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SIZING MULTI-PURPOSE RESERVIORS: A METHODOLOGICAL APPROACH AND APPLICATION

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INTRODUCTION

The original mission of the Bureau of Reclamation to construct large water resource projects soon will be fulfilled. Of increasing importance is the nation's demand for high quality water and the necessity for for effective, efficient water resource construction and management. Current objectives are to improve management and use of resources, which, in many cases are already in place. Accordingly, Reclamation is developing new analytical tools to aid in the planning of new projects and the management of existing ones.

The process of sizing a reservoir is an example of where such an analytical tool is appropriate. The Bureau of Reclamation has not had formalized criteria in the past regarding how large to construct a reservoir. Some Bureau regions have used a heuristic rule-of-thumb which states reservoirs should be built large enough so irrigation uses are never shorted more than 50 percent of normal in the most critical year of record, and no more than a cumulative 100 percent over any 10 year period. Municipal and industrial uses (M&I) should never experience shortages under this rule.

In response to the need for consistency and to examine the relationship between reservoir size and economic benefits. reclamation is overseeing the development of a modeling framework in which to estimate total and marginal benefits of alternative reservoir sizes. Benefits estimated within this framework can then be matched against marginal cost of reservoir construction to arrive at an economically optimal sized reservoir.

The economic benefit of a reservoir, as a whole, is the sum of benefits to individual sectors using water, whether their demand be for consumptive or nonconsumptive uses. Model development has so far concentrated on 3 sectors, irrigation, M&I, and instream flows. However, the analysis presented here will emphasize only irrigation and M&I demands. Other uses, including recreation, hydropower production, and flood control will be addressed in later phases of the reservoir sizing study. Several goals for modeling system, intended to maximize its utility were specified prior to model development. The goals which had a significant impact on design of the modeling system included:

(1) The models should be able to address annual and seasonal variation in water deliveries, and any priority of uses in times of shortage.

(2) All model components, or sectors, should be separable. For instance, the irrigation component should be able to stand alone without the other components.

(3) The methodologies used for each

component should be consistent with Bureau of Reclamation procedures and guidelines for project planning.

The remainder of this discussion focuses on development of model components and their application to a case study.

MODEL COMPONENTS

Reservoir operations model

The first of the above goals precipitated the construction of a spreadsheet-based reservoir operations model to simulate annual and seasonal deliveries to the demand sectors considered. It uses historical stream gauge data 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 data, a monthly time series of deliveries to each sector is constructed for each reservoir size considered. Operating criteria concerning priority of use and shortage criteria for each user group are explicitly considered.

Figure 1 contains a flowchart of the overall reservoir sizing modeling system. The first 3 levels of the chart summarize input and output of the operations spreadsheet and the linkages between the model components.

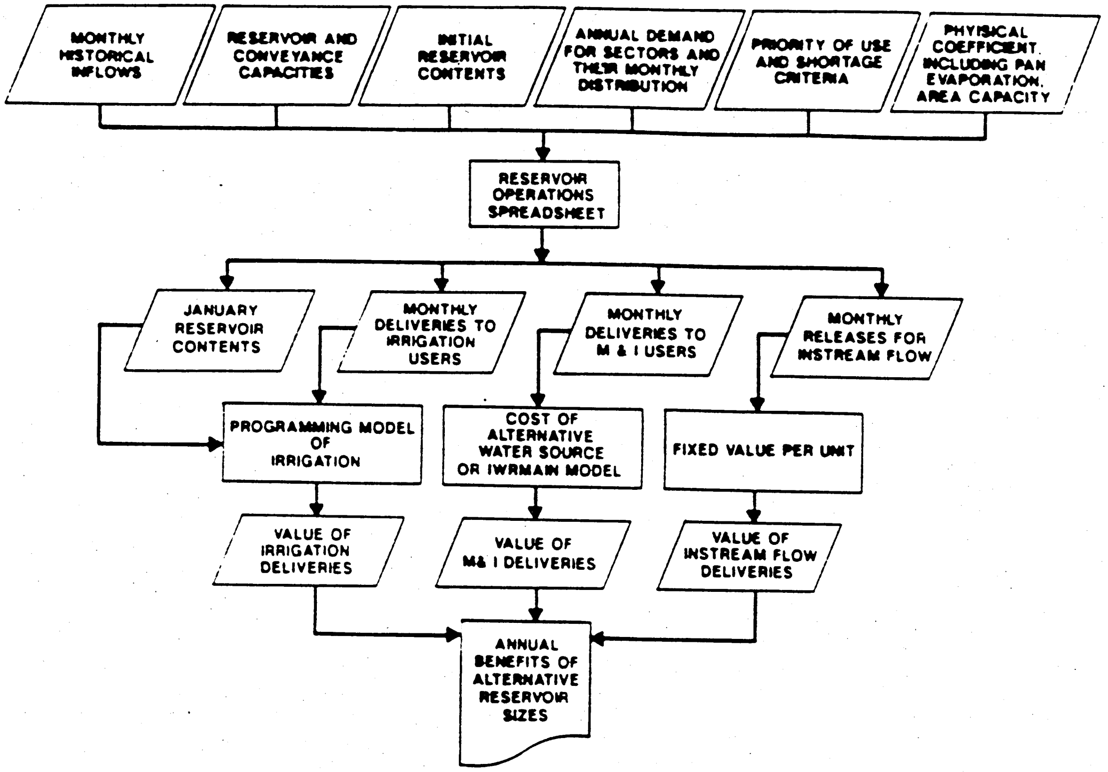
A drawback of the second goal, model separability, becomes apparent in Figure 1 by the lack of feedback loops between the components. This lack of direct linkages between the operations and economic components is not a problem when water is in adequate supply. However, even with a fully developed water priority system, intra-seasonal water distribution is typically an iterative process between the reservoir operator and water users. Instead, the operations model uses fixed rules to allocate shortages among the various uses.

Irrigation component

The operations model passes monthly, per acre-foot water deliveries, and other data, to the irrigation component. The irrigation component optimally distributes monthly water supplies over a range of crops in the project service area, using a profit maximizing mathematical programming approach. When the service area has a known cropping pattern, such as an area receiving supplemental irrigation water, Positive Quadratic Programming (PQP) is used to calibrate the baseline mathematical programming model to historical crop acreage levels (Howitt and Mean, 1985). If the service area is coming under irrigation for the first time, and does not have an established irrigated cropping pattern, a traditional linear program is used.

The first step in implementing the PQP approach is to run the model as a traditional LP, using historial crop acreage levels as crop acreage constraints. The dual values associated

Figure 1. Flow chart of modeling system linkages



with the acreage constraints are then used to derive a quadratic cost term for the objective function. A second run with the quadratic terms, and without the acreage constraints, will result in the model calibrating to the historical acreage levels. Subsequent scenarios will use the latter, quadratic model without flexibility constraints. There are many arguments for and against the PQP approach which will not be discussed here. It is worth noting, however, that PQP will result in the objective function measuring something other than net income. Income must be measured by a separate accounting routine.

To better anticipate irrigators' reaction to variable water deliveries, the irrigation component incorporates an expectation component. In effect, it incorporates rational expectations in water deliveries. The other data passed on by the operations model, in addition to monthly water deliveries, are end-of-year (previous year) reservoir contents and the actual criteria used by the operations model to allocate shortages. It is assumed that, on January 1, irrigators observe the contents of the reservoir, and by knowing the actual criteria used by the reservoir operator, develop an expectation of project water deliveries for the coming year. They then base their crop production decisions, regarding crop acreage and water application levels, on this expectation. Later in the year, the irrigators realize the actual water deliveries and, if an unanticipated shortage occurs, they can either conjunctively use groundwater to make up the deficit, cut back water applications, abandon some irrigated acres, or use any combination of the 3 adjustments.

The irrigation model, then, is run twice for every year in the period of record. Once using anticipated water deliveries to lock in crop acreages for the coming year and set preliminary rates of water application, and a second time to update this information using actual deliveries. Figure 2 illustrates this process. End of year reservoir contents and shortage criteria are used to develop expected monthly deliveries. This, along with regional crop production data are used by the PQP (or LP) model to set preliminary values of land use (LU), project water use (SU), and conjunctive groundwater use (GU). Actual monthly deliveries are then used in the model to arrive at updated values of LU, SU, and GU. Regional net farm income is calculated from the model solution. A series of net farm income results when this process is run over a period of record for a given reservoir size.

Regional crop/water production function information is incorporated to allow irrigators to move down the production function when water is in short supply (CH2M Hill, 1987). Other data used in the irrigation model include variable crop production costs (from crop enterprise budgets), crop yields, monthly crop water requirements, water delivery and application efficiencies, land availability, and availability of alternative sources of water. The irrigation component is coded and solved using GAMS/MINOS ver. 2.04.

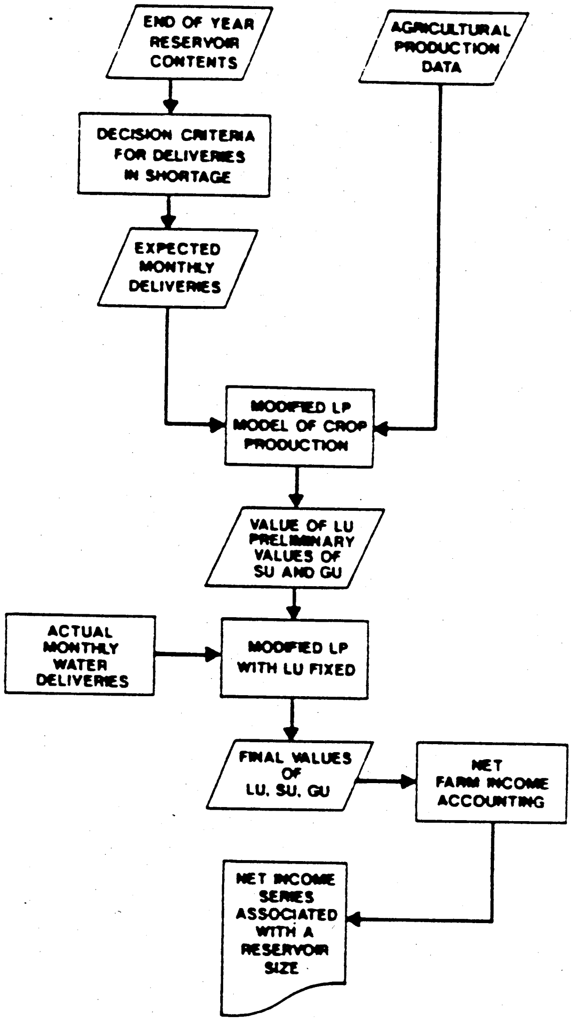
M&I Component

In contrast to the relative complexity of modeling the irrigation component, the M&I component uses a single value measure to calculate the 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. In other words, the municipality's per acre-foot avoided cost. This approach is consistent with Bureau project planning procedures, although little consideration is given to annual and seasonal variabilities in delivery.

CASE STUDY

A preliminary application of the reservoir sizing modeling system addressed the issue of enlargement of an existing reservoir, Lake Cachuma, California. Lake Cachuma is a 205,000 acre-foot, multi-purpose reservoir located about 100 miles northwest of Los Angeles. Its annual average release of approximately 30,000 acre-feet is distributed to irrigation in

Figure 2. The irrigation modeling process for a single year.the



Santa Ynez valley (3,300 AF), irrigation along the Pacific South Coast (13,300 AF), and a large municipality on the coast. No releases are made specifically for maintenance of instream flows. This is an area of extremely tight water supplies, and from a geographic standpoint, a very difficult area to import additional water supplies into. Groundwater is fully utilized. Pumping in excess of annual safe yield will result in salt water intrusion within a very 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. There was sufficient difference in the two regions to segregate them from a modeling standpoint, resulting in two irrigation models rather than one.

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, assuming the current reservoir size of 205,000 acre feet. An exteme drought during the late 1940's and early 50's, with over 40 months of zero reservoir inflows, made this 30 year period the most critical of record. In addition to a reservoir size of 205,000 acre-feet, 6 other sizes were evaluated for comparison purposes: 154,000, 179,000, 231,000, 256,000, 308,000, and 410,000 acre-feet. There is a common operating criteria throughout the range of sizes. It dictates a 50 percent reduction in irrigation deliveries when the reservoir level falls below 90,000 acre-feet. M&I deliveries are reduced 20 percent when the reservoir falls below 50,000 acre-feet.

The South Coast portion of the irrigation model was modified to better recognize the carry-over effects that drought periods have on tropical (avocados) and sub-tropical (lemons) 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. Lemons can be deficit irrigated and the recovery period for non-irrigated acreage is a single year.

RESULTS AND CONCLUSIONS OF CASE STUDY

Table 1 summarizes the results of alternative reservoir sizes on the irrigated regions served by Lake Cachuma. As expected, average shortage levels and their variability are reduced, and income levels increase, as reservoir size increases. It is of interest to note the wide variation in income in the South Coast area. More frequent and severe shortages are economically very disastrous to growers here. Examination of annual results (not included) indicated a dramatic drop in income after the first year of successive drought years. Table 1 also suggests that South Coast growers are, on the average, losing money under the current reservoir size. This is probably due more to the severe nature of the period of record used than the actual situation in this area in recent years.

Table 2 presents results of various reservoir sizes on the M&I sector, assuming an avoided cost by the municipality of $240 per acre-foot. Due to the high priority given M&I uses in the operations model, there is only approximately a 10 percent difference in benefits between the smallest and largest size.

The final column of Table 3 aggregates the sectors to arrive at a measure of cumulative changes in net benefits across the

TABLE 1

Net farm income for Lake Cachuma reservoir size alternatives

Reservoir size AF	Avg. annual shortage %	Avg. annual net farm income $	Change from baseline /1 $	Total net farm income /2 $	Standard deviation $
Santa Ynez service area, 1945-1974 period of record:					
154.000	22%	7.501	(5.703)	225.016	17.828
179.000	19%	10.704	(2.500)	321.122	18.313
205.000	14%	13.204	0	396.118	15.741
231.000	12%	15.462	2.258	463.864	14.664
256.000	10%	16.366	3.162	490.981	14.365
308.000	7%	19.502	6.298	585.047	12.617
410.000	1%	25.069	11.865	752.066	5.687
South Coast service area, 1945-1974 period of record:					
154.000	22%	(2.928.203)	(2.022.271)	(87.846.087)	4.791.821
179.000	18%	(1.916.178)	(1,010.246)	(57.485.333)	5.054.432
205.000	14%	(905.932)	0	(27.177.947)	4.888.243
231.000	11%	(122.889)	783.043	(3.686.660)	4.858.537
256.000	10%	356.286	1.262.218	10.688.585	4.623.197
308.000	7%	1.503.814	2.409.746	45.114.421	3.755.999
410.000	1%	3.788.441	4.694.373	113.653.219	836.274

1/ The baseline size is 205.000 AF, the current capacity of Lake Cachuma

2/ This is the undiscounted sum of annual net incomes over the period of record

TABLE 2

M&I benefits for Lake Cachuma reservoir size alternatives

Reservoir size AF	Avg. annual shortage %	Avg. annual M&I benefit $	Change from baseline /1 $	Total M&I benefits /2 $	Standard deviation $
1945-1974 period of record:					
154.000	9%	3.414.341	(182.604)	102.430.229	720.676
179.000	6%	3.523.919	(73.026)	105.717.569	475.215
205.000	4%	3.596.945	0	107.908.335	284.776
231.000	3%	3.639.617	42.672	109.188.518	228.734
256.000	2%	3.674.162	77.217	110.224.858	187.973
308.000	1%	3.722.934	125.989	111.688.013	69.535
410.000	0%	3.744.000	147.055	112.320.000	0

1/ The baseline size is 205.000 AF, the current capacity of Lake Cachuma

2/ This is the undiscounted sum of annual incomes over the period of record

TABLE 3

Summary of annual benefits for alternative reservoir sizes

1945 - 1974 period of record

Reservoir size (AF)	M&I benefits	change from base /1	South Coast ag income	change from base	Santa Ynez ag income	change from base	Cumulative change
154.000	$3.414.341	($182.604)	($2.928.203)	($2.022.271)	$7.501	($5.703)	($2.210.578)
179.000	$3.523.919	($73.026)	($1.916.178)	($1.010.246)	$10.704	($2.500)	($1.085.772)
205.000	$3.596.945	$0	($905.932)	$0	$13.204	$0	$0
231.000	$3.639.617	$42.672	($122.889)	$783.043	$15.462	$2.258	$827.973
256.000	$3.674.162	$77.217	$356.286	$1.262.218	$16.366	$3.162	$1.342.597
308.000	$3.722.934	$125.989	$1.503.814	$2.409.746	$19.502	$6.298	$2.542.033
410.000	$3.744.000	$147.055	$3.788.441	$4.694.373	$25.069	$11.865	$4.853.293

1/ The baseline case is the reservoir's current capacity of 205.000 AF irrigation and M&I sectors. At reservoir sizes larger than 205,000 acre-feet, the cumulative change can very loosely be interpreted as the maximum annual payment the region could afford to make to enlarge Lake Cachuma. Of course, these figures would have to be matched against the marginal costs of enlargement, including marginal O&M costs. Using a discount rate of 10 precent over an infinite time horizon would indicate the region could afford to pay up to approximately $8.3 million to increase Cachuma's capacity to 231,000 acre feet, and $48.5 million to double its size. However, these figures are very preliminary and for illustration only.

Space prohibits the presentation of results for individual years within the period of record. However, they lend insight to the adjustments irrigators might make when faced with anticipated and unanticipated water shortages. For anticipated shortages, results indicated groundwater will be conjunctively used as long as it is available. When depleted, growers will cut back acreage in nearly all cases, and apply a full irrigation to remaining acres. Faced with unanticipated shortages, whether they be due to groundwater depletion or a mid-year drought, they will cut back water application levels on most acres and abandon the rest. However, the acres recieving the deficit irrigation will still receive in excess of 90 percent of its required consumptive use.

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