THE MARGINAL ECONOMIC VALUE OF STREAMFLOWS: A SYSTEMS APPROACH

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ABSTRACT

What are small increases in streamflow worth if they could be optimally allocated, and how much of that value is due to the perfect foresight that optimal allocation allows? This paper attempts to answer these questions for a hypothetical water resource system in the Western United States. Small increases in streamflow that could be produced by timber harvest are optimally allocated to instream and offstream demands, based on their economic value, using a nonlinear optimization algorithm operating on a monthly time step. This analysis is performed for alternative storage capacities, water demands, and hydroenergy prices to determine the sensitivity of the economic value of small flow increases to major water use determinants.

INTRODUCTION

Water scarcity in the western United States is expected to increase with population and economic growth, and this scarcity may be exacerbated by climate change. This prospect enhances the need for an improved understanding of the impacts of flow changes on instream and offstream water uses. This improved understanding would facilitate analysis of opportunities for increasing streamflow (by interbasin transfers, reductions in upstream diversions, timber harvest, and other means), and of the consequences of flow reductions. One opportunity for increasing streamflow that has received considerable study is vegetation management. Watershed research has shown that overstory removal in some vegetation types can reduce evapotranspiration and thereby increase streamflow (Hibbert 1983, Troendle 1983). In this paper, we will focus on vegetation removal as the source of small streamflow changes, but the analysis has implication for other sources of flow change.

While much study was devoted over many years to understanding the effects of vegetation on runoff, little care was given to the downstream implications of the runoff changes. It was typically assumed that, once flow increases reached a major stream channel or reservoir, all or nearly all of the increases could be delivered to consumptive users and would be valued equally to the existing flow deliveries. Recent case studies, however, showed that several factors may severely limit the ability to deliver flow increases to users when needed. In the Verde River watershed of Arizona, Brown and Fogel (1987)

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found that on average about 40% of a small increase in flow would be delivered to consumptive users in the Phoenix area under existing institutional arrangements, compared with about 75% of normal (preincrease) flow. Most of the increase would have been lost to spills and evaporation. In the Colorado River Basin, Brown et al. (1990) found that only about 12% of a small flow increase would be consumptively used given existing institutional conditions compared with 73% of normal (preincrease) flows. Although storage is roughly four times mean annual flow on the Colorado River, current institutional arrangements obviously do not facilitate delivery of small flow increases to users. Moreover, while 55% of the economic value of the increase in flow was attributable to additional hydropower production, only 18% of the increase was attributable to additional consumptive use.

The case studies demonstrate that the timing of flows and flow increases, the capacity and management of reservoirs, and the timing of demand all affect the ability to deliver flow increases to consumptive users and the utility of flow increases in nonconsumptive uses. They also demonstrate that the use and value of flow increases are highly dependent on the unique physical and institutional arrangements of individual basins. Then, we can raise the question -- What is the potential for use of flow increases? How much of the flow increases could be delivered to users if water allocation institutions were tailored to most efficiently deliver streamflow to users, and how sensitive is this potential to the major physical constraints of water storage and use ?.

The purpose of this study is to determine, for a hypothetical river basin, the effect on disposition and value of flow increases of variations in a series of water demand and supply characteristics. The flow increases to be considered will be relatively small increases in streamflow that could potentially be caused by vegetation management. The configuration of the hypothetical river basin, the flow regime, and the levels of water demand were chosen to be representative of typical conditions in the semi-arid western United States. We optimally allocate water to offstream and instream uses using a nonlinear optimization model. Such a deterministic approach assumes perfect foresight, that is, that future flows are known. The difference in water allocation between enhanced and normal flow conditions indicates the optimal allocation of the flow enhancement.

CONFIGURATION OF HYPOTHETICAL RIVER BASIN

The hypothetical water resource system implemented for this study includes the following basic requirements for the analysis of flow increases: (1) one or two tributaries with headwater basins where flow increases can be generated, (2) storage capacities that can potentially collect and regulate flows, (3) points of diversion to offstream water users, and (4) a representative group of instream, hydrogeneration and recreation, and offstream (irrigation, municipal, and urban water uses.

The system was conceived as the combination of two equal subsystems in series with an intermediate tributary, as depicted by Figure 1. Natural and regulated flows enter the reservoirs as inflows. Outputs from the reservoirs include evaporation, powerplant releases and spillages. The latter encompass two types of outputs, excess water drawn from the top of the pool by means of an uncontrolled spillway, and controlled spills by means of a submerged pressure valve. Diversion points downstream from the impoundments supply water to demand zones. The most downstream portion of each subsystem is designated for water recreation purposes, as well as to guarantee satisfaction of downstream water rights.

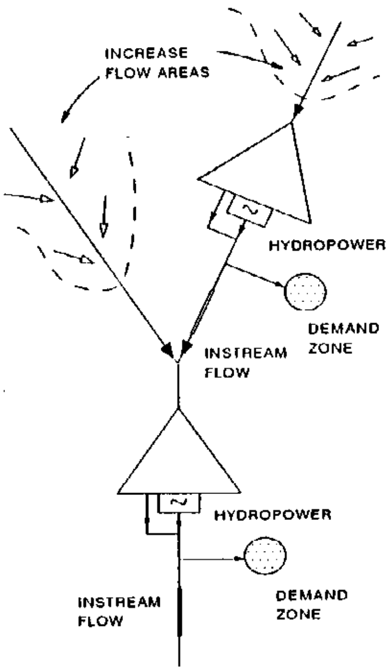

Fig.1 Hypothetical River Basin

The current application utilizes 66 years of mean monthly flows recorded by the USGS at Clearwater River at Spalding, and Salmon River at White Bird, both in the State of Idaho. Increases in natural flows were distributed monthly, to occur largely during the spring and snowmelt season, based on experience at Frazer Experimental Forest (Troendle, 1983).

COMPONENTS OF THE OPTIMIZATION MODEL

Economic Structure of the Objective Function

Decisions for water allocation throughout the system are made on the basis of the objective to maximize the sum of all economic benefits accruing from hydrogeneration and offstream water supply, subject to instream flows constraints for environmental and recreational purposes.

Revenues Accruing from Hydrogeneration. The purpose of the hydropower objective function is to fully exploit the economic opportunity to generate energy more efficiently (economic efficiency), given the available heads and flows in the reservoirs. Its formulation is based on two main concepts: the energy rate function, i.e., the physical capability of a powerplant to generate energy; and the marginal price function for energy, representing how much the power market pays for different types of energy being sold, such as peak energy, off-peak energy, etc., (Laufer and Morel-Seytoux, 1979). In essence, as release from a powerplant increases, the corresponding return per MWh sold (unit price) diminishes, according with the law of diminishing returns. The return accruing from the operation of a powerplant during a given time period i, B_i^{POW}, is given by,

$$
\begin{aligned}
B_i^{POW}[\$] = \eta \frac{p_i}{P} \Big\{ & T_i \left[a_1 a_2 + b_1 a_2 S_i^{\circ} + \frac{b_1 a_2}{2} INF_i - \frac{b_1 a_2}{2} LOS_i \right] \\
& + T_i^2 \left[\frac{a_1 b_2}{2} - \frac{b_1 a_2}{4} + \frac{b_1 b_2}{2} S_i^{\circ} + \frac{b_1 b_2}{4} INF_i - \frac{b_1 b_2}{4} LOS_i \right] \\
& - T_i^3 \left[\frac{b_1 b_2}{6} \right] \Big\} \qquad \textit{for } i = 1,2,\dots,N_p
\end{aligned} \tag{1}
$$

where η is the generator efficiency; (p_i/P) accounts for seasonality in energy prices; T_i is the powerplant release during period i; S_i° is the reservoir storage at the beginning of period i, INF_i accounts for all inflows during the period; LOS_i encompasses water losses and spillages from the reservoir; and $\{a_1,b_1\}$ and $\{a_2,b_2\}$ are coefficients of the linear equations representing the energy rate and marginal price functions respectively. N_p is the total number of periods for the optimization problem. Notice that Eq.(1) is a third order function of powerplant release.

Revenues Accruing from Water Supply. Three types of offstream water use are considered: agricultural, industrial, and municipal use. Each use type is represented by a demand curve that indicates the maximum price that the user is willing to pay to acquire an extra unit of water. Water usage increases at lower prices and decreases at higher prices. Figure 2 shows typical demand curves. While the municipal users are willing to pay high prices for relatively small amounts of water, farmers using water for irrigation are represented by a flatter curve, with low prices for large allocations of water. Industrial users' demand typically lies in between the demand of the other two use types.

Demand curves for mutually exclusive water uses can be summed horizontally to obtain an aggregated or market demand curve for the use area. Thus, water diverted to a demand zone can be considered as a lump volume. After solving the allocation problem, disaggregation at the optimal marginal price gives the allocation per use type. Assuming that the aggregated demand curve can be represented by an exponentially decreasing function, the aggregated benefit accruing from offstream water supply during period i is expressed by Eq.(2), where $\{a_3,b_3\}$ are coefficients of the exponential model, and D_i represents the aggregated water volume demanded during period B_i^{WS}. Notice that Eq.(2) is a nonlinear function of the quantity demanded.

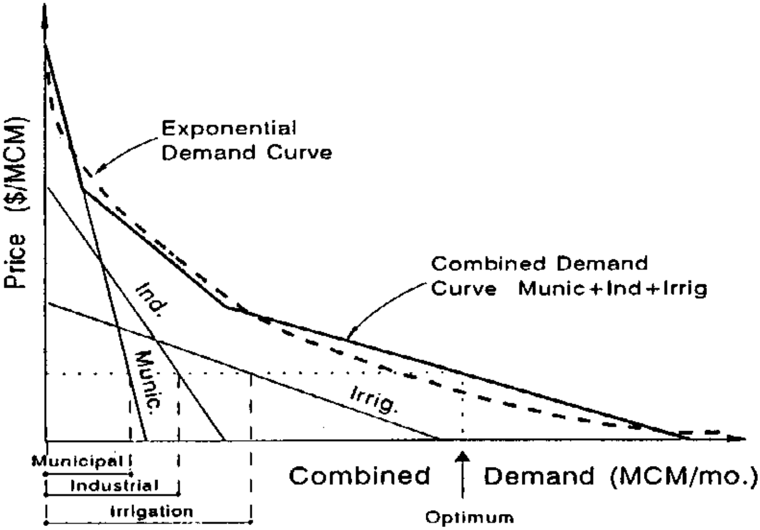

Fig.2 Offstream Water Demand Curves

$$B_i^{WS}[\$] = \frac{a_3}{b_3}\left\{\exp\left(b_3\, D_i\right) - 1\right\} \qquad \textit{for } i = 1,2,..,N_p \tag{2}$$

Instream Flows. Water for instream recreational activities may consider nonconsumptive uses such as fishing, boating, rafting, etc. The present model formulation does not account for recreational benefits in a manner commensurable with that for offstream benefits. Rather, it imposes minimum flow requirements in reaches downstream from the diversion points, in order to guarantee the existence of the recreational activities. If so desired, recreational activities could be represented in the model by their economic benefits, provided that their corresponding demand functions are known.

Total Revenues from the System. The overall objective of the management of the water system is to maximize benefits across uses, sites, and time periods, given the demand functions representing benefit or revenue received. Mathematically, the total benefit "TB" is expressed by the double summation over all water uses and all periods,

$$TB[\$] = \sum_{i=1}^{Np} \sum_{j=1}^{Ns} (B_{i,j}^{POW} + B_{i,j}^{WS}) \tag{3}$$

for $i=1,..,N_p$, and $j=1,..,N_s$, where N_p and N_s represent the total number of time periods and subsystems in the basin, respectively. This formulation treats all time periods as equal in importance, i.e., it assumes a zero discount rate. Alternatively, future returns could be discounted by incorporating standard discounting factors in Eq.(3).

The multiobjective function, Eq.(3), identifies the optimal tradeoffs between the competing water users, basing the allocation of water on its economic value. For instance, the model determines whether water released by the upstream powerplant at a given time step should continue flowing downstream toward the second reservoir, or be diverted to the first offstream use zone. The decision is based on the combination of physical and economic factors during the whole optimization horizon. The economic components of the model, the demand functions for hydropower and offstream use, are shown in Figure 3. The points of intersection of the hydropower and offstream use demand curves indicate the points of indifference between allocation to hydropower use and offstream use. To the left of an interseccion point (for low quantities of water available), deliveries to offstream use will prevail over hydropower. To the right of an interseccion point (for larger quantities of water), the higher prices of hydropower will prevail in deciding the allocation of the excess water.

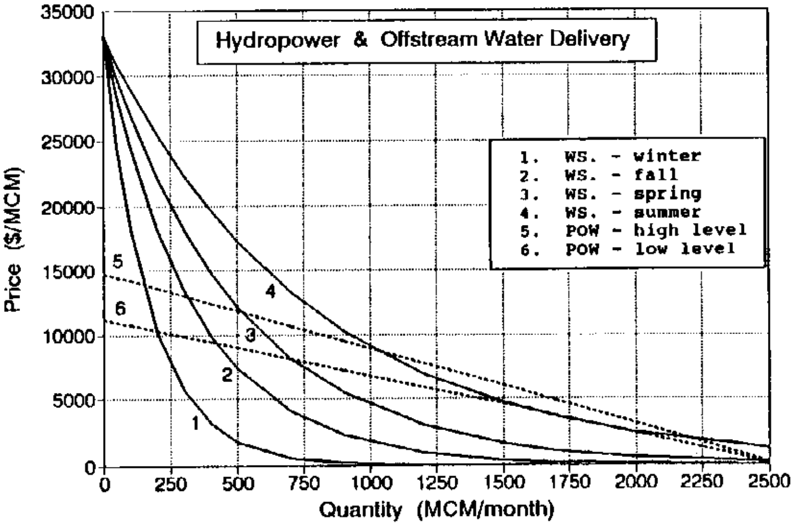

Fig.3 Demand Curves for Both Water Uses

Although Figure 3 displays only four demand curves for water supply, one per season, the model accounts for monthly variations in demand by utilizing a set of twelve pairs of coefficients $\{a_3, b_3\}$ that resemble a typical monthly pattern of water supply in the Western United States. Two hydropower curves are also shown, lines 5 and 6, for maximum and minimum water heads at the powerplant, respectively.

Operational Constraints

Formulating the operational problem in terms of economic objective functions minimizes the number of constraints necessary to solve the allocation problem. However, physical limits in the operation of the reservoirs and other parts of the system are unavoidable. The model has the following types of constraints:
Maximum Reservoir Capacity: to ensure that reservoir storages at the end of any period does not exceed the maximum reservoir capacities;
Minimum Reservoir Storage: to ensure that reservoir releases at any period will not deplete reservoirs beyond their minimum operational levels;
Final Reservoir Storage: to prevent the model from generating extra benefits at the expense of depleting reservoirs by the end of the optimization horizon;
Instream Flow: to ensure instream flow maintenance for recreational activities and aquatic resources.

As explained in the following section, the optimization problem is solved by a sequential-approximation algorithm. Evaporation losses and spillway releases are considered as constant terms during the solution of each sequential problem, whose estimation is based on a previously obtained solution. By treating evaporation and spills as constants terms, the nonlinear relations between outflow-storage and evaporation-storage, typical of the reservoir dynamics, are omitted, yielding a strictly linear set of constraints.

PROBLEM SOLVING TECHNIQUE

Definition of the Problem

The problem is to maximize a general nonlinear objective function (Eq.4a), subject to linear equality (Eq.4b) and inequality (Eq.4c) constraints, and bounded variables (Eq.4d),

$$\underset{x}{Max} \left\{ y = f(x) \right\} \tag{4a}$$

$$\sum_{n=1}^{N} a_{kn} X_n = r_k \qquad for\ k = 1,2,....,K_e \tag{4b}$$

$$\sum_{n=1}^{N} a_{kn} X_n \geq r_k \qquad for\ k = K_{e+1},...,K \tag{4c}$$

$$x_n^L \leq x_n \leq x_n^U \qquad for\ some\ of\ the\ x_n \tag{4d}$$

where $f(\mathbf{x})$ can be any type of nonlinear function subject to the requirement of being differentiable. N is the number of control variables, K_e the number of equality constraints, and K the total number of constraints.

Description of the Technique

Except for the nonlinear, nonquadratic objective function Eq.(4a), the above problem statement is similar to any standard linear programming (LP) or quadratic programming (QP) problem. A sequential-approximation algorithm (Hillier and Lieberman, 1986) is utilized to solve the nonlinear programming problem. The procedure approximates the original nonlinear objective function by a quadratic function using Taylor series expansion about an initial feasible solution (IFS). Although a quadratic function is the simplest nonlinear approximation that can be used for a nonlinear objective, it has been shown to be particularly suitable to solve reservoir operation problems (Díaz and Fontane, 1989).

The quadratic approximation of the nonlinear objective function by Taylor series should be further manipulated until it conforms to the standard quadratic form, and the problem then being solved as a QP problem. A succession of these approximations is performed until the solution of the quadratic programming problem reaches the optimal solution. More details about the method of solution can be found in Díaz and Fontane (1989). A standard QP routine, QPTHOR (Leifsson and Morel-Seytoux, 1981), is used to solve the QP problem. QPTHOR is based on the General Differential Algorithm (Wilde, 1967), which requires an IFS to start the optimization process. IFS's are often difficult to find for large and highly interacting systems. In order to find an IFS for the original operational problem, the model solves a problem equivalent to Phase-1 of the Two-Phase Method of Linear Programming. The efficiency and numerical stability of Phase-1 of the Two-Phase Method assure a very good chance of finding IFS's under all flow conditions.

Quasi-Continuous Optimization

Optimizing the operation of a water system based on perfect foreknowledge of inflows and demand levels assures that the benefits of storing excess water during wet years for release during dry years can be realized. However, optimizing the continuous operation of complex water systems for a very large number of years becomes computationally impractical. Contrarily, when a very short horizon is chosen, the imposition of final storage conditions on the reservoirs exerts a very noticeable effect on the state of the system. The question thus arises: What is the proper time horizon for the optimization ? Certainly, the characteristics of each system impose different requirements.

This study analyzed the effect that imposed final storage conditions at the end of the optimization horizon has over the state of the system during previous years of operation. Figure 4 depicts a simplified picture of the findings. The solid line represents a typical reservoir storage trajectory as a result of optimizing the operation of the system for a relatively long number of years. When running the model for only the first three years, the resulting state curve, shown by the dashed line, changes because of adjustments necessary to meet the final storage condition. The study showed that for the water system at hand, the effect of a prescribed final storage rarely extends back significantly for more than one year; that is, the dashed and full lines only depart from each other during the last year of operation.

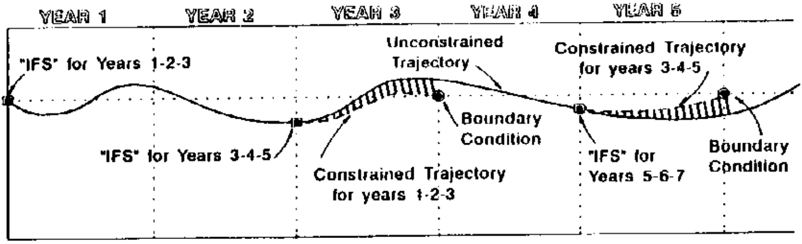

Fig.4 Scheme of Quasi-Continuous Optimization

Consequently, the optimization model was commanded to solve the operational problem for overlapping sets of n consecutive years, $n=3$ in this case. After each n-year solution is obtained, the results from the operation for the n^{th} year are discarded, and the optimization for the next n-year set of years begins with the n^{th} year of the previous set. Thus, the state of the system at the end of year n-1 becomes the initial state of the system for the subsequent n-year solution. For a total of T years of operation, linked optimizations are needed for $T/(n-1)$ sets of years. For $n=3$ and 66 years of flow records, a total of 33 solutions are required. This procedure of quasi-continuous optimization is believed to circumvent to a large extent the undesirable effect of final boundary conditions on reservoir operation.

PRELIMINARY RESULTS

We obtained model results for normal (preincrease) flows and increased flows for numerous scenarios that differed in terms of the following three dimensions: reservoir storage capacity, offstream water demand, and hydroelectric energy prices. In addition, we investigated the effect of alternative amounts of flow increase. In order to limit the number of runs, we did not obtain results for all possible combinations of storage capacity, demand level, and energy prices. Rather, we selected a base scenario and then investigated changes from this base along each of the three dimensions of interest.

The Base Scenario

The base scenario had the following major characteristics: (1) reservoir storage capacity of each reservoir equal to 0.4 times mean annual virgin flow at the reservoir location, (2) a moderate level of water demanded for consumptive use (see Figure 3), (3) a mean annual energy price of 30 mills per kwh, (4) a minimum instream flow constraint equal to 10% of mean annual virgin flow, and (5) powerplant capacities rated at a discharge equal to approximately 20% of natural flow (obtained from flow duration curves).

Normal Flows. Given normal flows, in the average year, only 0.1% of inflows spilled from either reservoir, and only 4.4% evaporated. Eighty-five percent was delivered to consumptive water users, with the remainder leaving the system as evaporation or instream flow. Most of this consumptive use delivery was to the downstream use area, which is below both power plants (Figure 1).

The annual returns to hydroenergy and offstream use range from $336 million to $470 million, and average $418 million, or $17.60 per thousand cubic meters (TCM) of inflow. About 44% of the return was to energy production, with the remainder to water supply.

Increased Flows. The 5% flow increase caused increases in delivery to offstream users of 6.4% and increases in turbine releases of 5.8%. That is, the increases in use of revenue-producing water allocations were greater, in percentage terms, than the flow increases. This occurred largely because the flow increase allowed the instream flow constraint to be met more efficiently, causing an actual 4% decrease in outflow from the system.

The 5% flow increase produced increases in total annual return ranging from 1.5% to 4.2 % over the 66 years, and averaging 2.4% (Figure 5). Thus, the average ratio of percent change in return to percent change in flow is about 0.5. The average value of the increase was $8.38 per TCM, compared with $17.60 per TCM of normal inflow. The lower value of the increase, compared with the value of normal flow, reflects the diminishing marginal utility of water as modeled by the downward sloping demand curves.

Effect of Storage Capacity

Ratios of reservoir storage capacity to mean annual virgin flow (S/X) from 0.1 to 2.0 were investigated. For each scenario, both reservoirs were changed to the indicated S/X ratio by increasing the heights of the dams given fixed topographic configurations of the two reservoir sites.

Normal Flows. Figure 6 shows the mean annual disposition of normal flow for these alternative storage levels. Spills decreased from 8% of inflow with the smallest reservoir to nearly 0 at S/X = 0.4. Evaporation gradually

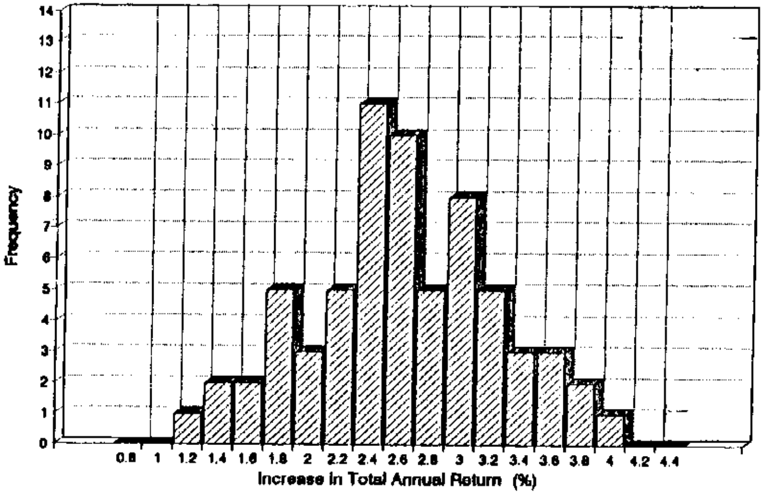

Fig.5 Annual Economic Return with a 5% Flow Increase

increased from 3% of inflow with the smallest reservoir to 10% with the largest reservoir. Offstream use deliveries and flow through the two power plants increased slightly with increases in S/X up to about 0.4 (reflecting the decrease in spills), and gradually decreased for each increase in reservoir size thereafter, largely because of the increases in evaporation. While turbine releases remained roughly constant over all storage capacities, energy production continually increased, by 128% from the smallest to the largest reservoirs, because of increased water head in the powerplants.

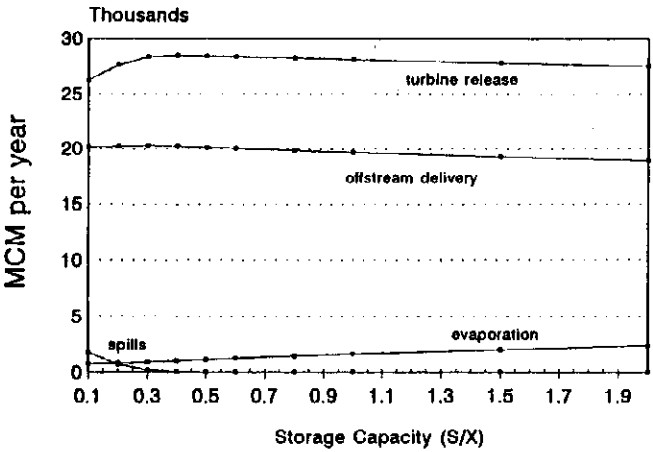

Fig.6 Average Annual Water Disposition versus Storage Capacity

Economic return to offstream consumptive use increased for initial increases in reservoir size up to S/X = 0.4, and then dropped gradually for further increases in storage capacity, but the drop in return was minor (Figure 7). The effect of changes in reservoir size on total economic return was largely a function of hydroenergy production. Average annual return to inflow increased from $15 to $24 per TCM over the range in reservoir size (Table 1).

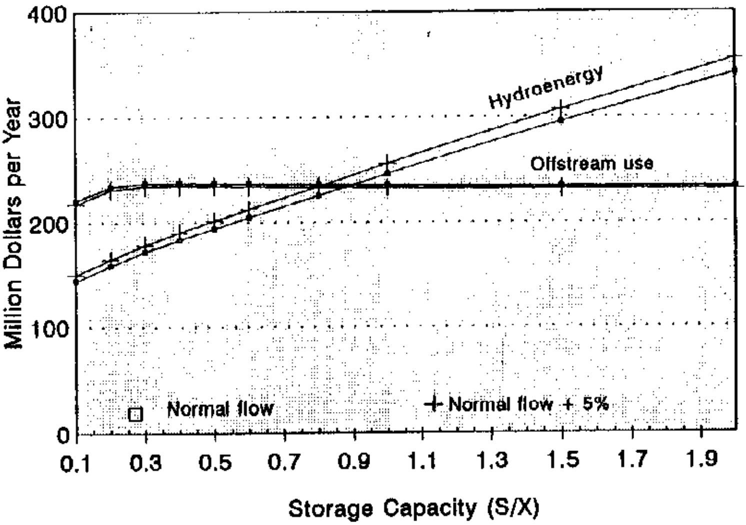

Fig.7 Average Annual Return versus Storage Capacity

Increased Flows. Changes in reservoir size had relatively little impact on the use and value of flow increases. Increases in total deliveries to offstream users that were caused by the 5% flow increase varied only from 5.6% to 6.4% over the range of storage capacities, while increases in turbine releases that resulted from the flow increase varied from only 5.2% to 5.9% (Figure 6). This lack of sensitivity to changes in reservoir size resulted from the fact that, under optimum management, spills are small, even for relatively small reservoirs, with or without the flow increases.

Increases in total return caused by the flow increases ranged from 2.4% to 2.9%, with the largest percentage increases occurring with the largest reservoir (Figure 7). Hydroenergy accounted for roughly three-quarters of the total increase in economic value of the flow increase. At all reservoir sizes, the value of the flow increase was about half the average value of normal-flow (Table 1).

Table 1. Average Annual Economic Return to Inflow for Selected Scenarios ($ per TCM)

Scenario	Normal flow	5% flow increase
Ratio of storage capacity to virgin flow (S/X)		
0.1	15.25	7.79
0.2	16.47	7.85
0.4 (base level)	17.60	8.38
0.6	18.48	9.10
1.0	20.17	10.39
2.0	24.10	13.81
Offstream demand		
0.2 * base	10.56	5.59
0.5 * base	13.45	6.20
1.0 * base	17.60	8.38
2.0 * base	23.24	15.49
4.0 * base	27.98	24.68
Average hydroenergy price (mills/KWh)		
10	12.58	4.69
30 (base level)	17.60	8.38
50	22.19	12.21
100	36.19	21.55

Effect of Offstream Demand Level

As more and more water was demanded at a given price (i.e., as the demand curve was shifted to the right while keeping the maximum or zero-quantity price constant), with other variables such as reservoir size held constant at the base levels, deliveries to water supply naturally increased at the expense of energy production, and total return increased (Figure 8). For normal flows, the 20-fold increase in quantity demanded at a given price shown in Figure 8 increased total return by a factor of 1.6 (Table 1). The effect of increasing demand on total return was constrained by the amount of available flow.

Increasing the offstream demand caused an increase in the value of the 5% flow increase. For example, the 5% flow increase caused a 4.4% increase in mean annual total return at the highest demand level depicted in Figure 8, compared with the 2.4% increase in return at the base demand level. At the largest demand level, the value of the flow increase ($25 per TCM) approached the average value of normal flow ($28 per TCM, Table 1), largely because the demand curves become more elastic (flat) over the diversion quantity at the higher demand levels.

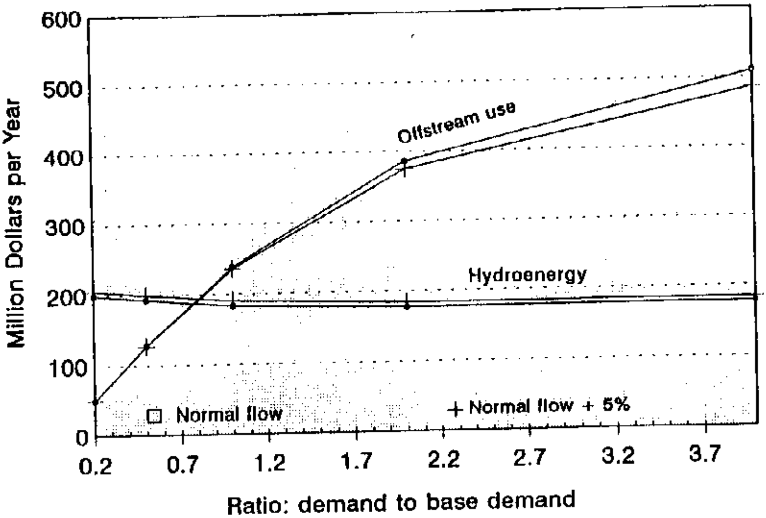

Fig.8 Average Annual Return versus Offstream Demand

Effect of Energy Prices

As energy prices increased, holding other variables constant at the base levels, turbine releases naturally increased at the expense of deliveries to water supply, and total returns increased. The 5% flow increase caused a 3.0% increase in mean annual total return at the highest average energy price (100 mills per KWh), compared with the 2.4% increase in return at the base average energy price of 30 mills per KWh. The value of the flow increase was quite sensitive to the energy price, rising from $5 at an average price of 10 mills to $22 at an average price of 100 mills (Table 1).

Effect of Amount of Flow Increase

Given the base scenario, the ratio of percent change in total return to percent change in flow remained about 0.5 for flow increases ranging from 1% to 10% of normal flows. The ratio was insensitive to flow increase amount largely because the effects of the flow increases on spills and evaporation were minimal, so that the flow increases were nearly completely utilized. Overall, the ratio was thus largely dependent on the shape of the demand curves. More elastic (flatter) demand curves would have produced larger ratios of percent change in total return to percent change in flow.

CONCLUSIONS

Flow increases from vegetation management in the mountainous West tend to occur during the spring snow melt. Because the largest consumptive use demands occur during the summer and early fall, such flow increases are of little utility for offstream use unless reservoir storage is sufficient to hold the increases until they are needed. However, storage alone is not sufficient to make efficient use of flow increases. Two recent studies of the effect of flow increases on water use in actual river basins (the Verde and Colorado River studies cited in the Introduction) indicated that much of any flow increases would be lost via evaporation and spills, and that less than half of the increases would be delivered to users.

These two site-specific simulation studies of actual management practices are not directly comparable to the current study of optimal water allocation in a hypothetical basin because of several differences, principal among them being differences in hydrology, instream flow constraints, and the way consumptive use demand was modeled. Regarding the latter, in the current study, quantity of offstream water demanded was modeled as an exponential function of price, allowing ever-increasing quantities of water to be delivered (albeit at continuously decreasing prices), while in the site-specific studies, water quantities requested were fixed (although of course not always satisfied).

Although these differences are substantial, it is instructive to examine the most obvious difference between the site-specific simulation studies and the current optimization results, which is that losses are much less in the optimum case. For similar ratios of storage capacity to mean annual flow, losses of increased flows were below 10% for the optimum case but over 50% in the actual cases. The primary reason for this difference is that institutional constraints on efficient water allocation were lacking, and perfect foresight was possible, for the hypothetical optimization. However, as the current study shows, even where losses are largely eliminated and perfect foresight is assumed, the value of flow increases is substantially less than the average value of preincrease flow because of the diminishing marginal utility of water use. Thus, given optimal management and a realistic treatment of the true economic value of water use, we reach a similar conclusion to the earlier simulation studies--flow increases are worth considerably less than the average value of normal flows.

REFERENCES

Brown T.C., and M.M. Fogel; 1987. "Use of Streamflow Increases from Vegetation Management in the Verde River Basin", Water Resources Bulletin, 23(6), 1149-1160.

Brown, T.C., B.L. Harding, and E.A. Payton; 1990. "Marginal Economic Value of Streamflow: A Case Study for the Colorado River Basin". Water Resources Research, 26:2845-2859.

Díaz G.E., and D.G. Fontane; 1989. "Hydropower Optimization via Sequential Quadratic Programming", Journal of Water Resource Planning and Management ASCE, 115(6), 715-734.

Hibbert, A.R.; 1983. "Water Yield Improvements Potential by Vegetation Management on Western Rangelands. Water Resources Bulletin, 19:375-381.

Hillier, F.S., and G.J. Lieberman; 1986. "Introduction to Operations Research", Holdel-Day, Inc., 4th Edition.

Laufer F., and H.K. Morel-Seytoux; 1979. "Optimal Weekly Releases from a Seasonal Reservoir, I. Deterministic Future". Water Resources Research, 15(2), 383-398.

Leifsson T., and H.J. Morel-Seytoux; 1981. "User's Manual for QPTHOR: a FORTRAN Quadratic Programming Routine", HYDROWAR Reports Division, 1005 Country Club Road, Fort Collins, Colorado, 80524.

Troendle, C.A.; 1983. "The Potential for Water Yield Augmentation from Forest Management in the Rocky Mountain Region". Water Resources Bulletin, 19:359-373.

Wilde D.J. and C.S. Beightler; 1967. "Foundations of Optimization", Prentice-Hall, First Edition, 480p.

Published in: Proceedings of American Geophysical Union Twelfth Annual Hydrology Days, March 31 - April 3, 1992, Colorado State University, Fort Collins, Colorado, Hubert J. Morel-Seytoux, ed. 419 pages.

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