A METHODOLOGY FOR ANALYZING ALTERNATIVE RESERVOIR SHORTAGE AND OPERATING CRITERIA

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ABSTRACT

The Bureau of Reclamation's shifting emphasis from a construction oriented agency to a water management agency has initiated the development of analytical tools for estimating the benefits, and changes in benefits, of alternative reservoir sizes (for new projects) and operating criteria (for existing projects). This paper presents a new methodological approach for estimating the marginal, or change in, economic benefits for a project and applies it to several case studies.

The modeling system developed from this effort links a spreadsheet-based model of reservoir operations to economic models of various demand sectors, including irrigation, municipal and industrial uses (M&I), and instream flow. Linking the models results in quick response in estimating the annual marginal economic benefits of alternative reservoir sizes and operating criteria.

When applied to a case study of an existing Southern California reservoir, the modeling system estimated the annual benefits of reservoir enlargment and changes in operating criteria. Additional case studies for projects in Oregon, Kansas, and Colorado have demonstrated the ability of the methodology to be adapted to a wide range of hydrologic conditions and project purposes.

INTRODUCTION

Evaluating the economic trade-offs between competing uses of water is of critical importance during times of drought. Under normal conditions, volume and timing of Bureau of Reclamation project deliveries are contractually fixed. Specific contract provisions provide for the operation of the facilities during drought conditions. However, the Bureau of Reclamation is interested in the re-evaluation of the marginal, or change in, economic benefits of alternative water allocations during drought conditions and to re-evaluate reservoir operation strategies which, in turn, would maximize the economic benefits of available supplies. This paper presents a methodology for measuring the marginal benefits of alternative reservoir operation plans which explicitly consider priority of use for various types of users and alternative shortage criteria.

The methodology is a linked system consisting of two models, a reservoir operations

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model which incorporates hydrologic data, water demands, priorities in use, shortage criteria, and other information, and an economic model to estimate the economic benefits of alternative combinations of the above variables. The operations model drives the system by computing water deliveries for three groups of users over a period of record. Irrigation, municipal and industrial (M&I), and instream flows are the water uses considered. The modeling system is sufficiently flexible to be applied to a range of geographic areas, hydrologic conditions, and project uses.

The following sections describe the models and their application to two case studies.

RESERVOIR OPERATIONS MODEL

A spreadsheet-based model of reservoir operations simulates annual and monthly deliveries to project uses considered. Based on a water balance concept, it uses a homogeneous hydrologic sequence (adjusted for historical use) to construct a monthly time series of reservoir inflows. Using this, and data regarding the physical characteristics of the reservoir site, including area-capacity, rainfall, and pan evaporation, a monthly time series of deliveries to each sector is constructed for each reservoir operation strategy considered. Operating criteria concerning priority of use and shortage criteria for each user group are explicitly considered, and can be altered to consider a range of criteria.

During a drought period, the operations model assumes the reservoir operator, whether it be the Bureau or a private agency, has two variables to consider for allocating available water. One is the shortage trigger, which defines the beginning of drought period operations. Defining a shortage, or drought condition, within the operations model requires the user to specify a reservoir level at which reduced deliveries are initiated. In the first case study, for example, deliveries to irrigators are reduced when the volume of water in the reservoir falls below 90,000 acre-feet. This level is referred to as the "trigger" level because it initiates reduced deliveries to one or more groups of water users. The model assumes each group of water users has a unique shortage trigger. Priority of use in times of shortages is directly related to the trigger since the lower the trigger is set, the higher priority for water the user has.

The second variable, shortage criteria, is defined as the reduction in deliveries imposed when the reservoir falls below the trigger level. Shortage criteria is expressed in percentage terms. For the case study example, the baseline shortage criteria for irrigation uses is 50 percent. Therefore, when the reservoir volume falls below 90,000 acre-feet, deliveries to irrigators are reduced 50 percent of normal.

Figure 1 contains a flowchart of the reservoir operations model. The data input requirements, shown on the left side of the figure, illustrate the flexibility of the modeling system. Any of the listed data parameters can be varied to observe their effect on economic benefits. Of interest is the priority of use, shortage trigger, and shortage criteria for each water use classification. However, the second box, identifying reservoir and conveyance capacities, has been of interest in past studies regarding reservoir sizing or enlargement. As can be seen in Figure 1, other variables such as alternative periods of record, flood pool requirements, and intra-season demand distribution can be examined within this methodology.

The output of the operations model mainly consists of deliveries to the water user groups. Additional output includes reservoir contents at user-specified intervals, and the

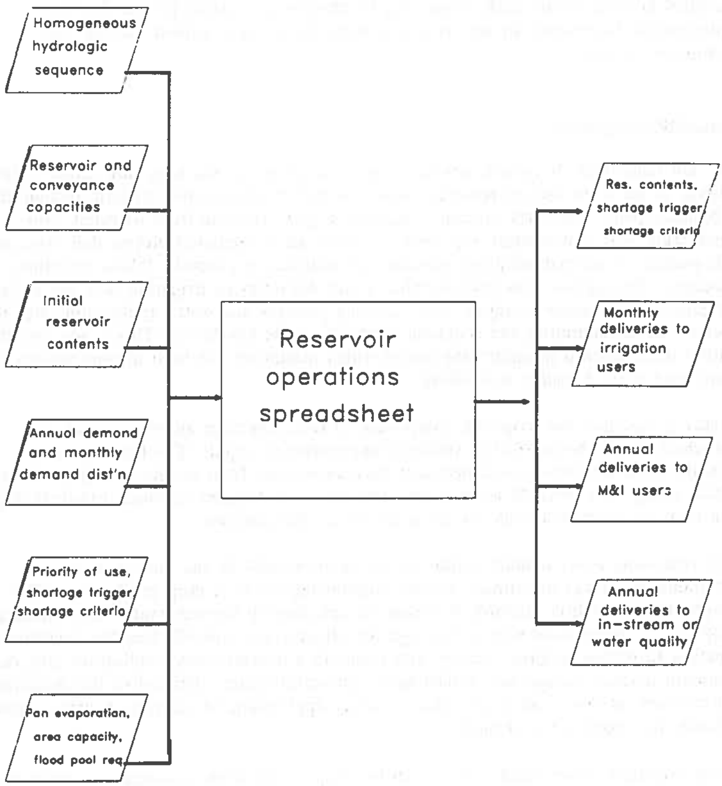

Figure 1. Operations model flowchart

shortage trigger and shortage criteria for irrigation uses. The purpose of the latter output will be explained in the following section.

ECONOMICS MODEL

The Economics model consists of three sectors corresponding to the water uses identified above - irrigation, M&I, and instream flow. The methodologies for estimating marginal benefits within each sector vary in complexity, ranging from a detailed optimization framework for the irrigation sector to a single- valued avoided cost technique for M&I.

Irrigation component

The net benefit of alternative reservoir operation plans for the irrigation sector is the change in net farm income resulting from a proposed plan minus net farm income from a baseline plan. Net farm income is defined as gross revenue from irrigated crop production minus production expenses. In years when simulated project deliveries are 100 percent of normal, cropping patterns are assumed to generally follow historical acreages. During low flow periods, when water deliveries to irrigation uses are reduced, irrigators are assumed to adjust their cropping patterns and water application rates in a manner which minimizes the economic damages of the low flows. This is accomplished with a mathematical programming model which maximizes net farm income subject to water and other resource availability.

Figure 2 describes the irrigation component of the economics model in terms of a flowchart. Eight boxes stacked vertically summarize its input. The two top boxes contain economic information necessary to compute net farm income. Crop prices and yields, along with irrigated acreage, are used to calculate gross income. Production costs can then be subtracted from this to arrive at net farm income.

The remaining boxes contain additional information used by the mathematical programming model to estimate income maximizing levels of crop production. The crop/water production function describes the relationship between water application and crop yield. When faced with a shortage, an irrigator will typically face the decision of whether to reduce irrigated acreage and maintain a normal water application rate, or maintain normal acreage and reduce water application rates. Critical to this decision is information on how crop yields relate to water application, or alteratively stated, how tolerant the crops are to drought.

Crop irrigation requirements, the fourth box, report the crops' consumptive water use requirements, net of rainfall, on a month by month basis. Availability of other water sources in addition to project water, such as groundwater, is the fifth box. Other water sources are of obvious importance because they can help mitigate the adverse impacts of reduced project deliveries. The sixth box contain water costs from project and non-project sources. Water costs may include pumping costs, ditch assessments, and other related costs. Non-water irrigation costs, such as labor and equipment are included as production expenses in the first box.

The reservoir operations model provides information in the final two boxes. As previously mentioned, in addition to monthly water deliveries the operations model provides the irrigation component with periodic reservoir contents, the shortage trigger, and the shortage criteria. The latter parameters are used in the irrigation component to

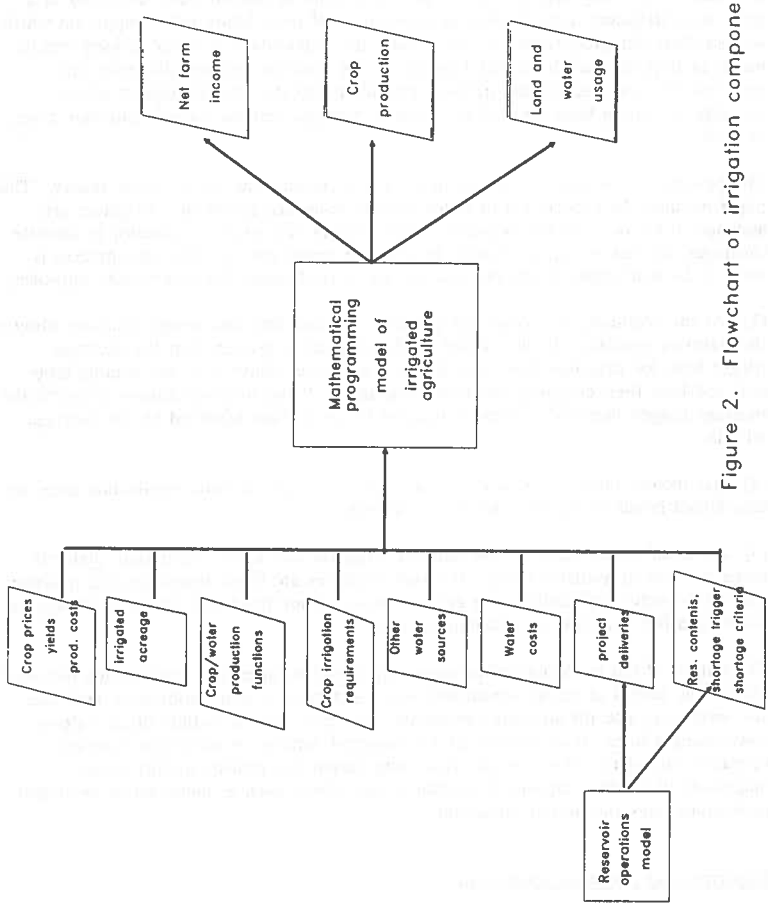

Figure 2. Flowchart of irrigation component

estimate "expected" water deliveries for an irrigation season. Their significance is explained below.

Many water projects cannot assure irrigators 100 percent reliable deliveries from year to year. The volume of water deliveries to irrigators is then a random variable due to the variability of rainfall and/or winter snowpack. Obviously, reservoirs help to smooth out this variability, but the remaining uncertainty has an impact on how irrigators make decisions. Since they may not be 100 percent certain of normal water deliveries in a given year, irrigators must develop an expectation of their future water supply on which to base their cropping decisions. As a result this expectation of water delivery can be nearly as important as the actual delivery. If, for example, reduced deliveries are expected, and are realized, the irrigator has minimized the adverse impacts of the shortage by cutting back some of his irrigated acreage, reduced water application rates, or both.

The process of how expectations are formed is a current issue in economic theory. This paper assumes the expectation of water delivery is formed rationally. Irrigators are assumed to be aware of the decision process used by the reservoir operator to allocate shortages and can anticipate changes in reservoir operation. A three step process is used in the mathematical programming model to implement this expectations approach:

(1) At the beginning of a crop year (January 1 in the first case study) irrigators observe the reservoir contents. If the volume in the reservoir is greater than the shortage trigger level for irrigation uses, they expect a full water delivery for the coming crop year and base their cropping decisions accordingly. If the reservoir volume is below the shortage trigger, expected delivery is reduced to the percent specified by the shortage criteria.

(2) Net income maximizing cropping patterns and irrigation water application rates are determined based on the expected water delivery.

(3) As actual water deliveries are realized, irrigators can update their farm plans to make best use of available water. If actual deliveries are lower than expected, irrigators can reduce water application rates and/or abandon some previously irrigated acreage to maintain a full irrigation on remaining acres.

The output of the mathematical programming model includes net farm income for every year of the period of record considered, and a summary of crop production, land use, and water use, also for all years considered. Net farm income is the critical output, since changes in net farm income are the marginal benefits of alternative reservoir operation strategies. However, the remaining output can provide insight to the magnitude of indirect impacts of alternative operations, such as increased or decreased farm input sales and output processing.

Municipal and industrial component

In contrast to the relative complexity of modeling the irrigation component, the M&I component uses a single value measure to calculate benefits, and change in benefits, of project deliveries. Specifically, the per unit cost of the next cheapest single purpose alternative available to the municipality is used to measure M&I benefits. This approach is consistent with Bureau of Reclamation project planning procedures, although little consideration is given to seasonal variabilities in delivery. As a result, only annual deliveries from the reservoir to the M&I sector are transferred from the Operations model to the M&I component.

Instream flow component

As its name indicates the instream flow component estimates the benefits, and change in benefits, of making reservoir releases to maintain flows in the watercourse. Instream flow releases, if they are made at all, can be made for a number of reasons. Some examples are maintenance of riparian and fish habitat, increased recreation opportunities, and improved downstream water quality. Appropriate valuation techniques will likely be different depending on the purpose of the instream releases.

Instream flow releases are considered in only one of the case studies examined here. In this instance they are made for water quality purposes. The benefit of releases were estimated as the avoided cost of water treatment. Similar to the M&I component, annual deliveries from the Operations model are considered rather than monthly deliveries.

CASE STUDIES

Two case studies demonstrate the modeling system. The first looks directly at alternative operating criteria by examining a range of shortage triggers and shortage criteria. The second focuses on the ability of the models to evaluate alternative reservoir sizes for a given site.

It is important to note that the case studies are for illustration of the methodologies and are not intended to accurately represent the actual situation in the study areas. However, since a portion of the hydrologic and economic data come from actual Bureau projects, the case studies carry the names of actual reservoirs.

Lake Cachuma, California

Lake Cachuma is a multi-purpose reservoir located about 30 miles northwest of Santa Barbara. Its annual average release of approximately 30,000 acre-feet is distributed to irrigation in the Santa Ynez valley (3,300 AF), irrigation along the Pacific South Coast (13,300 AF), and municipal supply for Santa Barbara. No releases are made specifically for maintenance of instream flows. This is an area of extremely tight water supplies, whose geography prohibits economical importing of additional water supplies. Groundwater is fully utilized. Pumping in excess of annual safe yield results in salt water intrusion within a short period of time.

The Santa Ynez region is characterized by a ranching economy, where project water is dedicated (in order of magnitude) to irrigated pasture, grass hay, alfalfa, barley, wheat, dry beans, and tomatoes. Conversely, irrigation in the South Coast area concentrates on high valued tree crops, such as avocados and lemons. The difference in types of agriculture between these two sub-areas motivated a decision to consider separate shortage triggers and shortage criteria for each.

A 30 year period of record, using the flow years 1945-1974 were used to generate a baseline series of monthly deliveries to the irrigation and M&I components. An extreme drought during the late 1940's and early 50's resulted in 57 months of zero reservoir

Table 1. Operating criteria, Lake Cachuma service area

		User 1: M&I		User 2: South Coast irrigators		User 3: Santa Ynez irrigators	
Reservoir size AF	Operation strategy	Shortage trigger AF	Shortage criteria %	Shortage trigger AF	Shortage criteria %	Shortage trigger AF	Shortage criteria %
308,000	A	50,000	20%	90,000	50%	90,000	50%
308,000	B	50,000	50%	50,000	50%	50,000	50%
308,000	C	50,000	20%	50,000	20%	90,000	50%
308,000	D	30,000	20%	60,000	30%	60,000	50%
308,000	E	75,000	20%	125,000	30%	125,000	30%
308,000	F	125,000	40%	125,000	40%	125,000	40%
308,000	G	0	0%	0	0%	0	0%

Table 2. Summary of annual benefits for alternative operating criteria assuming 1945 - 1974 period of record

Operation alternative	M&I benefits	change from base /1	South Coast net farm income	change from base	Santa Ynez net farm income	change from base	Cumulative change
A	$3,722,934	$0	$1,503,814	$0	$19,502	$0	$0
B	$3,624,816	($98,118)	$3,338,478	$1,834,664	$23,437	$3,935	$1,740,481
C	$3,696,252	($26,682)	$4,007,390	$2,503,576	$18,024	($1,478)	$2,475,416
D	$3,728,350	$5,416	$3,564,594	$2,060,780	$22,645	$3,143	$2,069,339
E	$3,669,519	($53,415)	$1,745,793	$241,979	$19,502	$0	$188,564
F	$3,367,154	($355,780)	$1,305,301	($198,513)	$19,031	($471)	($554,764)
G	$3,744,000	$21,066	$4,066,920	$2,563,106	$25,880	$6,378	$2,590,550

1/ The baseline operating alternative is A inflows, making this the most critical period of record. For purposes of illustration, it was assumed the reservoir at Lake Cachuma has a capacity of 308,000 acre-feet, rather than its current 205,000 acre-foot capacity.

The irrigation model was modified to better recognize longer term effects that drought periods have on avocados and citrus fruits. Contact with area horticulturalists and water district personnel indicated that, when expecting a water shortage, avocado growers will cut back acreage to give a full irrigation to remaining acres rather than attempt to practice deficit irrigation. Additionally, a full two year post-drought recovery period is needed before a yield can be expected from avocados. Citrus can be deficit irrigated and the recovery period for non-irrigated acreage is a single year.

The next cheapest single purpose alternative for acquiring M&I supplies appears to be reclamation of wastewater. The recycled water would mainly be used for irrigation of parks and golf courses in Santa Barbara. A per acre-foot cost of reclamation was estimated to be approximately $240.

In addition to baseline operating criteria, 6 other reservoir operation strategies are considered, encompassing a range of shortage triggers and shortage criteria. Table 1 summarizes the strategies for the two subareas of the irrigation component and the M&I component. Each strategy is designated by a letter, with Strategy A serving as the baseline operating criteria.

Strategy A favors M&I uses by declaring a smaller shortage trigger (50,000 acre-feet, compared to 90,000 acre-feet for irrigation users), and a lower shortage criteria (20 percent reduction in deliveries in shortage situations, as opposed to a 50 percent reduction to irrigators). Strategies F and G are of interest because they treat all water users equally in terms of the shortage trigger and shortage criteria. However, Strategy F is conservative in the sense that shortages are imposed when there is still a significant volume of water remaining in the reservoir (125,000 acre-feet). In contrast, Strategy G does not define either a shortage trigger or criteria.

Incorporating the above operating criteria into the modeling system over the period of record 1945-1974 yielded the results summarized in Table 2. From the perspective of an M&I water user, only operating strategies D and G would be preferred to the baseline strategy. South Coast irrigators would prefer all strategies, except F, over the baseline. Santa Ynez irrigators would prefer alternatives B, D, and F. Only strategies D and F increase benefits to all water use groups. However, cumulative results summarized in the last column of Table 2 indicate that from a project-wide perspective, all operating strategies except F result in higher overall economic benefits.

The results for alternatives B, C, D, and G indicate that an operating strategy which raises the relative priority of use for a component, or lowers their shortage trigger, will tend to be favored. For instance, Santa Ynez irrigators would likely support alternative B because they are put on equal footing with M&I users. They would also support D because it lowers the shortage trigger and leads to increased average annual net income. For the same reasons, South Coast irrigators would favor either of B, C, or D, and the M&I component would favor D.

Ironically, the alternative which maximizes economic benefits, and benefits all components, is Strategy G. This strategy states that maximum benefits are achieved when full deliveries are maintained until the reservoir runs dry, implying that reservoir operators may not need a drought strategy at all. It should be noted, however, that some non-consumptive uses of the reservoir which may have an effect on its operation, such as recreation, are not considered in this analysis. Nor is the variance of economic benefits from year to year considered.

Whether the strategy of running the reservoir dry is acceptable from a standpoint of risk management is beyond the scope of this study.

Tualatin Project, Oregon

Economic theory would suggest the optimal size of a multi-purpose reservoir is where the marginal benefits of the reservoir, summed across all uses, are equal to the marginal cost of the reservoir development costs. The modeling system is capable of estimating marginal benefits of alternative reservoir sizes for proposed projects. This is illustrated in an ex post analysis of the Tualatin Project in Northwest Oregon.

The Tualatin Project area lies near the City of Portland, Oregon. The main project features are Scoggins Dam, which forms Henry Hagg Lake. The reservoir has an active capacity of 59,170 acre-feet. Of approximate annual releases of 62,000 acre-feet, about 25,000 acre-feet are dedicated to M&I uses in suburban Portland, 20,000 acre-feet are used to maintain water quality in the Tualatin River, and the remaining 17,000 acre-feet are tagged for irrigation purposes. Due to the difference in climate and related hydrology the Tualatin can deliver more water than Lake Cachuma with a reservoir less than one-third the size.

Little modification of the Operations model was necessary to accommodate the Tualatin case study. Historical inflows were estimated for the period of record 1929 through 1952. Annual and monthly demands were obtained from the Bureau's 1970 Definite Plan Report (DPR), and updated with information published in their annual project reports. Physical coefficients, such as area capacity and pan evaporation were obtained form the DPR also.

The next cheapest single purpose alternative for suburban Portland to acquire additional M&I supplies is contracting directly with the city itself. The suburbs face a delivered price of $180 per acre-foot for Portland city water of similar quality.

The economic benefit of instream flow releases is the avoided cost of advanced water treatment. The Tualatin DPR estimated the avoided cost to be $13.60. Updating this cost with a construction cost index results in a 1988 avoided cost of $45 per acre-foot.

Ten crops are considered in the irrigation component: alfalfa, grass hay, pasture, corn silage, processing beans, sweet corn, onions, potatoes, seed crops (clover and bluegrass), and berries (strawberries and blackberries). Unlike the Cachuma case study, the perennial crops considered in the Tualatin Project do not suffer the longer term drought impacts such as those seen with avocados and citrus. Therefore, little modification of the model was necessary. The rainfall volume in the study area is more than adequate to provide crop consumptive water use requirements. However, rainfall is seasonal. Supplemental irrigation is required in the months of May through August to ensure acceptable crop yields.

Active capacity of the reservoir is reduced by 30,000 acre-feet in the months of October and November for flood control purposes. Occurring after the irrigation season, this can result in nearly draining the reservoir. Flood space requirements are relaxed to

25,000 acre-feet in December, 17,000 acre-feet in January, and 5,500 acre-feet and 2,000 acre-feet in February and March, respectively.

The Tualatin Project has never experienced a significant water shortage since it was developed. Intuitively, this suggests the marginal benefit of extra capacity in the reservoir is near zero. As part of the ex post analysis, smaller reservoir capacities are considered to observe how project benefits change with reservoir size. Capacities considered range from 50 percent of the current size, about 29,500 acre-feet, and incrementally increase up to its current capacity, 59,170 acre-feet. Operating criteria are not defined for this case study; the shortage trigger and shortage criteria are set at zero for all users.

Results of the model runs are summarized in Table 3. The first column details the reservoir size considered and the last column shows cumulative changes in economic benefits over the range. The middle columns summarize the marginal benefits of the alternative reservoir sizes for the individual components.

Marginal benefits for irrigation go to zero at capacities greater than 40,680 acre-feet, implying that capacity between this level and the current size has little economic value to irrigators. Marginal benefits of additional capacity go to zero at sizes larger than 33,283 acre-feet for M&I uses. For water quality purposes, the point of zero marginal benefits is reached at sizes larger than 48,076 acre-feet. It should be reiterated, however, that despite carrying the name of the Tualatin Project, this case study is simply for illustration and does not reflect actual conditions in the study area.

Figure 3 plots the marginal benefits of alternative reservoir sizes. Recall these are marginal, or change in benefits, rather than total benefits. Marginal benefit curves are typically downward sloping, implying diminishing marginal benefits as reservoir capacity increases. Note that the curve meets the X-axis at a capacity slightly larger than 48,076 acre-feet. This indicates that regardless of reservoir construction and maintenance costs, additional capacity above this level has little economic value. If marginal costs of reservoir construction and maintenance were known, they could be plotted on in the same graph as an upward sloping curve. The intersection of the marginal benefit curve and the marginal cost curve would indicate the economically optimal reservoir capacity.

CONCLUDING REMARKS

The above case studies, and additional case studies involving the Dolores Project in Colorado and the Cheney Project in Kansas, have demonstrated the adaptability of the modeling system to a variety of hydrologic conditions and economic objectives. In addition to examining alternative reservoir operating criteria and reservoir sizes, the models can assess alternative hydrologic records, demand data, conveyance capacities, water costs, and a host of other parameters affecting project management. Subsequent case studies will be less hypothetical in nature, beginning with an operations study of the Sevier River system. This case study will focus on reservoir operations, particularly how alternative operating plans will affect marginal benefits of irrigated agriculture in the Sevier basin.

TABLE 3
Summary of annual benefits for alternative reservoir sizes, Tualatin Project

Reservoir size (AF)	Net farm income	change from base /1	M&I benefits	change from base	Water quality benefits	change from base	Cumulative change
29,585	$3,985,026	($222,012)	$3,902,871	($597,129)	$633,377	($316,419)	($1,135,560)
33,283	$3,955,353	($251,685)	$4,368,806	($131,194)	$669,053	($280,744)	($663,623)
35,132	$3,998,864	($208,174)	$4,500,000	$0	$722,566	($227,230)	($435,404)
36,981	$4,098,425	($108,613)	$4,500,000	$0	$776,079	($173,717)	($282,330)
40,680	$4,197,987	($9,051)	$4,500,000	$0	$807,307	($142,489)	($151,540)
44,378	$4,207,038	$0	$4,500,000	$0	$838,535	($111,261)	($111,261)
48,076	$4,207,038	$0	$4,500,000	$0	$938,000	($11,796)	($11,796)
51,774	$4,207,038	$0	$4,500,000	$0	$949,796	$0	$0
59,170	$4,207,038	$0	$4,500,000	$0	$949,796	$0	$0

1/ The baseline case is the reservoir's current capacity of 59,170 AF

FIGURE 3
Average annual marginal benfits of alternative reservoir sizes, Tualatin Project