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VALUE OF STORING STREAM RUNOFF FOR IRRIGATION USE[1]

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Public and private agencies spend millions of dollars each year for the entrapment and delivery of irrigation water. Very little is known about the demand function for irrigation water storage, especially when surface supplies are used in conjunction with ground water sources. The objective of this paper is to explain one method of arriving at an estimate of the value of storing irrigation water, using linear programming.

Most rivers and streams have a peak flow early in the spring and very small flows during the hot summer months. This causes them to be undependable for summer irrigation without storage reservoirs. The capacity of the reservoir sets the maximum amount of water that will be available for summer irrigation; the amount of runoff available will be limited during years when it is inadequate to rise to full reservoir capacity. Adequate quantities of water are a necessary condition for successful irrigating; however, the timing of water availability is equally important as we propose to demonstrate.

Suppose we have a stream with a high spring runoff coming from the melting snowpack (see Figure 1). Flow in this stream extends from late February to the middle of June, with a peak during May. The unimpeded flow in this stream during most years is large enough and continues long enough to make construction of diversion works and a distribution system feasible without storage. Such facilites will provide irrigation water for pre-planting and early summer irrigations, but an intensive agricultural use requiring full season irrigation must depend on underground water supplied by wells.

If a small dam is built on this stream, some of the water that is unused in the peak flow month can be stored and used later in the season during the peak demand periods. If a slightly larger dam is built, a greater amount of this presently unused water can be stored and used during a still later time period. This expansion can extend until it is possible to provide optimum water distribution. In essence, then, a storage dam can move a block of water from a time period

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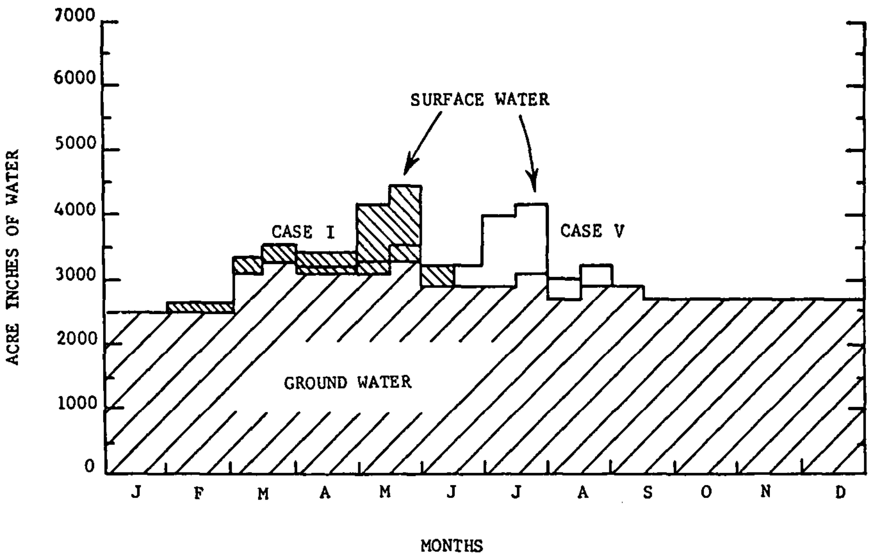
1. Several persons have pointed out the problem at hand. See Tolley & Hastings, *Optimal Water Allocation: The North Platte River,* 74 Q.J. Economics 279 (1960); McPherson, *Can Water be Allocated by Competitive Pricing?,* 38 J. Farm Economics 1259 (1956).

Figure I
WATER SUPPLY 640 ACRE FARM

Eastern San Joaquin Valley
California



when the water has a low value to a time period when it has a higher value. The difference between the value of the water in the first time period and the value of the water in the second time period represents the value of the storage.[2] This problem is somewhat analogous to the classical inventory problem.[3]

The procedure in this study was to divide the irrigation season into twelve time periods and to use the water supply (both surface and ground) as constraints in a linear programming model. Other constraints used were, the supply of land broken down into two soil types, institutional restrictions represented by a cotton allotment, sugar beet contract, and a maximum acreage of blackeyed beans. Well water came from four wells pumping about 900 g.p.m. at mid-season (adjustment was made for seasonal drawdown in the wells). Cost co-efficients, acreage allotments, land availability, and other parameters were from a "typical" 640 acre farm in Tulare County in the San Joaquin Valley of California. The technical co-efficients for irrigation water were synthesized by time

2. Value of Storage $= Z_{t+1} - Z_t$. Where $Z_t =$ net farm income in period t and $Z_{t+1} =$ net farm income in later time period.
3. P.A.P. Moran, Theory of Storage (1959).

periods, using a procedure outlined in another paper.[4] All water in this problem is priced at $3/acre-foot regardless of the source; for the surface water this covers the cost to the farmer of diverting and transporting the water exclusive of storage, for the ground water, the variable cost of pumping.

The hypothesis in this paper is that as the block of surface water available shifts by discrete time periods from the normal runoff conditions to time periods when the supply more nearly corresponds to the period of peak crop demand, the value of the linear functional, $Z_0 = C_1X_1 + C_2X_2 + \ldots + C_kX_k$ or farm income will increase. Further, the difference in this functional (farm income) from the base time period to succeeding time periods will be the value of storing this block of water during such time periods.

EMPIRICAL RESULTS

Figure 1 shows graphically the distribution of the total water supply by source as the block of water shifts in time. Case I is the distribution under normal runoff conditions when no storage exists. Case II (not shown) results when this basic block of water is moved forward in time by 15 days by a small dam. Case III (not shown) would require a slightly larger dam in order to shift the water forward a month. Finally, in Case V, the basic block of water has shifted forward two months to coincide with the peak crop demand period of July.

The activities in the final basis of the optimum solution and their level for each of the five cases and the value of the functional for each solution is given in Table 1.

The optimum solution for Case I (no storage), includes sugar beets, cotton, and blackeyed beans at the maximum acreage allowed by the restrictions imposed, although a small part (6.6 acres) of the cotton is not irrigated with the wettest irrigation treatment possible. About 41 acres of grain sorghum and 64 acres of barley, plus all alfalfa, are irrigated with the driest treatment possible. Water is not limiting in the time periods from the first of March through the middle of June; and part of the supply is in disposal.

In general, heavier water-consuming crops come into the optimum program and crops remaining use wetter irrigation treatments as the block of water shifts forward. In Case V, water is limiting only during the last half of June and the last half of August; cotton, beans, sugar beets, and most of the alfalfa are receiving irrigation at the wettest treatment allowed in the model. This final case contains no barley or grain sorghum, both of which are relatively low water-use crops.

The functional (farm income) does not increase uniformly as the block of water is moved in time: farm income increased only $1.00 between Case III and Case IV. The difference in farm income between Case I and Case V is

4. C. V. Moore, *A General Analytical Framework for Estimating the Production Function for Crops Using Irrigation Water*, 43 J. Farm Economics 876 (1961).

$3,388, which means that this is the maximum amount that a farmer could pay annually towards the construction and operation of a storage dam to redistribute the water in this manner, including all costs. This represents $5.63 per-irrigated acre for the 602 crop acres on the prototype farm. It is possible, by aggregating such gains for the entire service area of a stream, to estimate the total annual value of this storage. This figure, then, can be related to the cost of the dam under consideration.

Linear programming yields a dividend in the $Z_j - C_j$ values for the activities in the original basis; these can be interpreted as the marginal value productivity of the limiting factors.[5] They represent, therefore, the amount the functional would increase if one more unit is added to the supply. Most interesting among these are the values for the two land constraints. Soil number 1 is considered of higher quality than the number 2 soil. These marginal values productivities for land can be viewed as the maximum annual cash rental values per acre. This follows inasmuch as our unit is one acre. We find that the marginal value productivity of soil number 1 increases $36.24 from Case I to Case V while the lower quality number 2 soil increases only $18.65. The relative values of these figures suggest some strong implications for water pricing policy; however, an analysis of water pricing policy is not an objective of this paper.

LIMITATIONS OF THE ANALYSIS

The greatest limitation in this analysis is that it was not possible to redistribute the water optimally over all the time periods. This was closely approximated, however, as is evident from the fact that in Case V, water is limiting only during the last half of the month in June and August, whereas, there is surplus water in some of the other time periods. The surface water supply was not corrected for evaporation losses while in storage; this adjustment can easily be done when more is known about the reservoir site and its physical characteristics. Finally, this is a short run analysis and does not allow for the purchase of additional capital assets or alternative irrigation systems.

SUMMARY

An attempt has been made in this paper to show how linear programming can be used to arrive at estimates of the value of water stored for irrigation use. By moving a block of the unimpeded flow of a stream through time to more nearly coincide with the peak demand period for crops, the result was to change significantly the optimum cropping program and to increase farm income. It is contended that the increase in farm income represents the value arising from storing this water. Knowledge of this relationship can be related to optimum reservoir capacity, and lend more objectivity to dam design and water resource development.

5. E. O. Heady & W. Candlor, Linear Programming Methods 83 (Iowa State Univ. Press, 1958).

TABLE 1

Optimum Solutions as Water Supply is Varied
640 A. Farm Tulare County

Case I				Case II				Case III				Case IV				Case V			
Crop	Soil	Treatment[2]	Activity level	Crop	Soil	Treatment	Activity level	Crop	Soil	Treatment	Activity level	Crop	Soil	Treatment	Activity level	Crop	Soil	Treatment	Activity level
alfalfa	1	100	8	alfalfa	1	100	31	alfalfa	1	100	10	alfalfa	1	100	49	alfalfa	1	100	76
alfalfa	2	100	46	alfalfa	2	80	55	alfalfa	2	80	164	alfalfa	2	100	85	alfalfa	2	100	41
alfalfa	2	80	106	cotton	1	60	196	alfalfa	2	100	14	alfalfa	2	80	52	alfalfa	2	80	113
cotton	1	60	193	cotton	1	80	4	cotton	1	60	200	cotton	1	60	200	cotton	1	60	200
cotton	1	80	7	s. beets	1	80	72	s. beets	1	80	72	s. beets	1	80	72	s. beets	1	80	72
s. beets	1	80	72	beans	1	80-100	100	beans	1	80-100	100	beans	1	80-100	100	beans	1	80	74
beans	1	80-100	100	g. sorg.	1	100	18	g. sorg.	1	100	39	g. sorg.	2	100	44	beans	2	80	26
g. sorg.	1	100	5	barley/				g. sorg.	2	100	2	water	3/1		721	water	3/1		721
barley/				g. sorg.	1	80	55	water	3/1		819		3/16		1,822		3/16		2,031
g. sorg.	1	80	36	barley	2	100	30		3/16		1,686		4/1		2,087		4/1		1,895
barley	2	100	28	water	3/1		669		4/1		1,725		4/16		2,383		4/16		2,059
water	3/1		664		3/16		2,115		4/16		2,951		5/1		1,536		5/1		1,401
	3/16		2,275		4/1		2,022		5/1		1,104		5/16		761		5/16		579
	4/1		1,842		4/16		2,544		5/16		838		6/1		942		6/1		1,114
	4/16		2,804		5/1		1,578		6/1		2,517		6/15		737		7/1		483
	5/1		2,297		5/16		1,635		6/16		182		7/1		624		7/15		92
	5/16		1,839		6/1		2,156		8/1		293		8/1		299		8/1		596
	6/1		1,294		7/1		59												

	Case I	Case II	Case III	Case IV	Case V
Farm income[1]	$81,458.00	$81,838.00	$82,682.00	$82,683.00	$84,846.00
Change in farm income over Case I					
Total	0	$ 380.00	$ 1,224.00	$ 1,225.00	$ 3,388.00
per irrigated acre	0	$ .63	$ 2.03	$ 2.03	$ 5.63

1 Receipts over variable expenses; to obtain net farm income subtract $63,000 fixed costs.

2 100 = dry irrigation treatment, 80 = medium irrigation treatment, 60 = wet irrigation treatment (cotton only), 80-100 = medium treatment in spring = dry treatment after 1 July.