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RESERVOIR MANAGEMENT AND THE WATER SCARCITY ISSUE IN THE UPPER COLORADO RIVER BASIN

R. G. CUMMINGS* and J. W. McFARLAND**

INTRODUCTION

Current controversies concerning water scarcity and rights to water-use in the Colorado River Basin cover a broad spectrum of complex issues which are inter-state, inter-regional and international in character. An effort to give some perspective to these issues was made at the recent International Symposium on the Salinity of the Colorado River, the results of which are published in the January 1975 issue of this *Journal.*

In one of the papers presented at this Symposium, Weatherford and Jacoby present results from dendrochronological studies, ongoing at the University of Arizona, concerning historical estimates of virgin flows in the Colorado River.[1] These estimates, which cover a four hundred year period, suggest that average annual virgin flows in the Colorado River are some 13.5 million acre feet (maf) with a standard deviation of 3.4 maf.[2]

In contrast, the Colorado River Compact negotiations in 1922 used an estimate for average annual virgin flows of over 15 maf. A recent study by a state/federal inter-agency group suggests that virgin flows average 14.87 maf per year with a standard deviation of 4.20 maf.[3] The Department of Interior's most recent estimate of virgin

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[1] G. Weatherford & G. Jacoby, *Impact of Energy Development on the Law of the Colorado River,* 15 Nat. Res. J. 186 (1975). This work is a part of the Hydrology Subproject of the Lake Powell Research Project. *See* C. Stockton & G. Jacoby, *Long-Term Surface Water Supply qnd Streamflow Trends in the Upper Colorado River Basin,* 18 Lake Powell Research Project Bulletin (1976) [hereinafter cited as *Stockton and Jacoby*]; and Stockton, C. W., *Long-Term Streamflow Records Reconstructed From Tree-Rings,* Univ. of Arizona Press (1975) [hereinafter cited as *Tree-Rings*].

[2] *Stockton and Jacoby, id.* at 53. Professor Stockton has recently completed a *Reconstructed Series with Noise Component Added* which adjusts the estimated variance from 3.4 maf to some 3.9 maf.

[3] Upper Colorado Region State-Federal Inter-Agency Group for the Pacific Southwest, Inter-Agency Committee Water Resources Council, *Upper Colorado Region Comprehensive Framework Study,* appendix V, Table 8 (1971) [hereinafter cited as *Inter-Agency Group*].

flows for the 1906-1970 period is 14.95 maf.[4]

These differences in estimates of average annual virgin flows are relevant to a number of issues of immediate concern to policy-makers in Basin states, particularly in the Upper Colorado Basin States: Colorado, Wyoming, Utah and New Mexico. A primary concern of Upper Basin States, addressed by Weatherford and Jacoby, is the potential impediment to economic growth in these states which may be imposed by water scarcity. In Table 1, their data[5] are approximated which show the relationships between projected requirements for water in the Upper Basin and alternative estimates of average annual water supplies. These data suggest that Colorado River waters available to Upper Basin States may be fully utilized by around the year 1990 if one accepts either the Lake Powell Research Project's estimates of average annual water availability or the Department of Interior's "conservative estimate" of average water availability. Of course, if one accepts the estimate of water availability from the Department of Interior's 1906-1970 average, or the share of Colorado River water allocated to the Upper Basin by the 1922 Compact, water scarcity in the Upper Basin is not anticipated by the year 2000.

TABLE 1

Surface Water Available for Consumptive Use in the Upper Colorado Basin

		Estimates of Water Availability (million acre feet)			
Year Approximate	*Approximate Projected Water Demands*	*LPRP*[a]	*Conservative Hypothesis*[b]	*Department of Interior*	*Compact Shares*[c]
1975	3.8	5.25	5.8	6.5	7.5
1980	4.4	5.25	5.8	6.5	7.5
1985	5.2	5.25	5.8	6.5	7.5
1990	5.6	5.25	5.8	6.5	7.5
1995	6.0	5.25	5.8	6.5	7.5
2000	6.1	5.25	5.8	6.5	7.5

a. Estimate from the Lake Powell Research Project.

b. U.S. Dep't. of Interior's "conservative" estimate, *see Weatherford and Jacoby* Note 1 *supra* at note 64.

c. Estimate used at the time of the 1922 Colorado River Compact.

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[4] U.S. Dep't of Interior, *Critical Water Problems Facing the Eleven Western States*, at V-25 and V-26 (1974).

[5] Taken from *Weatherford and Jacoby, supra* note 1, Figure 1 at 186. Water available to the Upper Basin is taken to be estimated mean flows less the sum of 7.5 maf "committed" to the Lower Basin and .75 maf which is the Upper Basin's contribution to the Mexican Treaty burden.

The relevance of alternative estimates of average virgin flows in the Colorado River to planners in Upper Basin States is immediately obvious. There is some reason for concern that continued economic growth in the region may be impeded by the lack of water supplies, and such impediments may begin to be felt as early as 1990.

The meaningfulness of these data for Upper Basin planners is limited, however, due to two major considerations. First, there is no reason to believe that *average* virgin flows are necessarily the best measure on which to base water allocation plans. Certainly variations around the average are relevant. For example, taking as fixed an annual Lower Basin commitment of 8.25 maf,[6] the LPRP data with average basin-wide flows of 13.5 maf and a standard deviation of 3.4 maf imply that water available to the Upper Basin will be between 1.85 and 8.65 maf approximately 68% of the time. Should state engineers in the Upper Basin issue water use permits for the *average* of 5.25 maf, deficits or surpluses will occur a large percentage of the time. If the social costs and disruptions associated with deficits are relatively large, planners may wish to commit less than 5.25 maf, thereby decreasing the probability of deficit periods. Conversely, surplus waters imply foregone regional incomes that would obtain with these waters committed to productive uses. A critical question then concerns the *optimal* level of commitments for water use in the Upper Basin, given the stochastic nature of flows, and the sensitivity of such optimum levels to the alternative (statistical) distributions of flows described above.

Second, but inextricably related to the above discussions, water stored in dams and reservoirs along the Upper Colorado River might be used to supplement annual virgin flows in low-flow years, thereby allowing levels of water use which exceed average annual flows. Clearly, issues related to optimal levels of water use commitments in the Upper Basin must then include considerations related to storage in Upper Basin reservoirs.[7]

In this paper we wish to speak to the issue of optimum levels of water use commitments in the Upper Basin within a context that allows for the evaluation of alternative estimates of flow-regimes in the Colorado River, and storage as it relates to these commitments. The intent here is, first, to extend the Weatherford/Jacoby argu-

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[6] Subtracting 7.5 maf for Lower Basin commitments and .75 maf as the Upper Basin's half of the Mexican Treaty burden, as do *Weatherford and Jacoby* at 187, overestimates the impact on the Upper Basin from the Lower Basin commitment. The Compact requirement is for a 10-year *average* of 7.5 maf to the Lower Basin which is much less restrictive than the 7.5 maf *yearly* requirement implied here.

[7] The legal restrictions on reservoir operations policies for federally controlled reservoirs are discussed in *Interagency Group, supra* note 3, at 26-7.

ments as they relate to limits to growth in heavy water using activities along the Upper Basin, and second, to suggest an analytical method for evaluating alternative water allocation programs which can be modified for use in examining water allocation programs for sub-regions and/or states in the Upper Basin.

A FRAMEWORK FOR EVALUATING WATER ALLOCATION POLICIES

The analytical model used in this study to generate alternative patterns of water use commitments in the Upper Basin is based on a number of simplifying assumptions as to the physical, political, institutional and socio-economic structure of the basin as they relate to water use. The following are the major assumptions which underlie this model, and the biases implicit to the use of such assumptions.

(a) Following Weatherford and Jacoby, we take as given an *annual* commitment of 8.25 maf for uses downstream from Lee's Ferry. Of course, this requirement is much more stringent than the Compact requirements for a 10 year *average* of 7.5 maf (plus .75 maf for Mexican Treaty obligations), and our imposed requirement may then overstate water scarcity conditions in the Upper Basin during low-flow years. Our policies for water use commitments will thus be somewhat more conservative than those which might result from the use of the Compact's ten year requirement.

(b) We assume that water use commitments are irreversible in the sense that, once made, a water use commitment results in the assignment of immobile factors of production (land, labor and capital) to a particular activity; if the water commitment is unsatisfied in a low-flow year, incomes associated with these factors of production are foregone. For example, where withdrawal rights to Colorado River water are given to a power company, a coal fired electricity generation plant is constructed. During any year that water is not in fact made available to the plant, the plant, the associated labor force, and all other productive factors simply stand idle during that year. The incomes which they would have earned are viewed as a cost to the basin during that water deficit year. Results associated with this assumption are referred to as Case 1 results.

An alternative assumption which we use, referred to as Case 2, is that the region views the social costs of idle factors of production as being something greater than simply the loss of foregone incomes. The source of these extra-income costs may relate to a large number of things such as social unrest caused by instability and/or insecurity, etc. The measures for such costs would clearly be subjective in nature. While we do not pretend to know what this social weight might be, we do wish to include the possibility of such costs in our calculations, and arbitrarily choose 10% as a weight. Thus, in our Case 2 results, costs attributable to unsatisfied water use commitments are taken to be 110% of foregone incomes.

(c) Given our already stringent treatment of downstream flow commitments discussed above in (a), we abstract from existing legal restrictions concerning reservoir operations for Upper Basin reservoirs,[8] and assume that water stored in these reservoirs may be used for productive purposes in the Upper Basin. We also abstract from considerations related to hydropower generation in upstream reservoirs.

(d) Finally, we assume that water supplies in the basin are allocated to their highest valued uses in any year. Our estimates of income attributable to water-use are taken from an input/output-linear programming construct wherein water is allocated among subbasins in the Upper Colorado so as to maximize regional incomes.[9] Thus, incomes associated with the development of water use in the various sectors of the basin's economy, mining, electricity generation and agriculture, for examples, include the *regional* impacts—the multiplier effects of such developments. Within this construct, water is first allocated to high income-producing activities such as energy development; as higher levels of water commitments are allowed, water is used, for example, in various types of agricultural activities.

The characterization of the region as described by these few sets of assumptions clearly implies that our analyses abstract from a number of considerations which are of importance for some areas of policy-making in the Upper Basin, and our use of these assumptions is in no way meant to imply otherwise. Their use at this point greatly simplifies what is in any case a formidable computational-analytical task. The results obtained do provide insights as to the qualitative nature of water scarcity in the Upper Basin as it relates to the potential use of reservoir storage and alternative estimates of virgin flows in the basin—the range of policy issues of concern here. In our concluding section, we examine the restrictive nature of some of these assumptions in terms of water scarcity.

With this characterization of the basin, our optimization model then searches for the level of water commitments in the Upper Basin which maximizes the present expected value of basin incomes net of the social costs which occur during low-flow years. This search is

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[8] *Id.*

[9] *See* G. Morris, An Optimization Model of Energy-Related Economic Development in the Upper Colorado River Basin Under Conditions of Water and Energy Resources Scarcity (1976) (unpublished Ph.D. dissertation, University of Colorado).

conducted under several sets of assumptions which relate to water availabilities, the basin's evaluation of the social costs of over-commitments of water (cases 1 and 2 discussed in (b)), and the basin's preferences regarding risk. In terms of risk, we include in our model a chance constraint which requires that the probability of having a level of water commitments which may exceed available supplies in any year be no greater than some probability level α; we use values for α of .10 and .05. Two distribution functions for virgin flows in the river are used—the data used by the Upper Colorado Inter-Agency Group (referred to as IAG data) and the data developed in the Lake Powell Research Project (LPRP data). An examination of optimal water use commitment levels is made under various groupings of these assumptions described as follows:

Set 1: Incomes are maximized with social costs of deficits valued as simply foregone incomes (Case 1 in (b)); the IAG density function for flows is used without a chance constraint.
Set 2: Same as Set 1 except the LPRP density function for flows is used.
Set 3: Incomes are maximized with social costs of deficits valued as 110% of foregone incomes (Case 2 in (b)); the IAG density function on flows is used without a chance constraint.
Set 4: Same as Set 3 except the LPRP density function for flows is used.
Set 5: Set 2 with a chance constraint of 10%.
Set 6: Set 2 with a chance constraint of 5%.

Attention is now turned to an analysis of the results from our optimization model.

ANALYSIS OF RESULTS

Results from our optimization model generated with the six sets of assumptions described above are given in Figures 1-4. We first consider the ramifications for optimal commitment levels of the IAG and LPRP distributions for virgin flows, after which attention is turned to a discussion of risk, storage levels and optimal levels of commitments for water use in the basin.

In Figure 1, optimal commitment levels are given for each initial storage level wherein costs associated with deficits are taken to be simply foregone incomes. (The results are given for values of initial storage up to 16 maf.) Set 1 results use the IAG data where average flows are 14.87 maf with a standard deviation of 4.20 maf, and Set 2 uses LPRP data where average flows are 13.5 maf and the standard deviation is 3.4 maf. Examination of these data suggest that for any

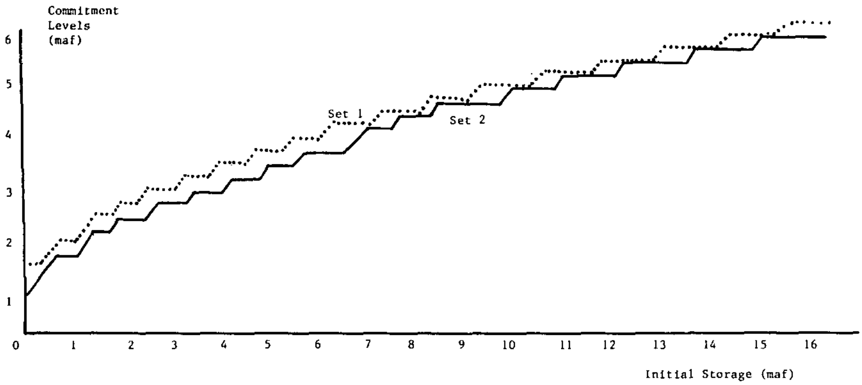

FIGURE 1
Optimal Commitment Levels with Alternative Initial Reservoir Storage
Set 1 and Set 2 Assumptions

initial level of storage optimal levels for water use commitments are relatively insensitive to the use of IAG or LPRP data for flows. The difference in commitment levels is generally only some .25 maf, with IAG commitment levels slightly higher than those associated with LPRP data, as one might expect.

The somewhat striking implication suggested by these data concerns potential water scarcity in the basin. Commitment levels which would correspond to adjusted *average* flows in the river—5.25 maf for LPRP data and 5.8 maf for the Department of Interior's "conservative" estimate—obtain at storage levels between 11.75 and 14.25 maf. Storage in the Upper Basin, excluding Glen Canyon Dam, is estimated to average about 9 maf, however.[10] With initial storage levels of 9 maf, commitments are held at 4.5 maf with the use of either IAG or LPRP flow data. Optimal commitment levels of 4.5 maf compare with *current* use levels of 3.5-3.75 maf. Bearing in mind the restrictive way in which Lower Basin commitments are treated in our model, these results suggest that relatively little slack in water availabilities may exist for continued water-intensive types of economic growth in the basin.

When costs associated with deficits are valued at 110% of foregone incomes, commitments at average flow levels obtain at storage levels of between 12-14.5 maf with IAG data and 13.5-16 maf with LPRP data (Figure 2). At initial storage levels of 9 maf, optimal commitment levels are 4.25 to 4.5 maf.

The fact that optimality requires commitment levels for water use

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[10] *Interagency Group, supra* note 3.

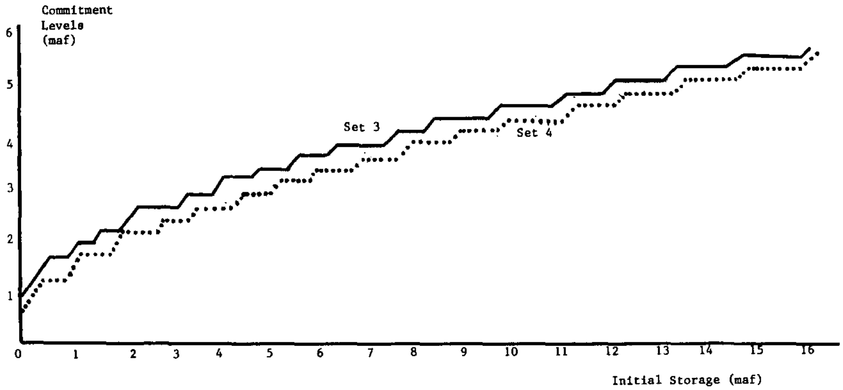

FIGURE 2

Optimal Commitments for Alternative Initial Storage Levels
Set 3 and Set 4 Assumptions

that are substantially below average annual flows (except in cases where high initial storage levels exist) is primarily explained by the costs of deficits *vis-a-vis* the diminishing marginal value of water commitments. At an initial storage level of 9 maf and commitments of 4.5 maf, an *additional* commitment of .25 maf would generate $31.88 million in regional incomes.[11] But such incomes must be compared with the costs to the region in all future years which will obtain in low-flow periods *given* a fixed level of commitments of 4.75 maf.

Using an extremely simplified example, suppose that commitment levels are increased from 4.5 maf to 4.75 maf, initial storage is 9 maf, and that a nine-year drought period occurs similar to that experienced during 1959-67.[12] Average flows during our hypothetical nine-year drought period are 2.75 maf, in which case commitments of 4.75 maf are maintained for 4.5 years by drawing down reservoir stocks. For the remaining 4.5 years (in this simple linear example) the basin incurs *total* annual costs of $396.02 million per year.[13] The annual costs attributable to the additional .25 maf (moving from optimal levels of 4.5 maf to 4.75 maf) is 34.33 million.[14] Thus, the

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[11] As described in the Appendix, net benefits to water-use are given by the expression $396.76C-28.35C^2, where C is the level of commitments. Marginal benefits evaluated at a level of C = 4.75 maf are thus $396.76 – ($56.68) (4.75) or $127.53 million for a 1 maf change in C. A .25 maf change thus gives rise to benefits of $31.88 million.

[12] *See Tree Rings, supra* note 1.

[13] Using the formula for benefits given in footnote 11, these costs are the difference between benefits evaluated at 4.75 maf and 2.75 maf.

[14] At commitment levels of 4.5 maf, total annual costs of delivering but 2.75 maf are $335.69 million, which is $34.33 million less than costs associated with the 4.75 maf commitment.

attractiveness of an increase in regional incomes of $31.88 million which may result from increasing commitments from 4.5 to 4.75 maf pales somewhat when one considers the prospect of incurring annual costs on the order of $34.33 million for some 4 plus years.

Implicitly then, our results suggest that at a level of commitments of 4.5 maf the increase in net regional incomes is just large enough to balance the expected value of all future costs which might be obtained in low flow periods. At higher levels of commitments (*e.g.*, 4.75 maf), expected costs are simply greater than the increase in incomes associated with larger commitment levels.

Turning now to the issue of risk as it relates to the possibility of assigning (committing) water rights at levels which may exceed water availabilities during drought periods, there are at least two ways in which one might speak to this set of problems. First, one may conceptually consider risk within the context of a trade-off between riskless alternatives and incomes. One would then think of a premium (in terms of foregone incomes) that the public would pay in order to reduce risk; this premium would then be included in our calculation of benefits and costs associated with alternative levels of commitments. In a very crude sense, this is the rationale used in Case 2 data—foregone incomes are given a weight of 110%. As shown in Figure 3 (LPRP flows are used for these results), optimal commitment levels for weighted incomes (Set 4) are somewhat less than those wherein incomes are not weighted (Set 2), reflecting a slightly more conservative policy for commitments when deficits are costed at higher values.

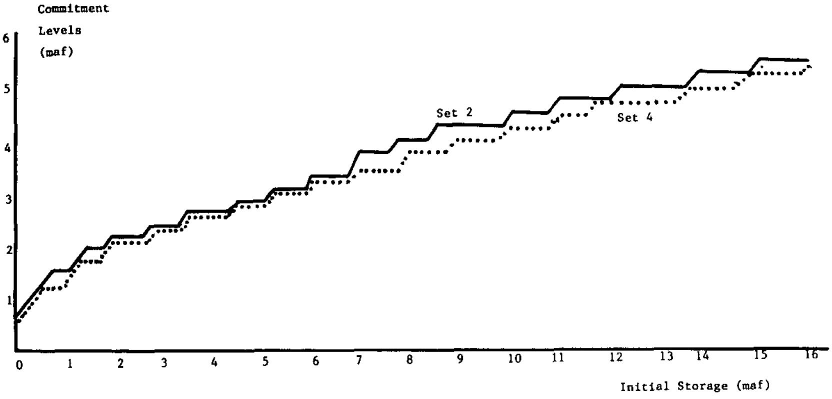

FIGURE 3

Optimal Commitments for Alternative Storage Levels
Set 2 and Set 4 Assumptions

A second method for dealing with risk simply involves restricting the set of admissible commitment levels to those which can be satisfied some fixed percent of the time. Of course, this is the role played by our chance constraint described in the previous section wherein we allow commitment levels to be greater than expected water supplies (flows plus storage) no more than α-percent of the time (we use α=.0 and α=.05 in sets 5 and 6, respectively); thus, commitments are met at least (1-α)-percent of the time.

Using LPRP flow data, results from our model applicable to chance constraints of α=.10 (Set 5) and α=.05 (Set 6) are compared with commitment levels without a chance constraint (Set 2) in Figure 4. At relatively low levels of storage (0 to 2.25 maf), optimal

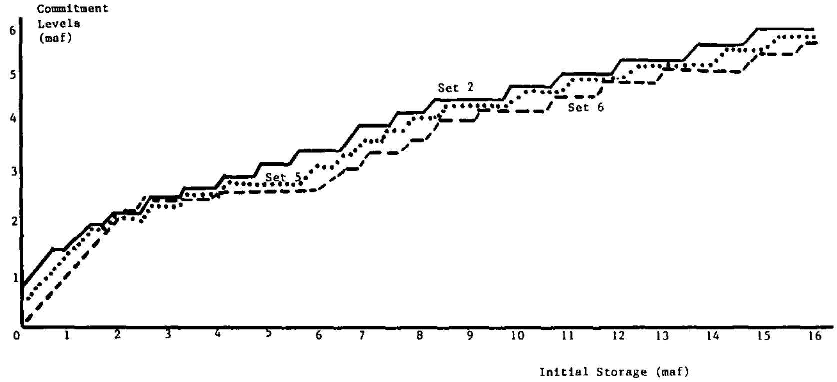

FIGURE 4

Optimal Commitments for Alternative Initial Storage Levels
Set 2, 5 and 6 Assumptions

commitment levels exceed *initial* storage under Set 2 and Set 5 assumptions. This implies that the probability of receiving sufficient flows to make up the deficits results in expected basin incomes which exceed expected costs of deficits. These commitment levels are satisfied at least 90% of the time. To satisfy commitments 95% of the time (Set 6), commitment levels will never exceed initial storage (compare storage levels and Set 6 commitment levels for initial storage between 0 and 2.25 maf).

As one would expect, at higher levels of initial storage, Set 5 commitments are somewhat less than those for Set 2, and Set 6 commitments are generally less than those for Set 5. At recent average storage levels in the Upper Basin, 9 maf, commitment levels which may be satisfied 90% and 95% of the time are 4.5 maf and

4.25 maf, respectively. With these results, the implied potential for near term water scarcity in the Upper Basin discussed above becomes even more real the greater the Basin's relative aversion to risk.

The following conclusions are suggested from the results in Section III:

1. Water commitments are substantially lower than average annual flows in all cases considered, except in cases where initial storage levels *exceed* existing usable storage capacity in the Upper Basin.
2. Water commitment levels are relatively insensitive to the particular probability distribution for virgin flows which is chosen, *i.e.*, the LPRP and IAG distributions.
3. When risk is integrated into the analysis, water scarcity is potentially an even more serious problem than is reflected in results from previous studies.

IMPLICATIONS FOR POLICY AND FUTURE RESEARCH

The implications of this study for the potential impediments to growth in the Upper Basin as such growth relates to the availability of surface water supplies may be deduced by comparing existing estimates of water demands with our estimates of optimal levels for water commitments as shown in Table 2. The Department of Interior's alternative estimates of water requirements which are essentially based on low, medium and high expectations concerning growth in Upper Basin requirements for water are in columns 2-4. Weatherford and Jacoby's estimates of water requirements are in column 5. The optimal ranges of water commitments which result from our study given initial storage levels of 9 maf (Figures 1-4) are in column 6.

TABLE 2

Estimated Demands and Supplies for Water in the Upper Basin, 1970, 1980, 1990 and 2000

	Estimated Demands				*Maximum (optimal) Levels of Water Availability*[3]
Year	*Alt.1*[1]	*Alt.2*[1]	*Alt.3*[1]	*W-J*[2]	*(maf)*
1970	3.0	3.0	3.0		4.25 – 4.5
1980	3.8	3.7	3.8	4.4	4.25 – 4.5
1990	4.6	4.8	5.1	5.6	4.25 – 4.5
2000	4.6	5.0	5.6	6.1	4.25 – 4.5

Source:
1. U.S. Dept. of Interior (1974, Table V-5, p. V-38).
2. Weatherford and Jacoby, 1975, taken from Figure 1, p. 186.
3. Figures 1-4 with initial storage of 9 maf.

These data suggest that optimal commitment levels may be obtained as early as 1980 with W-J estimates of water requirements and the imposition of a chance constraint of 95% (Set 6, Figure 4). For all other cases (Sets 1-5), optimal commitment levels are 4.5 maf and this level is approached by 1990 except in the Department of Interior's low-growth estimate of water requirements. In the main, however, these data suggest that maximum commitment levels may be reached within the next four to fourteen years.

The policy ramifications of these data must be viewed within a context that includes the major biases implicit to these data which result from the assumptions used and the manner in which our model was formulated. As noted above, a major scarcity-bias in our results is attributable to our imposition of an *annual* downstream commitment of 8.25 maf,[15] and it is tempting to argue that further research efforts to cast the optimal commitment level problem with the Compact's actual 10-year average requirement might be particularly productive. Such extensions would still be of limited scope, however, and would beg a number of computational[16] and legal questions of considerable relevance. We would argue for extensions which focus on basin-wide management of Colorado River waters which allow for an evaluation of private and social costs associated with basin-wide sharing of risk. The analytical construct suggested here can then be utilized to focus qualitatively on optimal commitment levels for the entire basin under alternative descriptions of flows and storage levels. The time frame for, and nature of, water scarcity in the Upper Basin would seem to suggest as paramount issues the costs of existing institutional arrangements[17] which serve as allocative mechanisms along the River.

In terms of overestimating water scarcity conditions in the Upper Basin, another possible bias in our results, which is related to our imposition of an 8.25 maf downstream commitment, concerns storage in the Glen Canyon Dam. With storage in the Glen Canyon Dam used to make up deficits incurred in drought periods, flows available for Upper Basin use would of course be larger. The inclusion of such storage might increase the upper limit on commitments in the Upper

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[15] As suggested to the authors by Professor William Schulze, the costs of water deficits to the Lower Basin may be quite high, particularly in California and Arizona. The greater these costs are, the less are the biases in our results that stem from the annual Lower Basin commitment.

[16] A number of formidable computations problems must be dealt with in such efforts. For most control analogs such as dynamic programming, *see* Burt and Stauber, *Economic Analysis of Irrigation in Subhumid Climates*, 53 Am. J. Agric. Econ. 1, 33-46 (1971). Computer storage requirements for such programs increase exponentially with the number of state variables.

[17] These are discussed in some detail in *Weatherford and Jacoby, supra* note 1.

Basin to the 6.3 maf figure currently used by water planners in the Upper Basin.[18]

While our treatment of downstream commitments may indeed lead to a potential overstatement of water scarcity (in terms of optimal commitment levels) in the Upper Basin, a number of considerations excluded from our model would lead one to conclude that in fact our results *understate* the potential for, and timing of, scarcity in the Upper Basin. Our use of virgin flows for beneficial use in the Upper Basin may overstate water availability by 1 to 2 maf per year due to substantial losses of water to evaporation at reservoirs and infiltration.[19] To allow, as we have, the 9-plus maf in storage at major reservoirs to be drawn down for water consumptive activities ignores the role of such storage for such things as providing head requirements for electricity generation and a source for a wide range of social benefits related to recreational uses and for fish and wildlife. These considerations would clearly impose costs on lower reservoir levels beyond some point thereby implying, *ceteris paribus,* more conservative commitment levels for water use.

In viewing the implications of our results within the context of the biases described above, one might argue that the Upper Basin will approach upper limits on commitments in as few as four years or as many as fourteen years. However, in terms of planning and restructuring the character of water supply conditions and/or water-use practices, even a 14-year time-horizon may be a short one. Studies concerning the ramifications of basin-wide management of water must begin soon if they are to include the potential for the conjunctive management of surface *and* groundwaters; discussions concerning flow augmentation alternatives[20] must move into the evaluative stage in order that *feasible* alternatives may be included in discussions as to options available to the Upper Colorado region.

Finally, it would seem that at a minimum these results suggest the need for the immediate implementation of signals to current and potential water users in the basin as to the growing scarcity *value* of water. Whether these signals are in the form of graduated reductions in water quotas or allotments, or in the form of higher water charges, something is required which will induce water users to view water in a context that reflects its true scarcity. Capital structures for water use in agriculture (*e.g.*, dirt or lined ditches, sprinkler systems, trickle techniques) or industry (cooling towers, recirculation systems, etc.),

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[18] *See, e.g.*, S. Reynolds, *Water for Energy in New Mexico,* paper presented at the National Conference of State Legislatures, Nov. 5, 1975.

[19] *See Weatherford and Jacoby, supra* note 1.

[20] *See, e.g.*, U.S. Dep't of Interior, *supra* note 4, at V-42 to V-46.

once installed, are expensive to modify at later dates. Choices of such techniques depend, among other things, on the perception of the relative cost and scarcity of water. It then behooves regional planners to assure that costs and scarcity conditions faced by such enterprises be consistent with these conditions as they might arise under a better managed system.

APPENDIX

The mathematical model used for generating optimum commitment levels for water use in the Upper Basin is a chance-constrained dynamic programming model with the following structure.

$$G^n (X_i^n, Y_a^n)_{C_k^n} = \underset{k=1,\ldots,K}{\text{Maximum}} \Big[EB^n(C_k^n + Y_a^n / X_i^n, e) + \beta \sum_{j=1}^{I} \Pi_{ij}^{ka} G^{n-1}(X_j^{n-1}, Y_b^{n-1}) \Big] \quad \text{(A.1)}$$

$$X_j^{n-1} = X_i^n + e - C_k^n \quad \text{(A.2)}$$

$$Y_b^{n-1} = Y_a^n + C_k^n \quad \text{(A.3)}$$

$$X_i^n \leqslant \text{CAPACITY, for all } i, n \quad \text{(A.4)}$$

$$P(C_k^n + Y_a^n \geqslant X_i^n + e) \leqslant \alpha, \text{ for all } n \quad \text{(A.5)}$$

$i,j = 1,\ldots, I;\ a,b = 1,\ldots, A;\ k = 1,\ldots, K;\ n = 1,2,\ldots$

The following notation is used in (A.1)-(A.4).

X_i^n = the i-th level of water stored in Upper Basin reservoirs at the beginning of stage n.

C_k^n = the k-th level of new water use commitments made during stage n.

Y_a^n = the a-th level of water use commitments at the beginning of stage n.

G^n = the present value of net basin-wide benefits for an n-stage decision process given the initial state X_i, Y_a.

E = an expectation operator.

e = virgin flows in the Colorado River, a random variable, net of downstream commitments to the Lower Basin (7.5 maf) and the Upper Basin's contribution to the Mexican Treaty (.75 maf).

β = the discount factor $(1 + r)^{-1}$; a 10% discount rate is used.

Π_{ij}^{ka} = the probability, given initial states X_i^n and Y_a^n, the choice during n of C_k^n, that the system will be in state X_j^{n-1} at the beginning of stage n-1.

In (A.1) EB^n $(C_k^n + Y_a^n / X_i^n, e)$ measures the expected value of basin incomes during the state (year) n given initial storage levels X_i^n and random flows e. $G^n(X_i^n, Y_a^n)$ then measures the present expected value of basin incomes over an n-stage planning horizon given the initial state described by X_i^n and Y_a^n, and given an optimal policy followed in all n-1 future periods. The periodic transformations of X and Y are described by (A.2) and (A.3), with storage levels constrained by storage capacity in (A.4). In (A.5) a chance constraint[21] is imposed. This constraint requires that committed levels of water-use in each stage n, $C_k^n + Y_a^n$, are greater than available supplies at most α-percent of the time, i.e., we require that water availabilities will meet committed levels of water use with at least a probability $1\text{-}\alpha$.

In applying the model (A.1) - (A.5), we begin by defining incomes to the basin associated with water use, $B(C_k + Y_a)$. Morris[22] generates a linear programming model which maximizes income in the Upper Basin subject to a variety of constraints on energy resources and water availabilities. The linear programming model contains three major sub-basins which are incorporated into the constraint set in the form of input-output models and resource restrictions. By varying water availability in the model, surrogate measures of marginal regional incomes attributable to water can be obtained. $B(C_k + Y_a)$ is then derived by integrating an estimated linear marginal regional income relationship, yielding:

$$B(C_k + Y_a) = \$396.76(C_k + Y_a) - 28.34(C_k + Y_a)^2 \qquad \text{(A.6)}$$

For any given values for C_k, Y_a, and X_i, and given the probability density function for net flows $\rho(e)$, the *expected* value of basin incomes is then $B(C_k + Y_a)$, as given in (A.6), less incomes lost in all instances where $C_k + Y_a$ *exceeds* water availability $X_i + e$. For each

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[21] *See* Charnes and Cooper, *Deterministic Equivalents for Optimizing and Satisfying Under Chance Constraints,* in Economic Models, Estimation and Risk Programming 425 (Fox, Sengupta, and Narasimhem eds. 1969).

[22] The authors are indebted to Mr. Glenn Morris, Staff Member of the Los Alamos Scientific Laboratory, for the use of preliminary results from his Ph.D. dissertation, note 9, *supra.*

combination of C_k, Y_a and X_i, $EB(C_k^n + Y_a^n/X_i^n, e)$ in (A.1) is $B(C_k + Y_a)$ minus foregone incomes associated with each level of e (wherein $C_k + Y_a < X_i + e$) weighted by the probability of obtaining that particular value of e.

Let $D = C_k + Y_a - X_i - e$ when $C_k + Y_a > X_i + e$, and equal to 0 otherwise. Foregone incomes are viewed in two alternative ways. Under Case 1 assumptions, foregone incomes are simply taken to be regional incomes associated with D-reductions in water use, i.e.,

$$EB(C_k^n + Y_a^n/X_i^n, e) = B(C_k^n, Y_a^n) - \sum_{e=0}^{C_k+Y_a-X_i} B(D)\rho(e) \qquad (A.7)$$

Under Case 2 assumptions, we implicitly assume a diminishing marginal utility for basin incomes, and assume that deficits in regional incomes relative to committed levels have greater weight than corresponding surpluses. We thus weight income losses by an admittedly arbitrary factor 1.1, and expected incomes become,

$$EB(C_k^n + Y_a^n/X_i^n, e) = B(C_k^n, Y_a^n) - 1.1 \sum_{e=0}^{C_k+Y_a-X_i} B(D)\rho(e) \quad (A.8)$$

Storage levels are allowed values ranging from 0 to 31 maf in increments of .25 maf (I=125); C_k, Y_a vary between 0 and 8 maf in increments of .25 maf (A,K = 33). Two alternative distributions for net flows are used. The first, referred to as IAG, is taken from the Upper Colorado Region study.[23] The second, referred to as LPRP, is taken from the works associated with the Lake Powell Research Project.[24] The means and standard deviations for these probability distributions are 14.87 and 4.20 and 13.5 and 3.4, respectively.

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[23] *Interagency Group, supra* note 3.

[24] *See Stockton and Jacoby, supra* note 2.