A Method for Estimating the Demand for Irrigation Water

By Charles V. Moore and Trimble R. Hedges

Estimating the demand curve for farm irrigation water is a matter of serious concern in most of the Western States today and may be so in portions of the humid East in the near future. Farmers and other users have filed claims to all readily available streamflow, and private and public agencies have exhausted nearly all low-cost storage sites. Additional water can be made available only at much higher costs. If these higher costs are to be repaid, facilities must be designed to be utilized to their full capacity. Such designs must take into account the slope and position of the demand curve for irrigation water. The results presented here should be useful to project planners undertaking to determine the feasibility of proposed water projects. These results will also provide guides for allocating water supplies in multiple-use projects among various users, and they will help water agency managers to assess how proposed price schedules will affect income accounts for their farmer patrons. The authors wish to thank B. C. French, G. W. Dean, J. N. Boles, H. O. Carter, and G. A. King for their comments and suggestions. This project was supported by the Water Resources Center, University of California.

THIS STUDY attempts to estimate the static-normative demand for irrigation water for individual farms in Tulare County, Calif., a highly intensive crop farm area. The individual farm demand relationships are aggregated by means of weights based on the distribution of farm sizes in the study area. The slope of the aggregate curve is found by fitting a regression equation to the weighted data. A total revenue function is developed based on this overall relationship. Finally, changes in the aggregate functions are explored by varying the proportion of soil qualities from the original presupposition.

The static-normative nature of the demand function estimated may not shed much light on what farmers *will* do in the short run if water prices undergo a sharp shift. However, it is the writers' opinion that over a longer timespan, farmers will tend to adjust to what the analysis indicates they *should* do.

The synthesized approach used in this analysis generated results for a wide range of water prices with a model representing a small geographic area. This parametric-objective function (variable-cost) programming method is a modification of the standard simplex linear programming model.[1 2] It enables the researcher to study the effects of a wide range of costs or prices on the optimum solution to the standard simplex problem.[3] For a purchased input such as irrigation water, it indicates the optimum quantities of water to be used in relation to water costs. It is possible to trace this relationship continuously through the entire range of all possible prices for water. This procedure thus provides data to construct a demand schedule for the particular resource under consideration, in this instance irrigation water.

Assumptions Regarding Resource Supplies, Technical Data, and Activities

A linear programming model must reflect as realistically as possible the actual conditions in the study area. A detailed survey of the area provided the data needed for quantifying resources, crops or activities, constraints, and technical data. In this model, the land resource consists of 70 percent Grade I land and 30 percent Grade II land.[4] Roads, ditches, and the farmstead occupy 6 percent of all farmland. Cotton allotments limit production to 33 percent of the cropland. Contract requirements, production regulations, and a pest problem restrict sugarbeet acreage to 12 percent of the cropland. Blackeyed bean production

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[1] Thomas Satty and Saul Gass, "Parametric Objective Function, Part I," *Jour. Operations Res.* 2: 316–319, 1954.

[2] Earl O. Heady and Wilfred Candler, *Linear Programming Methods*, Iowa State College Press, Ames, 1958. See discussion on variable-cost programming in chapter 8.

[3] James N. Boles has suggested that the same information could be obtained using variable resource programming from which marginal-value products can be determined.

[4] Grades of land based on the Storie Index system. See R. E. Storie, *Revision of the Soil Rating Chart*, Calif. Agr. Expt. Sta. unnumbered report, May 1953, 4 pp.

cannot exceed 16 percent of the irrigable land. The supply of irrigation water consists of the total quantities obtained from both pumps and surface sources. These quantities impose restrictions in 12 critical time periods during the growing season.

Nine alternative crops were considered for each of the two soil grades with 3 irrigation treatments for each crop, making a total of 54 producing activities. Although a complete listing of all crops, other than trees and vines, grown commercially in Tulare County would include more items, the nine considered here account for over 74 percent of all harvested acres.

Technical production coefficients for irrigation water by crops during the critical time periods represent a synthesis, based on a procedure outlined in another paper.[5]

Characteristics of Irrigation-Water Demand

Graphic presentation of the results of variable-cost programming as outlined above produces a "stepped" demand function (fig. 1). This result reflects the interaction of resource supplies and fixed production coefficients. The optimum cropping program, and therefore, the optimum quantity of water, holds for all the prices included within the vertical portion of any one step. At the "corner" of each step there are two optimum cropping programs, a situation similar to a border price in a price map. Each of the alternative optimum solutions results in exactly the same value for the objective function (farm income).[6]

Figure 1 shows the stepped demand functions for each of the five farm sizes analyzed. Regardless of farm size, the optimum quantity of water per acre changes very little in the cost range from zero to $3 per acre-foot (the present variable cost of pumping in the area). Except for the 1,280-acre farm, the greatest change in the optimum quantity demanded comes at water costs of about $16.50 per acre-foot. At $16.50 per acre-foot the lower grade of soil becomes idle, and farming continues only on the better soil with the highest valued crops (cotton and sugarbeets). At this water cost, gross receipts from alfalfa (a heavy

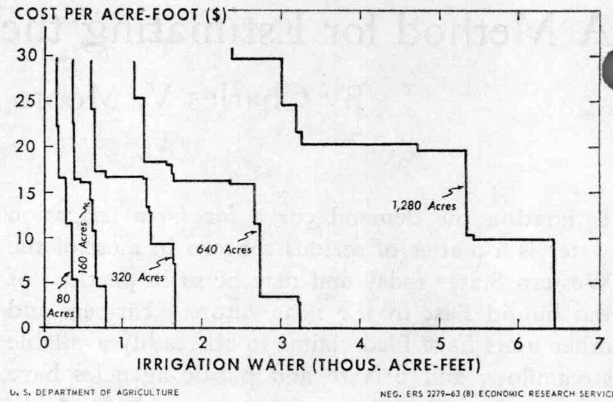

Figure 1.—*Farm demand for irrigation water at various prices, five farm sizes.*

water-using crop) are no longer adequate to cover variable production expenses (including water costs). In contrast, gross receipts exceeded the variable production expenses for alfalfa on the 1,280-acre farm until the cost of water was increased to about $20.50 per acre-foot. At this cost, all Grade II soil became idle. This variation reflects the lower variable cost of growing and harvesting alfalfa with the larger and more efficient equipment on the 1,280-acre farm.

Elasticity of Demand With Respect to Price of Water

The previous section presented, and briefly analyzed, the normative demand schedules for water on farms of five sizes. To estimate the demand schedule for an entire geographic area, or all farms of a specific type within a geographic area, it is necessary to aggregate or sum all of the individual farm demand schedules.[7] This was done by a weighting process, multiplying the number of farms in each size category by the quantity of water shown in the demand schedule at each border price for each of the typical farms.[8] The sum of these quantities according to varying prices is the aggregate demand schedule (fig. 2).

[5] Charles V. Moore, "A General Analytical Framework for Estimating the Production Function for Crops Using Irrigation Water," *Jour. Farm Econ.* 43 : 876–888, November 1961.

[6] Heady and Candler, *op. cit.*, p. 268.

[7] If large geographic areas were aggregated, the assumption of a perfectly elastic demand for commodities would not hold because changes in output would be sufficient to affect price.

[8] The number of farms in each size category is shown in T. R. Hedges, "Economic Adjustments on California Cotton Farms," Preliminary Statistical Summary No. 1, Farms, Acres and Cotton Allotments 1954, Calif. Agr. Expt. Sta., June 1955.

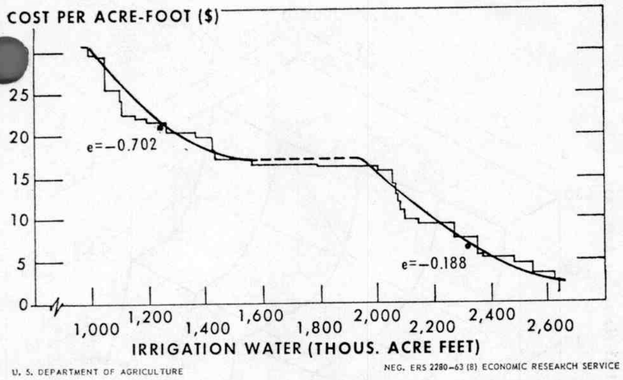

FIGURE 2.—*Demand for irrigation water at various prices, cash crop farms, with 70 percent Grade I soil.*

This procedure retains all of the steps found in the five original demand schedules, but tends to smooth them out.

It is obvious from the demand schedule in figure 2 that a distinct shift occurs when the cost of water reaches about $16.50 per acre-foot. To take account of the two segments of this discrete demand schedule, two second-degree polynomial regression equations were fitted to the stepped data by the method of least squares. It was assumed that the midpoints of the vertical portions of the steps were most stable with respect to price change; these points, therefore, were used as observations for fitting the estimating equations.[9] Such data do not meet the assumptions of normality and independence used in regression analysis; statistical inference and probability statements, therefore, cannot be made.

The point elasticity of demand is relatively more elastic for the demand curve above $16.50 per acre-foot (−0.702) than for the demand curve in the lower range of prices (−0.188) at their respective means. Thus, at a water cost of $9.44 per acre-foot, a 1-percent increase in price should cause a 0.188-percent decrease in the quantity of water taken. At the higher price of $23.30 per acre-foot, a 1-percent increase in price should cause a 0.702-percent decrease in the quantity used.

Public entities known as irrigation districts are responsible for most irrigation water deliveries made to farm headgates in the United States. In addition, mutual water companies distribute a small percentage, and private companies an even smaller proportion of the total water delivered. Public and mutual companies both regulate their prices to their customers in accordance with the same overall objective: to cover total costs, including bond repayments and interest due. Private concerns, in contrast, usually have a different objective: to maximize profits from their operations, subject to restraints imposed by the State through public utility commissions or other regulatory bodies. This analysis sheds some light on the question of how pricing policies might differ for organizations pursuing these different objectives.

Total revenues at the various water prices can be calculated by multiplying the prices in figure 2 by the associated quantities. A water distributor would obtain the maximum total revenue ($32,587,500) by selling 1,975,000 acre-feet of water at $16.50 each. Several price-quantity combinations along the demand curve will yield identical total revenues. For example, $26,400,000 can be obtained either by selling 1,500,000 acre-feet at $17.60 per acre-foot, or 2,080,000 acre-feet at $12.70 per acre-foot. This condition is due to both the discreteness of the overall demand curve and the difference in slope of the two segments of the curve.

Decisionmakers in public or private agencies will require information in addition to that presented here before they can determine how much water they will need to sell. They must know, for example, the shape and position of the total cost function for storing and delivering a wide range of water quantities. This analysis, even though it does not take all of these circumstances into account, does support several generalizations relevant to water resource development and pricing problems.

As suggested above, a publicly or mutually owned organization would attempt to set water delivery prices at a level that will equalize total costs and total revenues. These organizations sometimes derive a portion of their revenues from land assessments per acre or on some other basis not identified with a water delivery unit; then they need to recover only part of their total costs by levies on measured water deliveries.

In sharp contrast, the private agency, pursuing its profit-maximizing objective, should set its prices and sell the associated water quantities so as to obtain the greatest possible margin of net revenue. Private agencies are not permitted under the law to levy taxes or assessments. They must de-

[9] A similar procedure was used in an Iowa milk supply response study. R. D. Krenz, E. O. Heady, and R. V. Baumann, *Profit Maximizing Plans and Static Supply Schedules for Fluid Milk in the Des Moines Milk Shed,* Iowa Agr. Expt. Sta. Res. Bul. 486, October 1960.

pend entirely on prices related to water deliveries, usually metered, and therefore will not be able to sell as much water as the publicly or mutually owned agency. As a result, farm production will be lower in an area served by a private agency than if a publicly or mutually owned agency was the water distributor.

This analysis also indicates that, because of the relatively inelastic demand for water at prices ranging from zero to about $16.50 per acre-foot, irrigation districts and other distributing agencies, when necessary, can increase their total revenues by raising rates within this range. An established agency with facilities largely completed might obtain funds for further improvements through such increases in metered rates.

Elasticity of Demand With Respect to Soil Quality

Detailed soil classification data according to farm size were not available for this analysis. A presupposition was that for each farm size, Grade I soils represented 70 percent and Grade II soils 30 percent of all farmland. This assumption is somewhat unrealistic. In a large geographic area, some farms would have 100 percent Grade I soils, with others progressing through the entire range until some would be at the opposite extreme of 100 percent Grade II soil, assuming that these two grades account for all farmland in the area.

An alternative approach, useful for learning how soil quality variations might affect irrigation water demand, is to aggregate varying proportions of soils to produce traces on a three-dimensional surface, as shown in figure 3, in which the 75-percent trace is closely similar to the curve in figure 2.

The long horizontal step for each trace is caused by alfalfa going out of production on both soil grades when the price of irrigation water is above $16.50 per acre-foot. The demand for water in the lower range of prices is less elastic for the Grade II soil because of the lack of alternative low-water-using crops on this soil.

The greatest acreage of alfalfa is grown when the proportion of Grade I soil is 75 percent. This large acreage of a heavy-water-using crop explains why the total quantity of water used is so high on the 75-percent trace.

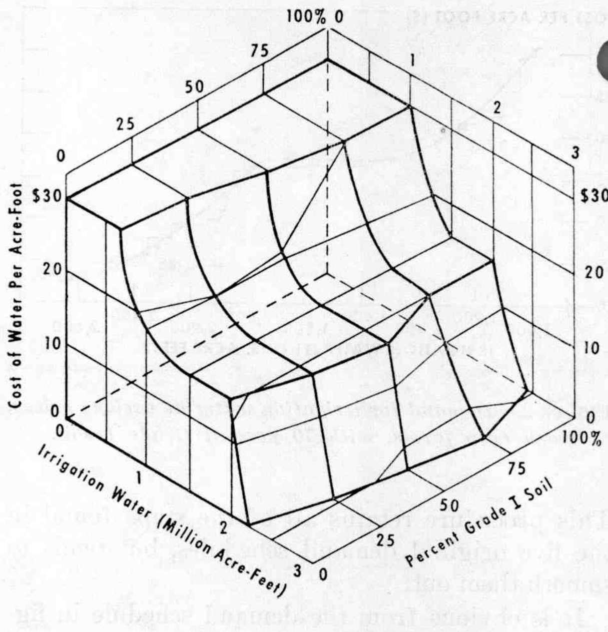

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FIGURE 3.—*Short-run demand surface for irrigation water, cash crop farms, two soil grades.*

Limitations of the Analysis

The limitations of the assumptions underlying linear programming such as divisibility of inputs and linearity of the production function are pointed out elsewhere.[10] These limitations fully apply here. Two critical assumptions are not necessarily valid: (*a*) that producers have complete knowledge of commodity prices, and (*b*) that each producer's goal is to maximize farm income. To the extent that these assumptions fail, producers' actual decisions may differ, sometimes markedly, from those indicated as optimum.

Other limitations include the uncertainties regarding changing technologies, economic and institutional elements in the decision context, the relatively small geographic area studied, and the fact that the method used does not permit probability statements to be made about the fitted equation. This last limitation, of course, applies to any synthesized approach. The writers warn that the results presented here cannot be generalized into a different area unless the new area duplicates all physical, economic, and institutional constraints found in the area included in this analysis.

[10] Heady and Candler, *op cit.*, chapter 1.

Conclusions

The U.S. Bureau of Reclamation has been able in the past to proceed on the assumption of a perfectly inelastic demand for water so long as the price of water does not exceed $8 per acre-foot. But preliminary estimates suggest that under the California Water Plan, unsubsidized prices at the farmer's headgate may be as high as $24 per acre-foot.

Demand for irrigation water in a specific highly commercialized area appears to be relatively inelastic in the lower range of water prices, but becomes increasingly elastic as prices rise. Demand for irrigation water in the lower price range also tends to be less elastic for lower quality soils because of the lack of economically adaptable alternative crops. Increasing water prices on farms with high proportions of low-quality soils thus leads to special problems.

This analysis also sheds some light on shifts in land use in relationship to soil quality and prices of irrigation water. Growers tend to take low-quality soils out of production at much lower prices than the better soils. This also is verified by the scanty empirical information that is available.

Distributing agencies will obtain the maximum total revenue, not at the highest water price studied ($30 per acre-foot), but rather at about $16.50 per acre-foot. This result accompanies the differential rates of slope on the two segments of the demand curve, and the important shifts in land use as water prices rise. These price-quantity-total-revenue relationships are critically important to planners and other officials responsible for water development and pricing policy decisions.

Policymakers should consider, further, the probable impacts of the type of organization used to develop and deliver irrigation water on quantities sold, and the volume of physical output on the farms serviced. Non-profit-seeking public or mutual organizations will tend to sell larger quantities of water, with resultant greater physical production by their customers, than private organizations which do seek to maximize profits. Public or semipublic organizations with power to levy taxes or assessments can encourage or discourage water consumption by changes in the proportions of total revenue that they derive from the two sources, metered tolls and fixed charges.

In spite of the definite limitations imposed by the approach, this study has yielded useful findings not otherwise obtainable. The approach, furthermore, offers possibilities for added study and use. Additional data and certain methodological refinements should enhance its effectiveness, not only for studying demand for irrigation water, but demand for other purchased inputs as well.