The Interstate River Compact as a Water Allocation Mechanism: Efficiency Aspects

Lynne Lewis Bennett, Charles W. Howe, and James Shope

Interstate river compacts are widely used to allocate water among riparian states. Twenty-one compacts are currently in force in the western United States, and these compacts are mostly of two types: those that allocate a fixed amount or flow of water to individual states; and those that allocate percentages of available water to the riparian states. This study compares the performance of the two resulting allocations with that resulting from basin-wide optimization without compact constraints. While widely varying hydrologic and economic characteristics of river basins create a large set of possible outcomes, a range of stylized case studies indicates that percentage compacts are likely to generate greater net benefits and to result in more equitable risk-sharing than fixed compacts under many circumstances. In light of recent compact negotiations in the southeastern United States, it is recommended that efficiency analyses under present and future conditions be made a part of all compact negotiations.

Key words: economic efficiency, interstate river compact.

In this paper we address the design of interstate river compacts, which have frequently been used to allocate water among riparian states in the western United States. In particular, we seek to identify the main factors that determine the economic efficiency and risk-sharing characteristics of the types of compacts most frequently found in the western United States: those requiring proportional sharing and those requiring delivery of a fixed amount of water. We find that either type of compact can be more efficient, depending on the benefit functions of the upper and lower basins and the distribution of streamflows. Further, a combination of the two compact types is frequently most efficient (e.g., a fixed delivery plus percentage sharing of the excess). We then evaluate the relative efficiencies of the two compact types in a case approximating that of the Colorado River. For that case, we find that the percentage design results in smaller deviations from the most efficient design. Further, the fixed design imposes greater variability on the upper basin. Variations on this case suggest that the most important hydrologic characteristic in determining the relative efficiencies is the mean (annual) flow, while the variance of flows has little impact on comparative efficiencies.

Much of the literature dealing with transboundary water allocation conflicts examines international river basins (see for example, Wolf). Some allocation models have focused on noncooperative game theory (Becker and Easter, 1995, 1998 and Bennett, Ragland and Yolles). Others have emphasized international agreements or treaties. Krutilla examines the Columbia River Treaty. Kilgour and Dinar characterize stable water-sharing agreements in international river basins. They show how flexible allocation agreements are more cost effective than those with fixed allocation schemes. Berck and Lipow examine water contracts and suggest tradable, prioritized rights in the Middle East.

Much of the literature dealing with *interstate* water resources focuses on transfers. There have been several examples in the literature of models that examine optimal allocation between the upstream segment and the downstream segment of a river basin (see for example, Howe, Shurmeirer and

The authors are: Lynne Lewis Bennett, Department of Economics, Bates College; Charles W. Howe, Professor of Economics and Director, Research Program on Environment and Behavior, Institute of Behavioral Science, University of Colorado, Boulder; and James Shope, senior programmer analyst, TKI Consulting.

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Shaw). Howe's model emphasizes the efficiency gains from maximization of the sum of the net benefits over both the upstream segment (the "upper basin" in our terminology) and the downstream segment (the "lower basin") in contrast to independent upper-and lower-basin optimization that is likely to occur under current institutional arrangements.

Johnson, Gisser, and Werner and Gisser and Johnson develop models of water allocation based on the principles of a "well-defined property rights system." They show that for an efficient allocation of water, the property rights must be defined in terms of consumptive use and not diversion. Their model is then expanded to include an instream flow constraint. The model maximizes total use value of water in the upper basin subject to upstream users leaving sufficient flow to satisfy the instream flow requirement. Their solution calls for an equalization of the marginal products of consumptive use across all upper basin users.

Anderson and Johnson show that on streams where the water is fully allocated to traditional uses, the addition of instream flow values will cause the reallocation of rights to downstream points.

Booker and Young present results of a river basin optimization model in which several alternative institutional scenarios for Colorado River water allocation are examined. They find that large benefits could be gained through interstate transfers to instream flows and reduced salinity levels. Comparing interstate and possible intrastate transfers, they find large potential gains from California intrastate transfers due to wide discrepancies among marginal values of different consumptive uses within California in comparison with the nearly equal marginal values in agriculture in upper and lower basins.

In a frequently cited article on water rights and economic efficiency, Burness and Quirk (1979) asserted that the appropriative doctrine[1] of water rights in the western United States leads to allocative inefficiency because of unequal sharing of risks among users, i.e., that senior appropriators bear less risk than junior appropriators. They go on to suggest a system of equal sharing when benefit functions are the same. They fail to note that an unequal allocation of risk may well be efficient, i.e., their result depends heavily on the risk averseness of the water users. A seniority system provides water users with explicit choices over the variability of water supply. The present paper addresses the risk issue not in terms of the attributes of individual water rights, but by comparing expected river system benefits under proportional water (and risk) sharing with expected system benefits under a fixed allocation that places all of the risk on one basin.

In a later paper, Burness and Quirk (1981) attempted to identify inefficiencies created by the appropriative doctrine under very restrictive assumptions using the Colorado River as an example. Their simplified case of two appropriators could be considered analogous to an upper basin-lower basin situation. They suggested that the introduction of competitive markets in proportional water rights would be efficient. They did not assess, however, the economic efficiency of the Colorado River Compact itself as a large-scale water allocation mechanism nor did they address the effect of the compact on the exercise of appropriative rights.[2]

More recently, Bennett and Howe examined the incentives for noncompliance embedded in the allocation rules of interstate river compacts, while Naeser and Bennett examined the impacts of noncompliance with the Arkansas River Compact. There has been no work to our knowledge that specifically addresses the economic efficiency of the allocation rules embedded in interstate river compacts.

In light of recent allocation negotiations on both interstate and international rivers, it is useful to examine the structure of current compacts. For example, Florida, Alabama and Georgia are currently negotiating the allocation formula for a compact in the Appalachicola-Chattahoochee-Flint River Basin. India and Bangladesh have recently signed a long-term water sharing agreement for the Ganges River Basin. This paper presents an analysis of the allocation formulas most frequently found in interstate river compacts.

[1] The appropriative doctrine is a seniority system based on first-in-time, first-in-right.

[2] It is usually the case that an interstate compact agreement will supersede or effectively cancel appropriative rights established within the riparian state.

The Interstate River Compact

In arid and semi-arid regions, the reliable streamflow in many river basins is fully allocated and in some cases *over allocated* under drought conditions. Thus agreements over water sharing are necessary. In the United States water allocation and administration have been reserved mostly to the individual states. For rivers and lakes extending beyond the borders of a single state, three methods of resolving interstate conflicts over water allocation or use have been used: (1) judicial allocation under which states may bring an action to the Supreme Court for an "equitable apportionment"[3]; (2) negotiation by riparian states of a compact with final approval being given by Congress; or (3) legislative allocation by an act of Congress.[4] These methods of apportionment do not govern how the water can be used within a given state, only the quantity or percentage of water to which each state is entitled.

Interstate compacts have been the most common approach. An interstate compact is a negotiated agreement among states which, once ratified by Congress, becomes both a federal law and a contract among the signatory parties. While compacts have been used for water allocation, flood control, water quality control, and basin planning, (e.g., Tarlock) only those dealing specifically with interstate water quantity allocation will be considered here.[5]

Bennett presents a summary of each of the western interstate river compacts. Within the seventeen western states there are twenty-one interstate river compacts of which five allocate fixed amounts of water among states, eight allocate water based on a percentage of flow, and eight use some combination of the first two or incorporate other features. There is a wide range of compact allocation mechanisms, even within the fixed and percentage categories. For example, while the Colorado River Compact allocates flows based on *annual* streamflow, other compacts incorporate seasonal and/or daily requirements. For example, the South Platte River Compact between Colorado and Nebraska is a fixed allocation compact that allocates a continuous flow of 120 cubic feet per second (cfs) to Nebraska during the months of April through September with any shortage to be made up within three days.[6] The La Plata River Compact is a percentage compact that allocates flows of the La Plata River between Colorado and New Mexico based on *daily* flows: Colorado must deliver to New Mexico one-half of the daily mean flow measured at Hesperas, Colorado during the spring and summer months.

Comparative Compact Efficiencies

Howe, Schurmeirer and Shaw presented a river basin optimization model in which benefits to both upper and lower basins were considered, but with no compact constraint. The Johnson et al. and Gisser and Johnson models maximized value products over the upper basin users given a *fixed* compact constraint, but ignored benefits to the lower basin. The current paper incorporates benefits to both basins. It is felt that most issues, including water quality and instream values, can be incorporated in a two agent model through appropriate forms of the two agents' benefit functions. Restricting the model to two agents does, however, preclude consideration of a game-theoretic issues such as coalition formation.

The "Universally Optimal Compact"

We will begin by deriving the necessary conditions for the universally most efficient allocation between upper and lower basins of a large river basin (e.g., the Colorado or the Mississippi), i.e., when the allocation rule is unrestricted in form.

Let

$\widehat{W}$ $\equiv$ random variable representing headwater streamflow available to the upper basin.

[3] See Tarlock for legal definition. Roughly, the Court attempts to find some basis of equity for apportioning the water. It does not imply equal division.

[4] See Tarlock, and Getches.

[5] For example, the Red River of the North Compact (1937–North Dakota, South Dakota, and Minnesota) provides for the administration of public works on boundary waters in the Tri-State Waters Area and specifically deals only with flood and pollution control, but not water allocation.

[6] If this daily delivery is not met, certain classes of water users in Colorado must be "called out", i.e., denied water use.

$f(\hat{w})$	$\equiv$	probability density function of $\widehat{W}$.
$F(\hat{w})$	$\equiv$	cumulative distribution function of $\widehat{W}$.
D_U	$\equiv$	amount of water diverted in the upper basin.
D_L	$\equiv$	amount of water diverted in the lower basin.
ρ	$\equiv$	return flow fraction from diversions, $0 \le \rho \le 1$.
C_U	$\equiv$	upper basin consumptive use of water. Thus, $C_U = (1-\rho)D_U$.
C_L	$\equiv$	lower basin consumptive use of water. Thus, $C_L = (1-\rho)D_L$.
$B_U(C_U)$	$=$	upper basin net benefits as a function of consumptive use, assumed to be strictly concave, with $B_U/\partial C_U > 0$.
$B_L(C_L)$	$\equiv$	lower basin net benefits as a function of consumptive use, assumed to be strictly concave, with $\partial B_L/\partial C_L > 0$.
λ	$\equiv$	weight given to lower basin social benefit function, perhaps a political weight.[7]

The water consumption constraint is

$$(1)\qquad C_U + C_L \le \widehat{W}.$$

We first seek the basin-wide optimal allocation rule to use as a benchmark of efficiency. This allocation can be described by $C_L(\widehat{W})$: for each level of $\widehat{W}$ we must decide how much is allocated to the lower basin and therefore how much is allocated to the upper basin. Throughout the remainder of this paper, we will assume the basin-wide benefit function to be additively separable. The general problem is to maximize *expected* basin-wide benefits, since $\widehat{W}$ usually must be treated as a random variable:

$$(2)\qquad \max_{C_L(\widehat{W})} E\{B_U(\widehat{W} - C_L(\widehat{W})) + \lambda B_L(C_L(\widehat{W}))\}$$
$$s.t.\ 0 \le C_L \le \widehat{W}.$$

[7] In the western United States, it has been common for the lower basin to develop more rapidly than the upper basin, implying a higher benefit function for the lower basin. λ represents this difference. This weight could be subsumed in the definitions of B_U and B_L.

If $\widehat{W}$ is known at the beginning of the relevant decision period (as is the case with snow-fed rivers), then finding the function $C_L(\widehat{W})$ can be reduced to solving the following problem for each possible value of $\widehat{W}$:

$$(3)\qquad \max_{C_L}[B_U(\widehat{W} - C_L) + \lambda B_L(C_L)]$$
$$s.t.\ 0 \le C_L \le \widehat{W}.$$

The first-order condition for an interior solution is

$$(4)\qquad B'_U(\widehat{W} - C_L) = \lambda B'_L(C_L).$$

This shows that the optimal allocation, $C_L(\widehat{W})$, is found simply by equalizing the (weighted) marginal benefits of consumptive use across the upper and lower basins for each level of $\widehat{W}$. This implies, in general, a changing percentage distribution as $\widehat{W}$ varies. Under low flow conditions, it may be optimal to allocate all the water to one basin (i.e., corner solutions may exist), showing that the optimal compact may contain both fixed and percentage components.

The Efficiency of Water Allocation Under Fixed and Percentage Compacts

We assume full consumptive use so that equation (1) holds with equality. We first derive the *optimal* percentage and fixed compacts.[8] For interior solutions, the consumption of each basin under the percentage compact will be

$$(5)\qquad C_L = \beta\widehat{W},\quad C_U = (1-\beta)\widehat{W},$$

where β is the fraction of streamflow allocated to the lower basin. A fixed compact constraint requires a minimum flow or volume at the basin boundary whenever river flows allow it. Letting $\widehat{W}$ be the required delivery, the following consumption will occur:

$$(6)\qquad C_L = \min(\widehat{W}, \bar{w}),\quad C_U = \widehat{W} - \min(\widehat{W}, \bar{w}).$$

We need to characterize the optimal β under the percentage compact and the optimal $\bar{w}$ under the fixed compact. To make this

[8] Comparisons should be among the most efficient compact designs within each compact type.

problem more tractable, we assume the benefit functions to be quadratic:

(7) $B_i(C_i) = a_i C_i^2 + b_i C_i + c_i, \quad i = U, L,$

with $a_i < 0$ and $b_i \geq -2a_i C_i$.[9] The basin-wide expected benefit function then becomes:

$$(8) \quad E[B_U(C_U) + \lambda B_L(C_L)] = a_U E(C_U^2) + b_U E(C_U) + c_U + \lambda a_L E(C_L^2) + \lambda b_L E(C_L) + \lambda c_L.$$

For the percentage compact, the expected basin-wide benefit can be expressed by

$$(9) \quad E(B_U(C_U) + \lambda B_L(C_L)) = a_U(1-\beta)^2 E(\widehat{W}^2) + b_U(1-\beta)E(\widehat{W}) + c_U + \lambda a_L \beta^2 E(\widehat{W}^2) + \lambda b_L \beta E(\widehat{W}) + \lambda c_L.$$

The optimal β can then be found by taking the derivative of equation (9) with respect to β and setting it equal to zero. This yields

$$(10) \quad \beta^* = \frac{2a_U E(\widehat{W}^2) + (b_U - \lambda b_L)E(\widehat{W})}{2(a_U + \lambda a_L)E(\widehat{W}^2)}.$$

For the fixed compact case, we first need to compute $E(C_L)$, $E(C_U)$, $E(C_L^2)$, and $E(C_U^2)$ that appear in equation (8). We find that one of the following two conditions on the optimal $\bar{w}$ must hold for the fixed compact [for derivation, see Appendix]:

(11) $1 - F(\bar{w}^*) = 0$

or

$$(12) \quad \bar{w}^* = \frac{2a_U E(\widehat{W} \mid \widehat{W} > \bar{w}^*) + b_U - \lambda b_L}{2(a_U + \lambda a_L)}.$$

Equation (11) implies that $\bar{w}^*$ is larger than any possible $\widehat{W}$. Therefore, all the water should be given to the lower basin. This would be optimal only if the marginal benefit derived from water consumption in the lower basin were greater than that derived by the upper basin even for very large flows. In the more usual case, the optimal compact is represented by equation (12). Notice in this equation that $\bar{w}^*$ is not solved for explicitly.[10] If we were given a tractable distribution function for $\widehat{W}$, such as the uniform distribution, we could solve for $\bar{w}^*$ explicitly. This is not the case for most distributions. However, even when we cannot solve for $\bar{w}^*$ explicitly, equation (12) may be useful in comparing the expected basin-wide benefits under the two types of contracts. In the appendix we show how to solve for $\bar{w}^*$ numerically, allowing us to show under what conditions each of the two compact types is more efficient.

An Example of an Optimal Mixed Contract ($a_L = a_U$, $b_L = b_U$, $\lambda \geq 1$)

In this section we will take a graphical approach to understanding the differing efficiencies of each type of compact. We again assume that $\widehat{W}$ is known at the beginning of each year. When the quadratic benefit functions in the two basins are identical and the weights placed on the basins are equal ($a_L = a_U$, $b_L = b_U$, $\lambda = 1$), the percentage compact dominates the absolute compact. Under the assumptions $a_L = a_U = a$, $b_L = b_U = b$, and $\lambda \geq 1$,[11] the benefit functions become

$$(13) \quad \lambda B_L = \lambda(aC_L^2 + bC_L + c), \qquad B_U = aC_U^2 + bC_U + c,$$

where $a < 0$, $b > 0$ and $C_i \leq b/2a$. This gives the following marginal benefit functions:

$$(14) \quad \lambda MB_L = \lambda(2aC_L + b), \qquad MB_U = 2aC_U + b.$$

The two marginal benefit curves are depicted in figure 1. We can see that at low levels of $\widehat{W}$, it is optimal to allow the lower basin to consume all the water since the lower basin has a higher marginal benefit curve. It can be easily shown that at $\widehat{W} = b(1-\lambda)/2a\lambda$ it begins to be optimal to divide the water between the two basins.

Thus, the universally most efficient compact can be described by:

$$(15) \quad C_L(\widehat{W}) = \begin{cases} \widehat{W}, & \text{for } \widehat{W} \leq \dfrac{b(1-\lambda)}{2a\lambda} \\[2ex] \dfrac{1}{1+\lambda}\left(\widehat{W} + \dfrac{b(1-\lambda)}{2a}\right), & \text{for } \widehat{W} > \dfrac{b(1-\lambda)}{2a\lambda}. \end{cases}$$

[9] This ensures non-negative marginal benefits.
[10] In fact, there may be multiple solutions for $\bar{w}^*$.

[11] We will not address the case $\lambda < 1$ in this paper since, empirically, it is very rare.

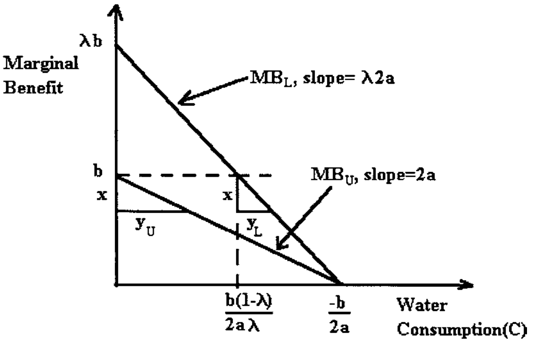

Figure 1.

Finding the more efficient compact when we are restricted to choosing between either a percentage compact or a fixed compact is the key question. Figure 2 portrays how both the fixed and percentage compacts compare to the universally optimal compact. The universally optimal compact has a kink at $\widehat{W} = b(1 - \lambda)/2a\lambda$. This figure suggests that when $b(1 - \lambda)/2a\lambda$ is small, the percentage compact more closely approximates the universally optimal compact. In fact, when $\lambda = 1$, $b(1 - \lambda)/2a\lambda = 0$ and the universal optimum is represented by a 45° line. When the two basins have identical quadratic utility functions and equal weights are given to the two basins, the best percentage compact entails splitting the water evenly at all levels of water flow. Thus, in this case, the percentage compact is the universal optimum. Therefore, it is more efficient than the absolute compact.

In this subsection it was shown that with identical quadratic benefit functions, but not necessarily equal weights on the two basins, i.e., $\lambda > 1$, the universally optimal compact is actually a combination of a fixed and percentage compact. In addition, it was shown that when restricted to choosing either the fixed or the percentage compact, it is possible for either type of compact to be more efficient, depending on the conditions.

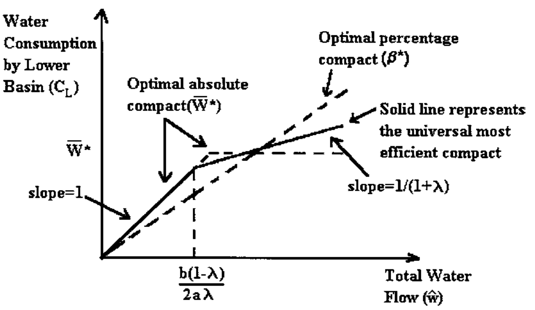

Figure 2.

The Colorado River

The first compact allocating the consumptive use of interstate waters was the Colorado River Compact of 1922. The Colorado River is the most well known example of a fixed compact. The waters of the Colorado River were divided between the Upper and Lower Basins[12] by requiring the Upper Basin to deliver 75 million acre feet (maf) per ten year period to the Lower Basin—or essentially 7.5 maf per year. There is no specific allocation to the Upper Basin. The Colorado River Commission (chaired by then Secretary of Interior Herbert Hoover) believed this to be an equal sharing of available water since the estimated average flow was 15 maf per year. It was later realized that average flows of the river have been lower than estimated at the time of compact negotiations. The Bureau of Reclamation now estimates that flows available to the Upper Basin, after ensuring required deliveries to the Lower Basin, range from 5.8 to 6.5 maf (Merrifield)—quite a bit less than the 7.5 maf (or half) the Upper Basin believed it was to receive. Thus, the Upper Basin assumes the risk of a shortage. This is the typical situation with a fixed allocation agreement.[13]

At a later date, the Upper Basin states unanimously chose to allocate their available Colorado River water by percentages through the 1948 Upper Colorado River Basin Compact. With this type of allocation rule, the Upper Basin states share proportionally in any shortages. Adoption of percentage allocations was based on the uncertainty of the amounts of water that would be available to the Upper Basin. During Upper Basin compact negotiations, the Colorado Commissioner stated:

> "The engineers have expressed doubt as to the total amount of water which will be available for use in the Upper Basin... since the amount of water which may be available is an uncertain quantity, it seems to me... the most satisfactory method of allocating the water is in terms of percentage and those terms of percentage can apply regardless of the amount of water which is available. And

[12] The Lower Basin states are California, Arizona and Nevada. The Upper Basin states are Colorado, New Mexico, Utah and Wyoming. (A sliver of Arizona is considered in the Upper Basin and receives a fixed allocation.)

[13] The risks to the Upper Basin have subsequently been modified by the large volume of storage in Lake Powell.

if you use terms of percentage rather than fixed acre-foot quantities, then you have a flexible method of apportionment which can apply under all conditions."[14]

Using the Colorado River as an example, we examine a case for which benefit functions are not identical. We will use equation (10) to calculate β^* analytically and equation (12) to calculate $\bar{w}^*$ numerically. Using other equations, we can then calculate $E(B(\beta^*))$ analytically and $E(B(\bar{w}^*))$ numerically.

We assume quadratic functions that imply that maximum benefits occur with a consumptive use of 6 million acre-feet for the Upper Basin and with a consumptive use of 10 million acre-feet (maf) for the Lower Basin with maximum benefits of \$10 billion and \$25 billion respectively, corresponding to the current stages of development of the two basins. These assumptions imply

$$(16) \quad B_U(C_u) = 3.334C_U - 0.2776C_U^2$$

$$(17) \quad B_L(C_L) = 5C_L - 0.25C_L^2$$

with C_i in millions of acre-feet/year and B_i in billions of dollars/year.[15] Streamflow for the Colorado River is assumed to be approximately normally distributed with mean $\mu = 13.5$ and variance $\sigma^2 = 2$ over the realistic range of flows.[16] Under these conditions, the universally optimal compact would allocate 3.33 million acre-feet to the lower basin plus 52.6% of the remainder. For the percentage rule, $\beta^* = .65$, and for a fixed rule, $\bar{w}^* = 8.0$.[17]

Table 1 illustrates the effects of changes in the mean and variance of streamflow on expected benefits. For mean flows of 13.5, the expected benefits with a percentage allocation compact exceed the expected benefits of the fixed compact for all variance levels. As the mean flow falls, however, the fixed rule starts to dominate (in this example, when the mean falls to 5). This is expected since a fixed rule will ensure that the lower basin receives flows first. Since water to the lower basin is more valuable at the margin with very low flows because of the differences in benefit functions, this will ensure a higher level of net benefits. The mean flow level at which the fixed compact begins to dominate the percentage rule, however, is an extremely low level and would not be expected for a river like the Colorado, particularly given the amount of storage on this river. While the percentage allocation dominates fixed allocation for all variance levels and when $\mu = 13.5$ maf/year, the differences in expected benefits between the two types of compacts are surprisingly small given the differences in benefit functions. It thus appears that compact type would not be critical for the Colorado River.

Finally, we examined the effects of compact type on the mean and variance of consumption for the upper and lower basins. Table 2 presents these results. Given our initial conditions, the variance of C is higher for the lower basin under the percentage compact and higher for the upper basin given a fixed delivery rule. If σ rises to 2.5, the fixed rule will dominate. This suggests that if the same analysis is done for each basin separately, a risk averse lower basin will prefer a fixed compact since under a fixed rule the upper basin absorbs most of the risk. By the same reasoning, the upper basin will favor a percentage rule since the risk will be distributed more evenly over the two basins.

Conclusions and Discussion

Several important conclusions can be drawn from this analysis. First, many factors affect the design of an efficient compact (μ, σ^2, distribution type, B_U, B_L), so it is difficult to make general assertions. Second, while in practice compacts tend to be fixed or percentage, the optimal design can be a mix of the two. Third, if B_U and B_L are the same (or very similar), then the percentage rule dominates. Finally, the fixed design creates very asymmetric risks, which can be good or bad, depending on B_U and B_L.

For many river systems, the lower basin has historically developed ahead of the upper, implying a higher benefit function for the lower basin that favors larger allocations

[14] From Muys.

[15] These assumptions are based on our interpretation of data in Booker and Young as described earlier in the paper.

[16] Variables μ and σ^2 enter into the analytical calculation of the optimal percentage share, β, using equation (10) and into the numerical simulation of the optimal fixed delivery, using $\bar{w}^*$, using equation (12).

[17] Note that this result is slightly different than if we had used equations (10) and (12). It was assumed that neither basin could become satiated (i.e., neither basin could reach a marginal benefit of zero). With a normal distribution of water flows and quadratic benefit functions, satiation of one or both basins is quite possible with a water flow of only 16 maf, which is only 1.25 standard deviations above the mean. Thus, for computational purposes, it is assumed that neither basin consumes beyond the point where marginal benefit falls to zero. When a basin becomes satiated, all excess water is given to the other basin. When both basins become satiated, excess water passes through the basins unused. (Computational details are available from the lead author.)

Table 1. Effects of Changes in Streamflow Characteristics on Expected Benefits

Streamflow Characteristics	β^*	Expected Benefits(β^*) \$ billions	$\bar{w}^*$	Expected Benefits($\bar{w}^*$) \$ billions	Optimal expected Benefits
$b_L = 5$					
$b_U = 3.334$					
$a_L = -.25$					
$a_U = -.2776$					
$\sigma = 2$					
$\mu = 13.5$	0.65	33.66	8	33.5	33.67
changes:					
$\sigma = 1$	0.64	34.05	8.5	34	34.05
$\sigma = 4$	0.66	32.38	7.3	32.1	32.43
$\sigma = 6$	0.67	30.62	7	30.4	30.7
$\sigma = 10$	0.68	27.29	6.8	27.2	27.38
$\sigma = 20$	0.69	23.01	6.7	23	23.07
$\mu = 20, \sigma = 2$	0.63	35	9.3	35	35
$\mu = 15$	0.64	34.45	8.4	34.4	34.46
$\mu = 10$	0.68	29.69	6.8	29.4	29.74
$\mu = 5$	0.8	18.39	5.1	18.4	18.52
$\mu = 4$	0.84	15.35	4.8	15.4	15.48
$\mu = 3$	0.9	12.13	4.6	12.2	12.25

Table 2. Effects of Compact Type on Variance of Consumption and Expected Benefits

	(β^*)	Expected Benefits(β^*) \$ billions	Var C_U (β^*)	Var C_L (β^*)	$\bar{w}^*$	Expected Ben.($\bar{w}^*$) \$ billions	Var C_U ($\bar{w}^*$)	Var C_L ($\bar{w}^*$)
$b_L = 5$								
$b_U = 3.334$								
$a_L = -0.25$								
$a_U = -0.2776$								
$\sigma = 2$								
$\mu = 13.5$	0.65	33.66	0.522	1.24	8	33.48	1.76	0.525
$b_L = 8.4$	0.87	68.39	0.07	3.02	12.4	68.39	2.25	0.638
$b_L = 8.4$								
$\sigma = 1.5$	0.88	68.73	0.032	1.74	12.4	68.68	3.71	1.46
$b_L = 8.4$								
$\sigma = 2.5$	0.87	67.97	0.129	4.65	12.6	68.03	2.88	1.38

to the lower basin. While not specifically addressed in this paper, evaporative transport losses and larger return flows favor a greater allocation to the upper basin while high instream flow values in the lower basin favor more water to the lower basin.

Risk aversion implies greater losses to the upper basin from the use of a fixed rule. Thus, the proportional rule would probably be considered by most to be more equitable. Overall, it appears that the proportional rule is likely to be more efficient than the fixed rule in many situations. However, since each river's situation is unique, efficiency calculations for the compact types should always play an important role in compact design.

Appendix: Derivation of Optimal Fixed Compact

$$\text{(A1)}\quad E(C_L) = \int_0^\infty \min(\hat{w}, \bar{w}) f(\hat{w})\,d\hat{w} = \int_0^\infty \hat{w} f(\hat{w})\,d\hat{w} + \bar{w}(1 - F(\bar{w})),$$

$$\text{(A2)}\quad E(C_U) = \int_0^\infty [\hat{w} - \min(\hat{w}, \bar{w})] f(\hat{w})\,d\hat{w} = \int_{\bar{w}}^\infty (\hat{w} - \bar{w}) f(\hat{w})\,d\hat{w} = \int_{\bar{w}}^\infty \hat{w} f(\hat{w})\,d\hat{w} - \bar{w}(1 - F(\bar{w})),$$

$$\text{(A3)}\quad E(C_L^2) = \int_0^\infty \min(\hat{w}, \bar{w})^2 f(\hat{w})d\hat{w} = \int_0^{\bar{w}} \hat{w}^2 f(\hat{w})d\hat{w} + \bar{w}^2(1 - F(\bar{w})),$$

$$\begin{aligned}\text{(A4)}\quad E(C_L^2) &= \int_0^\infty [\hat{w}, \min(\hat{w} - \bar{w})]^2 f(\hat{w})d\hat{w}\\ &= \int_{\bar{w}}^\infty (\hat{w}^2 - 2\hat{w}\bar{w} + \bar{w}^2) f(\hat{w})d\hat{w}\\ &= \int_{\bar{w}}^\infty \hat{w}^2 f(\hat{w})d\hat{w}\\ &\quad - 2\bar{w}\int_{\bar{w}}^\infty \hat{w} f(\hat{w})d\hat{w}\\ &\quad + \bar{w}^2(1 - F(\bar{w}))\end{aligned}$$

If we substitute these into equation (8) and take the derivative with respect to w, with simplification, we get:

$$\begin{aligned}\text{(A5)}\quad &\frac{E(B_U(C_U) + \lambda B_L(C_L))}{\partial \bar{w}}\\ &= a_U[-2\int_{\bar{w}}^\infty \hat{w} f(\hat{w})d\hat{w}\\ &\quad +2\bar{w}\int_{\bar{w}}^\infty f(\hat{w})d\hat{w}]\\ &\quad +b_U[-(1 - F(\bar{w}))]\\ &\quad +\lambda a_L[2\bar{w}\int_{\bar{w}}^\infty f(\hat{w})d\hat{w}]\\ &\quad +\lambda b_L\int_{\bar{w}}^\infty f(\hat{w})d\\ &= a_U[-2E(\widehat{W} \mid \widehat{W} > \bar{w})(1 - F(\bar{w}))\\ &\quad +2\bar{w}(1 - F(\bar{w}))]\\ &\quad +b_U[-(1 - F(\bar{w}))]\\ &\quad +\lambda a_L[2\bar{w}(1 - F(\bar{w}))]\\ &\quad +\lambda b_L(1 - F(\bar{w}))\end{aligned}$$

Setting this derivative equal to zero yields the optimal $\bar{w}$.

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