IRRIGATION MANAGEMENT AND WATER POLICY: OPPORTUNITIES TO CONSERVE WATER IN ARIZONA

by

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INTRODUCTION

Arizona is commonly perceived to have a water problem. Irrigation water is becoming increasingly more expensive to pump (its cost is frequently more than 30 percent of total variable costs), and several economic sectors compete for limited ground and surface waters in important agricultural and urban areas of the state. Three of the most recent manifestations of the water problem are the report of the Arizona Groundwater Management Study Commission (1980), which is making recommendations to the State legislature for laws to conserve groundwater; the set of laws and policies designed to conserve water in the Yuma area of the Colorado River (Arizona Water Commission, Water Resources Research Center and Office of Arid Lands Studies, May 1977; and U.S. Department of Agriculture, March 1979); and the controversy between city, mining and agricultural interests in the Tucson Basin over limited groundwater (Griffin, 1980).

Since Arizona agriculture typically consumes about 90 percent of all water consumed, much of the focus on water conservation pertains to the agricultural sector. Current and proposed water conservation measures include (1) encouragement or subsidy of conservation practices and technologies such as irrigation scheduling and canal lining; (2) water rationing schemes such as those in existence for water delivered from the Colorado River, or those proposed by the Groundwater Management Study Commission; and (3) financial policies such as the imposition of pumping fees or changing the institutional price of surface water.

The research reported here assesses the impact of several of these water conservation policies on water conservation in irrigated agriculture in Arizona. The research focuses on four of Arizona's most important crops, cotton, wheat, sorghum and alfalfa. The empirical estimates of water conservation are based upon statistical crop-water production functions for the four crops, and an economic analysis of how profit maximizing farmers would alter water applications given the crop-water response relationships. Specific policies analyzed include (1) those to use profit maximizing instead of yield maximizing levels of water, (2) those to improve irrigation delivery efficiency, (3) those to raise the price of surface water, and (4) those to place quantity restrictions on the amount of water which farmers can apply.

METHODS AND DATA

METHODS

Production and related functions. Crop-water production functions are estimated by regression analysis from data generated at agricultural experiment stations. The production functions are then used in the economic analyses. Figure 1A shows a classical, hypothetical production function. The function indicates the yield associated with each level of water, other factors of production held constant. The change in yield associated with each succeeding unit of water, called the marginal physical product, is shown in Figure 1B. And the dollar value of the yield associated with each succeeding unit of water, called the value of the marginal product (VMP), is depicted in 1C.

Profit and Yield Maximization. To maximize profits per acre, water is applied until the value of the marginal product just equals the price of water (cost per unit, such as cost per acre inch), or amount OW in Figure 1C. If a lesser amount of water is applied, then the value of output from the last unit of water is greater than the cost of the last unit of water, and clearly that unit, and more, should be applied to increase profits. If more than OW is applied, the value of the output from the last unit of water is less than its price, and water applications should be cut. Thus, the rule for profit maximization is that water should be applied until the value of the marginal product equals the price of water.

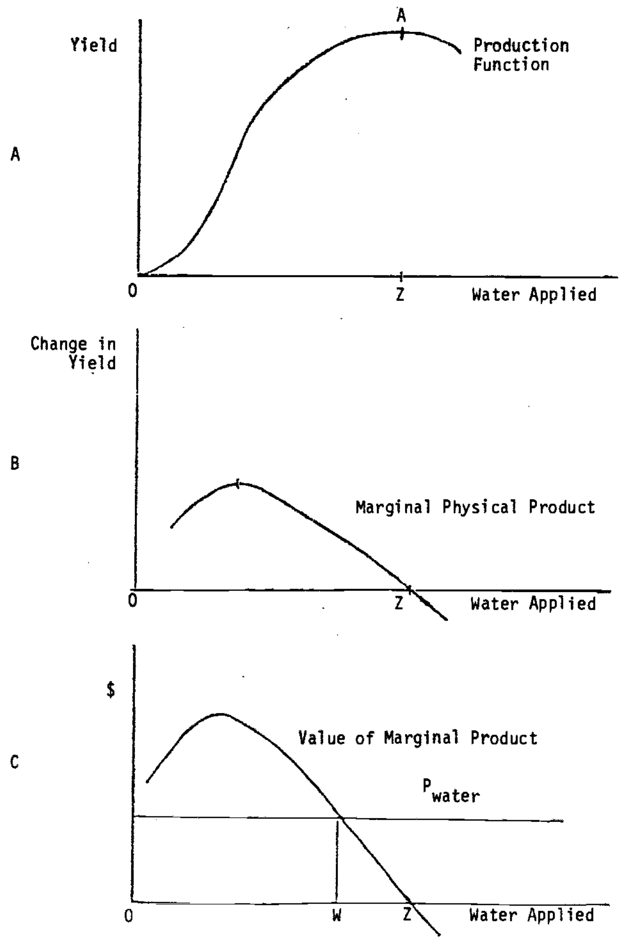

Figure 1. Production Function, Marginal Physical Product and Value of Marginal Product.

The rule for maximizing profits may be contrasted with the rule for maximizing yield. Yield is maximized at the apex of the production function, point A in Figure 1A, or correspondingly, where the marginal physical product and value of marginal product equal zero. As shown, yield is maximized when quantity OZ of water is applied. Only when the price of water is zero will the profit maximizing and yield maximizing level of water coincide. The amount by which the profit maximizing and yield maximizing level of water diverge depends on the shape of the underlying crop-water production function and upon the price of water: in Figure 1C, the difference is WZ.

The preceeding analysis has assumed that land is fixed, and that enough water is available to irrigate until the value of the marginal product of water (VMP) equals the price of water. In some situations, however, the total amount of water available to a region or to a farm is limited, and there may not be enough water to bring the VMP into equilibrium with the price of water on each acre. In these situations, profits for the farm or to the region can be maximized if the limited water is applied to each acre in an amount that equalizes the VMP on each acre.

Demand and Elasticity of demand. The concept of demand, as used here, contrasts with the concept of demand as commonly used by irrigation specialists and other physical scientists. Here, demand is used in an economic sense, and shows that the amount of water demanded will decrease as the price of water increases. Non-economic demand usually infers a fixed quantity of water--that required to maximize yield.

The demand for water is directly related to the underlying crop-water production function. In its simplest form, the demand function is the value of marginal product curve depicted in Figure 1C. The VMP is the demand curve because it indicates the amount of water that will be used, at each water price, in order to maximize profits. Of course, if the price of the product changes, then the VMP curve will also change and thereby effect the demand for water.

Elasticities of demand are derived directly from the demand function, and are useful, easy to understand, statistics. The elasticity of demand for water indicates the percentage change in the quantity of water demanded with a one percent change in the price of water. As an example, suppose that the elasticity of demand for irrigation water is found to be -.05. The elasticity indicates that for each one percent change in the price of water, there is only a .05 percent change in quantity of water demanded. When elasticity is less than one, demand is said to be inelastic. If demand is very inelastic, as assumed in the above example, water policy to conserve water through an increase in water price will be rather unsuccessful.

Elasticities may change as the price of the product changes and even as the price of water itself changes. The sensitivity of elasticities of demand for water to product and water price changes are examined.

DATA

Agronomic data. Data used to estimate production functions are from agricultural experiment stations in Arizona and New Mexico. All relevant agronomic data from current and past experiments in Arizona were collected and evaluated.

When possible, production functions are estimated for each of three soil textures; fine, medium and coarse. Fine texture soils are found at the Yuma Valley and Safford Experiment Stations, medium texture soils at the Mesa, Tempe and Phoenix stations, and coarse texture soils at the Yuma Mesa station.

In almost all agronomic experiments, water was applied by surface irrigation. Surface irrigation is used on over 90 percent of Arizona's irrigated acreage. Water measurements for the experiments are for gross water applied to the field or plot. Field efficiency (water remaining in the soil and useable by the plant as a percent of total water applied) was approximately 65 percent but varied by level of irrigation and other factors. Field efficiency is considered similar to that on farms with similar soil textures and reasonably good irrigation practices.

Prices. Economic analysis of the impact of water management, water pricing, and water restriction policies on water conservation and farm profits requires data on input and product prices. Expected product prices (late summer 1979) are taken from the Wall Street Journal and various government documents. These prices are respectively \$75 per ton of alfalfa, \$.65 per combined lint and seed per pound of cotton lint, \$.06 per pound of grain sorghum, and \$.07 per pound of wheat. In testing the sensitivity of various irrigation policies to product prices, historic high and low prices during the past decade are used, and are specified in the tables of results.

Typical water prices for three water source situations are estimated--prices for surface water and prices for water pumped from 300 and 600 feet. Surface water prices are typical of those paid by irrigators in the Salt River Project and in the Yuma areas. In the analysis, surface water prices are \$.50 per acre inch, and water from 300 and 600 foot lifts are \$2.50 and \$5.00 per acre inch respectively.

RESULTS AND ANALYSIS

THE PRODUCTION FUNCTIONS

Statistical production functions for cotton, wheat, sorghum and alfalfa are estimated with regression analysis. The functions are given and discussed in a separate manuscript (Ayer and Hoyt, 1980) and are graphed in Figure 2. Production functions and economic results are based on average nitrogen, pan evaporation, and other factors at the respective sites of the agronomic experiments, and therefore may not be directly applicable to specific, individual farms. Separate functions are shown for each of three soil textures--coarse, medium and fine--in accordance with soil textures at experiment locations. Functions graphed are considered the "best"--in terms of goodness of fit, expected signs, significance of coefficients, and in making both agronomic and economic sense--among the dozens of functional forms and variable definitions investigated and estimated. R^2's for the functions ranged

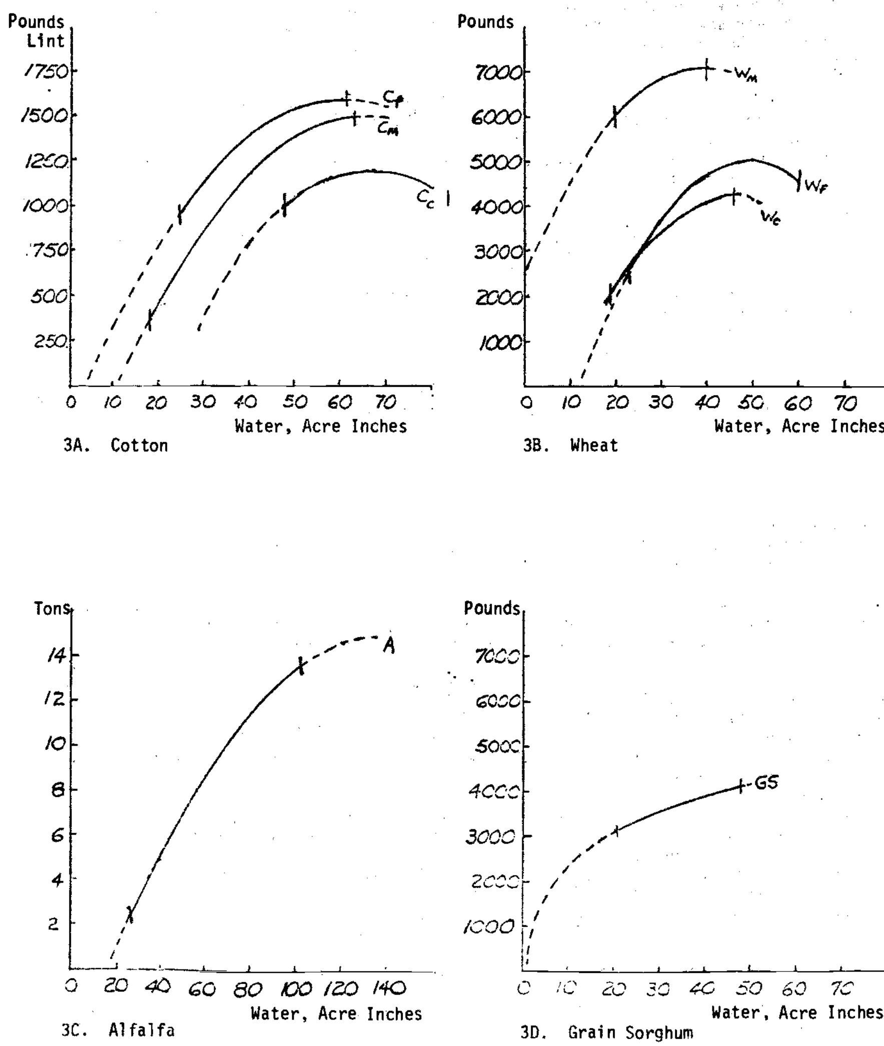

Figure 2. Crop-Water Production Functions for Cotton (C), Wheat (W), Alfalfa (A), and Grain Sorghum (GS) grown on Coarse (c), Medium (m), and Fine (f) Soils[a].

a. Based on crop-water production functions in Ayer and Hoyt (1980). Range of data depicted by the solid line. The locations of the functions for cotton and wheat are affected by both soil type and other factors which affect yield and are held at their mean levels at the respective sites.

from .66 to .95. The graphs illustrate the shape of the crop-water relationship, and in particular show that there are diminishing marginal returns to added irrigation water. The graphs also depict the range of data upon which the statistical production functions are based. Projections of yield beyond the range of the data must be made with caution, and often should not be made.

WATER CONSERVATION POLICIES

Application of profit vs. yield maximizing water levels. Water applications on cotton and wheat to maximize profits, to maximize yields, and common practice applications are shown in Table 1. At low ($.50 per acre inch) water prices, there is virtually no difference between profit and yield maximizing levels of water for either cotton or wheat, regardless of soil type. However, as water prices increase to $2.50 per acre inch, profit maximizing levels of water are typically four acre inches less than yield maximizing levels. And at high water prices ($5.00 per acre inch), water savings are eight or more acre inches. Since a sizeable portion of Arizona's agricultural land is irrigated with water pumped 300-600 feet (and therefore medium and high water prices are inferred), a large amount of water, relative to urban needs, can be conserved by using profit instead of yield maximizing practices. Conservative estimates, based on common practice and the production function analysis (see Appendix A), indicate over 144,000 acre feet of water could be saved by cutting water applications (often by about 6 acre-inches per acre) to an amount which maximizes profits. Such a savings is nearly as much as municipal-industrial use in Tucson--a city of nearly one half million people.

Several interrelated reasons explain why farmers may overirrigate, i.e., use more water than necessary to maximize profits. First, until very recently the farm price of water was extremely low and the difference between profit and yield maximizing levels of water was nil. Thus, previous economic conditions established the custom of applying water to maximize yield. Second, the practice of maximizing yield has been encouraged by both private and public irrigation management services. All of these extension type services have based their irrigation recommendations on yield maximizing criteria--apply enough water for evapotranspiration when the plant is not stressed. Yield maximizing criteria were appropriate when water was nearly free, but high water prices have rendered yield maximizing criteria inappropriate now. Third, very little research has been available to indicate what happens to yield as water is withheld and plants put under stress. Therefore, farmers have faced a risky situation in that the yield response to reduced water was unknown. This type of risk could be reduced by applying traditional, high levels of water. Fourth, and perhaps most importantly, economic analysis based upon our statistical production functions indicates that there is often little difference in profits between profit and yield maximizing levels of water. Thus, the economic incentive to cut applications is weak. For example, for medium priced water ($2.50 per acre inch) and for cotton grown on either fine or medium texture soil, profits are increased by only $5.00 per acre by switching from yield to profit maximizing levels of water.

Switching from yield to profit maximizing levels of water would not likely increase management, labor or other costs. In fact, some research (see Ayer and Hoyt) indicates that for cotton, wheat and sorghum the best way to reduce water by six acre inches is to simply eliminate the normal, last irrigation. Even if the reduction is spread over multiple irrigations, it is unlikely that management is crucial. The total reduction to maximize profits is usually a small (about 10 percent) portion of total water applied. And in either case, cutting out one (or more irrigations) or spreading the reduction over several irrigations, labor and pumping costs will be reduced.

There are two types of risk associated with the levels of water application. One type of risk has been mentioned--the risk associated with not knowing the yield decline associated with a smaller water application. This type of risk can be reduced through agronomic research which determines yield response to water stress, and by the subsequent communication of the research findings to farmers. Indeed, this report is to make known exactly this type of information. A second type of risk is that caused by the stochastic nature of weather, and the fact that weather and water applications interact in effecting yield. This type of risk is reduced (except possibly at very low water levels) as water is reduced. In summary, at least in arid areas which do not depend on rainfall (such as Arizona), the riskiness of reducing water levels appears minimal.

How, then, can the potential water savings be realized? Irrigation management services--including the Soil Conservation Service, the State Extension Service, the Bureau of Reclamation, and private management services--should base their recommendations on profit rather than yield maximizing criteria. Both agencies which offer irrigation advice and farmers should be appraised of the crop-water production function response, and the need to consider this response and the price of water (and other factors) in water management.

Improving irrigation delivery efficiency. Irrigation delivery efficiency, defined as the ratio of water reaching the head of the field to water at the wellhead, has a great effect on the costs and hence the profits of irrigated farming. Decreased irrigation delivery efficiencies have the effect of raising the price of water, since more water must be pumped for a given quantity to reach the field. Accordingly, delivery efficiency may effect the profit maximizing quantity of water pumped and actually applied. The effects on water pumped and applied, and on profits, are illustrated in Tables 2 and 3.

The amount of water pumped decreases considerably as delivery efficiency increases, as shown in the top portion of Table 2. Water conserved is substantial for nearly all crops and water prices.

Table 3 illustrates the effect of irrigation delivery efficiency on returns over total variable costs. The difference between returns over total variable costs at different efficiencies is the change in profits. Differences between numbers in a row indicate how profits are effected as delivery

Table 1. Profit Maximizing, Yield Maximizing and Common Practice Levels of Water for Cotton and Wheat Grown on Three Soil Textures and for Three Water Prices, Arizona (Acre-inches per acre).

Price of Water $/Ac.In.	Fine Soil Profit Max	Fine Soil Yield Max	Fine Soil Common Practice[a]	Medium Soil Profit Max	Medium Soil Yield Max	Medium Soil Common Practice[a]	Coarse Soil Profit Max	Coarse Soil Yield Max	Coarse Soil Common Practice[a]
				Cotton					
.50	59	60	48-60	64	66	42-60	64	66	72-84
2.50	56	60	48-60	61	66	42-60	62	66	72-84
5.00	52	60	48-60	58	66	42-60	58	66	72-84
				Wheat					
.50	48	49	39-50[a]	36	37	36-40[a]	47	49	72-84[a]
2.50	44	49	39-50	32	37	36-40	41	49	72-84
5.00	41	49	39-50	29	37	36-40	35	49	72-84

Source: Profit and yield maximizing levels of water are based on production functions in Ayer and Hoyt (1980).

a. Common practice levels vary for each soil type, by county and are particularly dependent upon climatic conditions in the county.

Table 2. Profit Maximizing Quantity of Irrigation Water,[a] Pumped and Applied; with Varying Irrigation Delivery Efficiencies, Fine Texture Soil. (Acre inches per acre)

Price of Water $/Ac.In.	Cotton .50	Cotton .75	Cotton .90	Wheat .50	Wheat .75	Wheat .90	Sorghum .50	Sorghum .75	Sorghum .90	Alfalfa .50	Alfalfa .75	Alfalfa .90
						Acre Inches Pumped						
.50	116	79	65	94	64	53	88	59	49	168	112	93
2.50	104	72	62	78	56	48	16[b]	20	22	168	112	93
5.00	90	57	57	60	48	42	6[b]	8[b]	8[b]	138	112	93
						Acre Inches Applied						
.50	58	59	59	47	48	48	44	44	44	84	84	84
2.50	52	54	56	39	42	43	8[b]	15[b]	20	84	84	84
5.00	45	50	51	30	36	38	3[b]	6[b]	7[b]	69	84	84

(Irrigation Delivery Efficiency: .50, .75, .90)

a. Based on production functions in Ayer and Hoyt (1980), expected 1979 product prices and expected pan evaporation for Safford, Arizona.

b. Insufficient water to produce a crop. Agronomists indicate water applications less than 12-18 inches, depending on weather conditions, are insufficient to produce a crop. Although the estimated water applications, based on the statistical production functions, are below the range of the experimental data, the outside information from agronomists suggests that applications more than a few inches below the experimental range is simply not sufficient for crop production.

Table 3. Returns over Total Variable Costs[a] with Varying Irrigation Delivery Efficiencies, Fine Texture Soil.[b] ($ per acre)

Price of Water $/Ac.In.	Cotton			Wheat			Sorghum			Alfalfa		
	Irrigation Delivery Efficiency											
	.50	.75	.90	.50	.75	.90	.50	.75	.90	.50	.75	.90
.50	619	640	646	151	167	172	66	81	86	646	674	684
2.50	392	485	517	-26	47	72	c	c	5	310	450	497
5.00	141	314	372	-224	-87	-42	c	c	c	-110	170	263

a. Variable costs include those for water, feed, fertilizer, pesticides, herbicides, labor and seed.

b. Based on production functions from Ayer and Hoyt (1980); expected 1979 product prices and expected pan evaporation for Safford, Arizona; Hathorn and Cluff.

c. Insufficient water to produce a crop. Agronomists indicate water applications less than 12-18 inches, depending on weather conditions, are insufficient to produce a crop. Although the estimated water applications, based on the statistical production functions, are below the range of the experimental data, outside information from agronomists suggests that applications more than a few inches below the experimental range is simply not sufficient for crop production.

efficiency changes. Columns illustrate the effect of water price on profits for any particular delivery efficiency. With low priced water, profits are not greatly affected by delivery efficiency. From a water conservation standpoint, then, there is almost no incentive for farmers who use very low priced water to improve delivery efficiencies. However, with higher priced water, profits drop dramatically as delivery efficiency declines. Under these conditions, investments in canal lining and other technology to improve delivery efficiency may be warranted. A long run, benefit-cost analysis similar to that of Wilson, Fox and Willett (1976), is required to assess the economic viability of particular investment.

Increasing the price of surface water. In general, the crop-water production functions imply a very inelastic demand for water. Table 4 shows the elasticity of demand for water on fine texture soil, for four crops, and for a wide range of crop and water prices. In all instances except for sorghum, the elasticity is far less than unity, and at low and medium water prices, the elasticity is from -.01 to -.30. Similar results were found for other soil textures.

Table 4. Elasticity of Demand[a] for Irrigation Water, by Crop, Fine Texture Soil.

Price of Water $/Ac.In.	Cotton		Wheat		Sorghum	Alfalfa	
	Price ($/lb.)		Price ($/lb.)		Price ($/lb.)	Price ($/ton)	
	.30	.65	.04	.07	All prices	50	75
.50	-.029	-.013	-.052	-.020	-1.45	-.037	-.027
2.50	-.160	-.069	-.304	-.108	-1.45	-.218	-.134
5.00	-.386	-.148	-.761	-.232	-1.45	-.592	-.328

a. Based on production functions from Ayer and Hoyt (1980) and expected pan evaporation for Safford, Arizona.

Since the elasticity of demand is so low, efforts to conserve water through marginal, or in many cases even large changes in the price of water, will not be successful. An extremely conservative example helps strengthen this implication. Assume wheat produced at a low price of $.04 per pound and surface water at $.50 per acre inch. The elasticity is -.052. Based upon the production function and assumed wheat and water prices, the profit maximizing level of water is 47 acre inches. If the price of water were to increase 20 percent from $.50 to $.60 per acre inch, and even if elasticity doubled to -.104 with the price increase, water use would decline from 47 to 46 acre inches per acre.

In a similar fashion, it might be illustrated that even with doubling the price of surface water (often priced near $.50 per acre inch), water use will not be significantly decreased on most crops. The initial price of water is simply too low and the underlying production functions shaped such that water use remains nearly unchanged as profits are maximized.

Water constriants. Constraints may be placed on the amount of surface or groundwater available to farmers. Along the Colorado River, constraints are already in effect. Proposals now before the State legislature would limit groundwater applications. Water constraints result, of course, in water conservation. Conservation is not costless, however. Where farmers are already using water in an economically efficient manner, farm profits will be cut as a result of water restrictions. For example, assume a 500 acre cotton farm in a fine texture soil area, using surface water at $.50 per acre inch and with 1979 cotton prices of $.65 for lint and seed per pound of lint. Fixed costs for the farm are assumed to be $124,000 as per Hathorn and Cluff. If the farm is operating efficiently, returns over total costs are $154,500 when no water restrictions are in effect. If water is cut to 80 percent of the no-restriction level, returns over total costs are $100,500. Thus, quantity restrictions can have significant impacts on farm profits. On the other hand, multi crop farms would experience a smaller impact because of the possibility of making product-product substitutions in the cropping plan.

SUMMARY

Crop-water production functions for four Arizona crops were estimated and used in economic analyses to estimate the impacts of various irrigation practices and policies on water conservation. Those practices most likely to succeed in the conservation of relatively large amounts of water (relative to urban needs) are (1) switching from yield to profit maximizing levels of water in medium to deep lift areas, (2) improving delivery efficiency if long run benefit cost studies show the fixed investment profitable and (3) quantity restrictions on water use. The first of these options, switching from yield to profit maximizing levels of water use, is particularly pertinent for two reasons. First, both profits will be increased and water conserved. Second, this option contrasts with common recommendations of public and private irrigation management services to maximize yield rather than profit. The third option, quantity restrictions, must be carefully weighed against its effect on farm profits--profits may be cut substantially.

Alternatives which do not appear promising are (1) switching from yield to profit maximizing levels of water in areas of low priced water, and (2) raising the price of surface water. Where water is low priced, profit and yield maximizing levels of water are nearly equal. Also, the price of surface water is currently so low and the elasticity of demand for water for most crops so low that even doubling the price of water has very little effect on water use. It would take a several fold price increase to achieve meaningful water savings.

APPENDIX A

COMPUTATION OF POSSIBLE WATER SAVINGS

Estimates of possible water savings are based upon a comparison of the profit maximizing level of water use, as implied by the statistical crop-water production functions, and the common practice applications of better farm managers as indicated by agricultural extension specialists. Estimates are based on the acres of cotton, wheat, and sorghum irrigated by groundwater in Arizona in 1978.

Several steps are used to estimate the profit maximizing level of water. First, estimates are made of the price of groundwater. Records on depth to groundwater by county and areas within counties (Arizona State Water Commission) are used to estimate energy costs of pumping. Based upon the pumping depths, a conservative price of pumping in all pump areas of the state is $2.50 per acre inch. This price, 1979 product prices, and expected pan evaporation by county are used in conjunction with our soil-specific crop-water production functions to estimate the per acre profit maximizing level of water for each soil type for each county. The per acre profit maximizing level of water, by crop, by county, is then multiplied by the acreage of each crop harvested in each county. The product is the total profit maximizing amount of water to produce the 1978 crop acreages in each county.

Estimates of the amount of water actually applied by the better managers in each county are then made. Estimates of the per acre amount of water actually applied by crop and by county are from agricultural extension specialists (Hathorn and Armstrong; Hathorn and Cluff; Hathorn and Farr; Hathorn, Little and Stedman; Hathorn and Sullivan). The per acre amounts are multiplied by the 1978 acreage of each crop in each county to estimate total water actually applied.

The difference between estimated profit maximizing levels of water and water actually applied, by crop and by county, are given in Table A-1.

Table A-1. Water Savings from Profit Maximization vs. Common Practice of the "Best" Farmers, Arizona, 1979.

County	Cotton	Wheat	Sorghum	Total
	Acre Feet			
Cochise	0	2,000	15,000	17,000
Graham	1,400	0	0	1,400
Maricopa	67,800	14,100	15,200	97,100
Pima	0	2,300	3,500	5,800
Pinal[a/]	0	13,200	10,000	23,200
[b/]	(20,900)	(6,600)	(10,00)	(37,500)
Total[a/]	69,200	31,600	43,700	144,500
[b/]	(90,100)	(25,000)	(43,700)	(158,800)

Sources: Based on production functions from Ayer and Hoyt: Hathorn and Armstrong; Hathorn and Cluff; Hathorn and Farr; Hathorn, Little and Stedman; Hathorn and Sullivan; Arizona State Water Commission; and U.S. Crop and Livestock Reporting Service.

a. Water savings based on the assumption that all soils in Pinal County are of medium texture.

b. Water savings based on the assumption that half the soils in Pinal County are fine and half are medium texture.

There are several reasons why the estimated water savings, which could result if profit maximizing levels of water were applied, are conservative. First, the price of pumped water is assumed to be $2.50 per acre inch. This price is somewhat less than depths to groundwater imply. Second, our estimates of the number of acres irrigated with groundwater in counties where both ground and surface water are applied (principally Maricopa and Pinal counties), are underestimated. Third, we do not attribute any savings to alfalfa because our crop-water production function for alfalfa is not satisfactory for such an estimate, even though savings would in fact likely result. And fourth, estimates of water actually applied are based upon current practices of the "best" farmers in each county, and it is likely that poorer farm managers overirrigate even more.

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