefits can and will be distributed in such a way that all of the participants and third parties will be better off or at least no worse off. Already, there is evidence of such change, coming as it often does through the courts and driven by entities whose self-interest is served by interstate transfers. (Sporhase, 1982; El Paso, 1983, 1984).

METHODS OF ANALYSIS

This study quantified the relative hydrologic effect of two market-based allocation schemes compared to the current system of compacts and operating rules. An estimate was also made of the relative economic effect of market-based operations.

This analysis was done using a model which simulated water flow, storage, use, and losses within the Basin. The simulation covered a 72-year period of record from 1906 through 1977. The model uses a linear programming network optimization approach based on the Out-of-Kilter Algorithm (OKA) (Fulkerson, 1962; Barr et al. 1974) which has been used by MODSIM (Shafer 1979; Labadie et al. 1983) and its predecessor SIMYLD (Texas Water Development Board, 1972). The OKA solves a circulating network of arcs connected at nodes which can describe a physical system. Each arc in the network can be assigned a characteristic unit transportation cost, along with upper and lower bounds to flow. The OKA performs a static optimization of flow at each time step by minimizing the objective function of total network transportation cost while respecting the specified constraints. By changing the mapping schemes for unit costs and upper and lower bounds for the arcs which make up the network, different allocation methods can be simulated. A more detailed description of the methods used for this analysis can be found in Harding et al. (1986).

Colorado River Basin Network

The Colorado River Basin network was configured with 41 nodes representing points of inflow/outflow, storage, and demand. The network contains six reservoirs with a total active capacity of 60 million acre feet. Each reservoir was represented as a "reserve" pool and "conservation" pool. In addition, Lake Mead included an "excess" pool and "flood" pool.

Seven consumptive water use areas were specified in the network. Five of these are in the Upper Basin: the Upper Green River area above Flaming Gorge Reservoir in western Wyoming; the Lower Green River area in western Utah, including such tributaries as the Duchesne and San Rafael; the Yampa area in the vicinity of the Yampa, White, and Little Snake Rivers in northwestern Colorado; the Upper Colorado area near Grand Junction, Colorado, including the Gunnison and Dolores drainages; and the San Juan drainage east of the Four Corners. Each of these areas was represented by individual nodes for agricultural, M & I, and energy uses. The Lower Basin use area was represented by six nodes, one for agriculture and one for M & I use in Nevada and Arizona along the Colorado River, one for the Phoenix-Tucson area via the Central Arizona Project (CAP), and three for California. The California nodes distinguished agricultural use, the Los Angeles area's Metropolitan Water District (MWD) authorized use under interstate agreement, and use by MWD in excess of the agreements. Mexico is the seventh use area.

Flows

Flows were based on a 72-year period (1906-1977) of reconstructed virgin flows developed by the U.S. Bureau of Reclamation for use with the Colorado River Simulation Model (USBR, 1982).

Water Demand

In order to test the effect of increasing demand for water, two demand levels, representing current and potential future conditions, were employed. Diversion and return flow were estimated separately for each demand node, and the net, consumption, was used in the model.

Annual demands for consumptive use are listed in Table 1. The figures were taken largely from those developed by the U.S. Bureau of Reclamation (1982) for use as input to the Colorado River Simulation Model for the purpose of modeling salinity in the Basin. The "current" levels reflect 1980 conditions with the following qualification: A few projects were considered completed by the Bureau and were assigned nominal levels of consumption. In fact, some of these projects, most notably the CAP, have not yet achieved the diversions specified in the 1980 data set. Rather than reflecting actual diversions in 1980, these data should be considered a baseline representing the current inventory of completed projects.

The "future" levels reflect demands that may exist in the year 2030. Future Upper Basin demands were derived largely from forecasts of water development to accommodate new energy development and municipal expansion. Complete realization of these projected increases in the Upper Basin would require construction of many new facilities. Some increases in Lower Basin demands were also included; however, some of these projections may be biased low by interpretation of existing institutional arrangements in light of projections of increased consumption in the Upper Basin. Neither Upper nor Lower Basin future demand levels reflect econometric projections of demand.

The Upper Basin demands for consumptive use total 3.5 and 5.3 million acre feet in the current and future scenarios, respectively. Considerable capital investment would of course be required before such use levels could develop, and they probably represent an upper bound on possible future use. The two corresponding Lower Basin demands total 7.4 and 8.9 million acre feet. Adding in the 1.5 million acre feet delivery to Mexico brings total demand to 12.4 and 15.6 million acre feet for the current and future scenarios, respectively (less evaporation from mainstem reservoirs).

Table 1. Annual Demand for Water Under Current and Future Conditions (1000 af)

Use Area and Demand Node		Current	Future
Upper Green:	Agriculture	286	342
	M & I	36	144
	Energy	32	187
Lower Green:	Agriculture	591	818
	M & I	65	143
	Energy	18	207
Yampa:	Agriculture	126	138
	M & I	13	39
	Energy	16	21
Upper Colorado:	Agriculture	1481	1658
	M & I	280	611
	Energy	0	100
San Juan:	Agriculture	405	729
	M & I	57	30
	Energy	48	90
Upper Basin Agriculture		2889	3685
Upper Basin M & I		451	967
Upper Basin Energy		114	605
UPPER BASIN TOTAL		3454	5257
Arizona/Nevada Agriculture		1310	1250
Arizona/Nevada M & I		198	384
Central Arizona Project (CAP)		765	2100
California Agriculture		3902	3902
California Metropolitan Water District (MWD)		498	498
MWD Excess		729	729
Lower Basin Agriculture		5212	5152
Lower Basin M & I		2190	3711
LOWER BASIN TOTAL		7402	8863
MEXICO		1500	1500
TOTAL BASIN DEMAND (less evaporative losses)		12356	15620

Allocation Systems

Three systems of allocation were examined in this study. These used two objective functions, one institutional and one economic. The institutional one reflected the interstate compacts, international treaties, court decisions, and operating rules for the system of federal reservoirs that were summarized earlier. This complex of institutions establishes a hierarchical relationship among claims on limited water supplies, which is represented in the first objective function by a series of weights on the various water demands (i.e., costs on flow in network links) according to the priority which existing institutional arrangements established for that demand.

The economic objective function assumes that, with the exception of the Mexico Treaty obligation, market forces alone would determine water use. It assumes that existing interstate allocation institutions are abandoned or modified and that alternative institutions exist that permit free transfer of water. The weights of this objective function for the various water demands were ordered in terms of the marginal value of water in each respective use.

The institutionally-based objective function was applied to both current and future demand levels. Under the priorities of this objective function, Upper Basin demands were satisfied before any reservoirs and Lower Basin demands, but were subordinate to the Lee Ferry delivery obligation. All beneficial consumptive uses in the Upper Basin were given identical priorities. Upper Basin reservoirs were filled after any demand in the Upper Basin but before any demand or reservoir in the Lower Basin.

Demands in the Lower Basin were given priorities that reflect the U.S. Supreme Court decision in Arizona v. California (1963, 1964). California's 4.4 million acre feet of high-priority consumption and the non-CAP consumption in Nevada and Arizona were satisfied first, CAP was satisfied next, and MWD's "excess" consumption (above the senior 4.4 million acre feet) was satisfied last. The Mead flood control pool storage had the lowest priority, such that any water in the flood control pool was available to meet MWD excess demands. Also, in recognition of the authority that the Secretary of the U.S. Department of Interior has to declare a surplus in Lake Mead and release water from the Mead conservation pool, MWD excess demands were satisfied if the Mead conservation pool was at least 75% full. Finally, in keeping with the requirement to operate Lake Mead to have available flood control storage of at least 5.35 million acre feet on January 1 of each year (USBR, 1982; USCOE, 1982), the flood control pool was evacuated on that date each year.

The economically-based objective function was applied only to the future demand levels. It was assumed that no delivery obligation was in effect at Lee Ferry and that releases from Glen Canyon were made only to satisfy Lower Basin demands and the Mexico delivery obligation. Demands of any kind had priority over storage. Demands throughout the Basin, with the exception of the Mexico delivery, were given priorities that reflected the average net marginal economic value of all projects in a demand class and area. These values were derived by first adopting the gross marginal values used by Krutilla, et al. (1983). Then, delivery costs and amortized costs of unbuilt projects that were necessary to realize "future" demand levels were subtracted.

A variation of the economic objective function, called the reserve scenario, maintained a reserve of 7 million acre feet in Lake Powell and Lake Mead. If reservoir storage was that low, only M & I demands could draw it down further and agricultural uses would be preempted to fill it. The scenario reflects an assumption that high-valued uses could purchase water from lower-valued uses for maintenance of a reserve. This provides some additional security for higher-valued uses at the expense of more frequent shortages in lower-valued uses. The reserve is necessary because, at the future demand level and without any value placed on storage, Lake Mead remained empty much of the time and total system storage reached zero on a few occasions. This precipitated isolated but severe shortages to all use sectors in both basins.

RESULTS AND DISCUSSION

It is necessary to qualify the results of this study with the caveat that they are based on the use of a single, marginal value for each use. No demand curves were used. Thus, the benefits quantified in the following paragraphs are only useful for relative comparisons, and then only when shortages are small relative to total use, i.e. where the assumption of constant value over the entire shortage is not violated. As will be seen below, this was not always the case. Table 2 and Figure 1 summarize the results for the four scenarios.

TABLE 2. Estimated Average Annual Water Supply Shortfalls and Associated Costs Under Different Scenarios

	Value-Based Allocation				Current Institutions			
	With Reserve Future Demand		No Reserve Future Demand		Future Demand		Current Demand	
	Shortfall (maf)	Value ($1000)	Shortfall (maf)	Value ($1000)	Shortfall (maf)	Value ($1000)	Shortfall (maf)	Value ($1000)
<u>Upper Basin</u>								
Ag	131	5402	96	4035	6	261	2	87
M & I	0	0	11	881	2	179	0	22
Energy	37	789	33	759	10	240	0	24
Total	167	6192	139	5674	18	680	3	133
<u>Lower Basin</u>								
Ag	129	6440	85	4257	7	342	0	0
M & I	0	0	3	235	528	43327	0	0
Total	129	6440	88	4492	535	43669	0	0
Total	296	12632	227	10166	554	44349	3	133

<u>Current Demands, Current Institutional Framework</u>

Average shortages estimated under this scenario were insignificant. Those which were observed are limited to the Yampa/White use area in the Upper Basin and are due to local supply shortfalls. That is, they are not caused by competition from other use areas. Flows at Lee Ferry averaged 10.8 maf and deliveries to Mexico averaged 3.6 maf. Total system storage averaged 51 maf with maximum of 60 maf and a minimum of 38 maf.

The nominal cost of shortages in this scenario was $133,000 per year.

<u>Future Demands, Current Institutional Framework</u>

Total Upper and Lower Basin future demands are 30% greater than current demands, with most of the increase in the Upper Basin (Table 1). With these increased demands, shortages occurred during some years in both basins (Fig. 1.a). Upper Basin shortages, which averaged 18,000 acre feet per year and occurred during 31 of the 72 years, occurred in the Upper Green, Yampa/White, and Upper Colorado use areas. These shortages were caused by local supply shortages rather than legal limitations on use by "compact calls".

Shortages in the Lower Basin were substantial. They were distributed among CAP, California Agricultural and MWD excess. Because MWD excess is the lower priority use, it experienced the greatest shortfall, averaging 456,000 acre-feet annually. All instances of shortage occurred when the Mead conservation pool was less than 75% full (the surplus criteria used herein) and Mead storage was therefore not available to meet MWD excess demands. During these years, releases from Powell never exceeded the minimum required (8.23 million acre feet per year). Greater releases from Powell could have alleviated the shortages somewhat, but would violate the interstate compact.

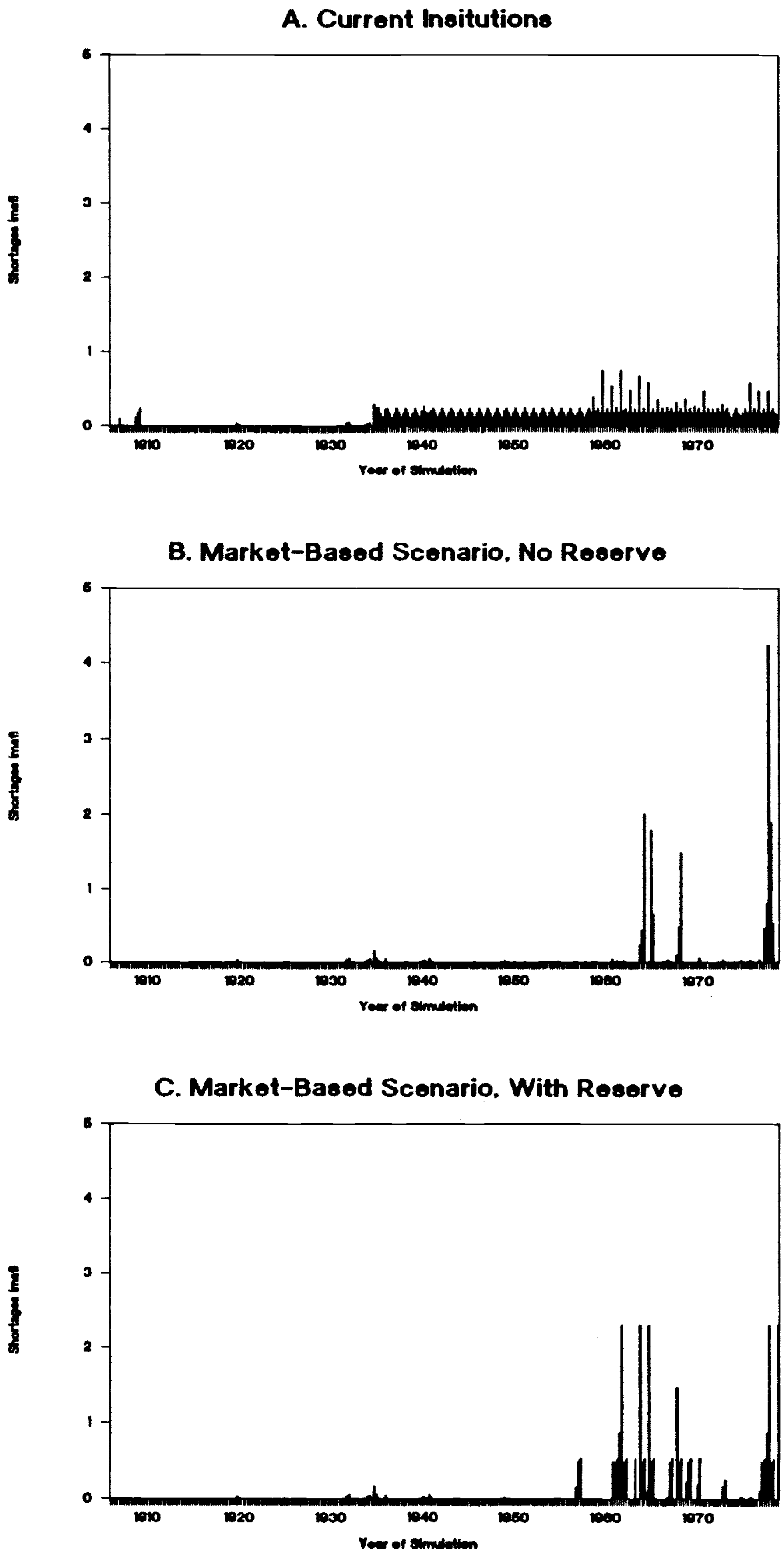

Fig. 1 Estimated Water Supply Shortage, Colorado River Basin

Deliveries at Lee Ferry averaged 9.3 maf and deliveries to Mexico averaged 1.9 maf. System storage averaged 32 maf with a maximum of 60 maf and a minimum of 3.1 maf.

The nominal cost of shortages in the Upper Basin were $680,000 annually. In the Lower Basin, the nominal cost of shortages was more than $43 million annually. However, the magnitude of these shortfalls probably exceeds the range of the assumed marginal value for this sector so these costs are probably understated.

Future Demands, Economically-based Priorities

The principal effect of allocating water to consumptive uses bases on marginal economic values rather than legally defined priorities was to increase deliveries to Lower Basin uses at the expense of Upper Basin uses. Total shortages were substantially reduced and the total cost of system shortages was dramatically lower.

Upper Basin shortfalls averaged 139,000 acre-feet annually, with a nominal annual cost of $5.7 million. Shortages occurred in every use area but predominantly in the agriculture sector. Lower Basin shortfalls averaged 88,000 acre-feet with a nominal annual cost of $4.5 million and occurred only in the agricultural sector.

Flows at Lee Ferry averaged 9.6 maf and deliveries to Mexico averaged 1.9 maf. Total system storage averaged 31 maf with a maximum of 60 maf and a minimum of zero (above dead storage).

The modest average shortage for this scenario conceals infrequent but deep shortfalls which individually have magnitudes which exceed the range of the assumed marginal values (see Figure 1.b). Thus, these costs are probably also understated.

Future Demands, Economically-based Priorities with Reserve

Under this scenario, total system shortages increased, the water being retained in storage at the end of the study period. Upper Basin shortages increased to 167,000 acre-feet with a nominal annual cost of $6.2 million. Lower Basin shortages also increased to 129,000 acre-feet with a nominal annual cost of $6.4 million. Compared with the previous scenario, these shortfalls were more evenly distributed and less severe individually. Thus, these costs may be relatively high when compared to the previous scenario. Figures 1.b and 1.c compare the pattern of shortfalls for the two value-based allocation systems.

Flows at Lee Ferry averaged 9.5 maf and deliveries to Mexico averaged 1.9 maf. Total system storage averaged 32 maf with a maximum of 60 maf and a minimum of 2.8 maf.

DISCUSSION

Two observations are offered regarding operations under the current institutional framework. First, based on the historical period of record used as the basis of this study and the assumption of full development in both basins, storage in the Upper Basin would fall to two million acre-feet on only one occasion, 1978, during the 72 year period of record. It would appear that the risk of a "compact call" is relatively small, though no attempt was made to quantify that risk. And because the critical period of the Upper Basin storage system is so long (more than 58 years in this study) additional storage above Lee Ferry would have a negligible effect on minimum reservoir contents.

The second observation is the imbalance between the two basins in projected shortfalls and associated costs. It should be noted, however, that the imbalance can provide the basis for an equitable adjustment of water allocation in the basin.

The economically driven scenarios demonstrate how such an adjustment could be made to work. The "Reserve" scenario produces economic impacts which are relatively equal between the two basins. Relative to allocations under current institutions, losses would increase by about $5.5 million annually in the Upper Basin. However, losses would be reduced by more than $37 million annually in the Lower Basin. Thus, after fully compensating the affected Upper Basin users, Lower Basin users would still save more than $30 million annually.

Alternatively, Lower Basin municipal users could purchase water from agriculture in the Lower Basin. Although the spread between the value of the two uses would be less, this would be partly offset by reduced carriage losses and lower transaction costs. However, it should be considered that purchases from upstream users would improve water quality in the Lower Basin. In fact, the benefits attributable to water quality improvements have been demonstrated to be sufficient to induce some users to sell water (SCS, 1980). Water quality is a common good and thus is not as amenable to market-based allocation as is water. However, the external effects of salinity reduction might be sufficient to warrant state or federal involvement. Unfortunately, this study was not able to quantify the impacts of new water allocation systems on water quality.

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