# The economics of crop response to irrigation quantity and scheduling: an Arizona case study

# THE ECONOMICS OF CROP RESPONSE TO IRRIGATION QUANTITY AND SCHEDULING: AN ARIZONA CASE STUDY

by

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## APPROVAL BY THESIS DIRECTOR

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TABLE OF CONTENTS

Page

LIST OF TABLES . . . . . . . . . . . . . . . . . . . . . . . . vi

LIST OF ILLUSTRATIONS . . . . . . . . . . . . . . . . . . . . . viii

ABSTRACT . . . . . . . . . . . . . . . . . . . . . . . . . . ix

1. INTRODUCTION . . . . . . . . . . . . . . . . . . . . . . . 1

Problem and Setting . . . . . . . . . . . . . . . . . . . . 1
Objectives of the Research . . . . . . . . . . . . . . . . 4
Organization . . . . . . . . . . . . . . . . . . . . . . . 7

2. LITERATURE REVIEW . . . . . . . . . . . . . . . . . . . . . 8

Physical Response to Total Water Applied. . . . . . . . . . 8
Physical Response to Water Scheduling . . . . . . . . . . . 10
General Models. . . . . . . . . . . . . . . . . . . . . . 10
Water Scheduling and Wheat Growth . . . . . . . . . . . . 12
Water Scheduling and Cotton Growth. . . . . . . . . . . . 13
Economic Models of Crop Response to Irrigation. . . . . . . 19

3. THEORY, METHODS, AND DATA . . . . . . . . . . . . . . . . . 22

Economic Theory . . . . . . . . . . . . . . . . . . . . . . 22
Statistical Technique . . . . . . . . . . . . . . . . . . . 28
Data. . . . . . . . . . . . . . . . . . . . . . . . . . . . 28
Crop-Water Data for Arizona Wheat and Cotton. . . . . . . 28
Prices. . . . . . . . . . . . . . . . . . . . . . . . . . 31
Scheduling. . . . . . . . . . . . . . . . . . . . . . . . . 33
Summary . . . . . . . . . . . . . . . . . . . . . . . . . . 34

4. EMPIRICAL ANALYSIS--CROP RESPONSE MODELS. . . . . . . . . . 35

Evapotranspiration Models Applied to Wheat. . . . . . . . . 35
Stewart . . . . . . . . . . . . . . . . . . . . . . . . . 35
Minhas. . . . . . . . . . . . . . . . . . . . . . . . . . 37
Blank . . . . . . . . . . . . . . . . . . . . . . . . . . 38
Other Models Applied to Wheat . . . . . . . . . . . . . . . 39
Square-root Model . . . . . . . . . . . . . . . . . . . . 39
Cobb Douglas Model. . . . . . . . . . . . . . . . . . . . 40
Quadratic Models . . . . . . . . . . . . . . . . . . . . . 41
The Best Crop-Water Production Functions For Wheat. . . . . 45
Fine-textured Soils . . . . . . . . . . . . . . . . . . . 46

TABLE OF CONTENTS--Continued

Page

Medium-textured Soils. . . . . . . . . . . . . . . . . . . . 47
Coarse-textured Soils. . . . . . . . . . . . . . . . . . . . 48
Evapotranspiration Models Applied to Cotton. . . . . . . . . 49
Other Models Applied to Cotton . . . . . . . . . . . . . . . 49
Cobb Douglas Model . . . . . . . . . . . . . . . . . . . . 49
Quadratic Models . . . . . . . . . . . . . . . . . . . . . 49
The Best Crop-Water Production Functions for Cotton. . . . . 50
Fine-textured Soils. . . . . . . . . . . . . . . . . . . . 50
Medium-textured Soils. . . . . . . . . . . . . . . . . . . 51
Coarse-textured Soils. . . . . . . . . . . . . . . . . . . 51

5. EMPIRICAL RESULTS--ECONOMIC ANALYSIS . . . . . . . . . . . . . . 53

Wheat. . . . . . . . . . . . . . . . . . . . . . . . . . . . 54
Profit Maximizing Quantity and Number of Irrigations. . . . . . . . . . . . . . . . . . . . . . 54
Comparison of Soil Texture Models with Other Models. . . 58
Demand and Elasticity of Demand for Water. . . . . . . . 62
Water Quantity Restrictions. . . . . . . . . . . . . . . 66
Cotton . . . . . . . . . . . . . . . . . . . . . . . . . . . 66
Profit Maximizing Quantity and Number of Irrigation-Cotton. . . . . . . . . . . . . . . . . . . 66
Comparison of Soil Texture Models with Other Models. . . 71
Demand and Elasticity of Demand for Water. . . . . . . . 73
Water Quantity Restrictions. . . . . . . . . . . . . . . 74

6. IMPLICATIONS. . . . . . . . . . . . . . . . . . . . . . . . . . 78

Farm Management. . . . . . . . . . . . . . . . . . . . . . . 78
Water Conservation Policy. . . . . . . . . . . . . . . . . . 79
Research . . . . . . . . . . . . . . . . . . . . . . . . . . 80

REFERENCES . . . . . . . . . . . . . . . . . . . . . . . . . . 82

## LIST OF TABLES


| Table | | Page |
|---|---|---|
| 1. | Estimated Withdrawals of Fresh Water for 1975 and 1985 for Domestic and Commercial, Manufacturing, Irrigation, and Minerals in Five Western Regions. . . . . . . | 2 |
| 2. | Crop Value and Consumptive Water Use of Principal Irigated Crops in Selected Western States . . . . . . . . . . | 5 |
| 3. | Water Requirement, Harvested Acreage, Total Revenue, and Percentage of Total Revenue of Principal Crops in Arizona in 1972, 1976, and 1977 . . . . . . . . . . . . . . . | 6 |
| 4. | Selected Soil and Climatic Data for Five Experimental Sites in Arizona. . . . . . . . . . . . . . . . . . . . . . | 30 |
| 5. | Profit-maximizing Quantity of Water and Number of Irrigations at Different Wheat and Water Prices for Wheat Raised on Fine-textured soil. . . . . . . . . . . . . . | 55 |
| 6. | Profit-maximizing Quantity of Water and Number of Irrigations at Different Wheat and Water Prices for Wheat Raised on Medium-textured Soil. . . . . . . . . . . . . | 56 |
| 7 | Profit-maximizing Quantity of Water and Number of Irrigations at Different Wheat and Water Prices for Wheat Raised on Coarse-textured Soil. . . . . . . . . . . . . | 57 |
| 8 | Water Applications Implied by the Six Wheat "Models" for Soils of Different Texture, Medium Wheat Price . . . . . | 59 |
| 9. | Arc and Point Elasticity of Demand for Water in the Production of Wheat . . . . . . . . . . . . . . . . . . . . . | 65 |
| 10. | Water Restrictions and Change in Returns over Total Costs for Wheat, Water Cut to 90 and 80 Percent of Profit Maximum Level, Medium Price of Wheat . . . . . . . . . | 67 |
| 11. | Profit-maximizing Quantity of Water and Number of Irrigations at Different Cotton and Water Prices for Cotton Raised on Medium-textured Soil . . . . . . . . . . . . | 68 |

LIST OF TABLES--Continued

Table Page

12. Profit-maximizing Quantity of Water and Number of Irrigations at Different Cotton and Water Prices for Cotton Raised on Medium-textured Soil. . . . . . . . . . . . 69

13. Profit-maximizing Quantity of Water and Number of Irrigations at Different Cotton and Water Prices for Cotton Raised on Coarse-textured Soil. . . . . . . . . . . . 70

14. Water Applications Implied by Six Cotton "Models" for Soils of Different Texture, Medium Cotton Prices . . . . . 72

15. Arc and Point Elasticities of Demand for Water in the Production of Cotton, by Water Source, Water Price, Output Price, and Soil Textures . . . . . . . . . . . . . 76

16. Water Restrictions and Change in Returns over Total Variable Costs for Cotton, Water Cut to 90 and 80 Percent of Profit Maximum Level, Medium Price of Cotton . . . . . . . . . . . . . . . . . . . . . . . . . . . 77

## LIST OF ILLUSTRATIONS


| Figure | | Page |
|---|---|---|
| 1. | Five Western Water Resource Regions. . . . . . . . . . . . . . | 3 |
| 2. | Daily and Semi-monthly Consumptive Water Use, Four High-yielding Wheats, Mesa, Arizona. . . . . . . . . . . . . | 14 |
| 3. | Cumulative Consumptive Water Use, Four High-yielding Wheats, Mesa, Arizona. . . . . . . . . . . . . . . . | 15 |
| 4. | Daily and Seasonal Consumptive Use, Cotton, Mesa and Tempe, Arizona, 1954-1962 . . . . . . . . . . . . . . | 17 |
| 5. | Cumulative Consumptive Use, Cotton, Mesa and Tempe, Arizona, 1954-1962. . . . . . . . . . . . . . . . . . . | 18 |
| 6. | Hypothetical Production and Marginal Physical Product Functions. . . . . . . . . . . . . . . . . . . . . . . . | 23 |
| 7. | Marginal Value and Average Value Products. . . . . . . . . . . | 24 |
| 8. | Short-run Normative Demand Curves for Water in the Production of Wheat by Soil Type, 600-foot Lift; Price of Output, $.0525/lb . . . . . . . . . . . . . . . . | 63 |
| 9. | Short Run Normative Demand Curves for Water in the Production of Cotton by Soil Type, 600-foot Lift, Price of Output, $.62/lb of Lint. . . . . . . . . . . . . . . | 75 |

# ABSTRACT

This research provides crop-water response functions and associated economic analysis for cotton and wheat on fine-, medium-, and coarse-textured soils in Arizona. Crop-water response data is analyzed using regression analysis. The economic analysis estimates the impact of changing surface water prices, water lift depths, energy prices, and product prices on profit maximizing levels of water use, profits, and the demand of irrigation water. The profit maximizing quantities of water predicted from this research are compared to common practice, yield maximizing models, and other models.

Highlights of the empirical results for wheat production include: (1) the estimated crop-water production functions explain a large part of the variation in yield; (2) the soil texture models generally call for 6 inches or less water than yield maximizing models; and (3) the demand for water is very inelastic except at the 600-foot pump level.

Highlights of the empirical results for cotton production include: (1) estimated crop-water production functions exhibit high $R^2$s; (2) water applications suggested by the profit maximizing models correspond closely with all other models and (3) the demand for water in the production of cotton is very inelastic.

Implications on farm management, government water policy, and research are given.

## CHAPTER 1

## INTRODUCTION

### Problem and Setting

There is little useful empirical knowledge of crop response to water quantity and scheduling in the arid Southwest or Arizona, although a number of current circumstances suggest that knowledge of these relationships is important. First, the quantity of water used in irrigated agriculture is far greater than water used in any other sector. As shown in Table 1, water used for irrigation has typically been, and is projected to be in 1985, nearly 90 percent of total water use in all Southwestern states (Figure 1).

Second, although surface water is still very inexpensive compared to ground water, there are increasing pressures from urban users, Native Americans, Mexico, and California to divert water from commercial agriculture in Arizona.

Third, the rising price of energy has increased the cost of pumping ground water. For example, in Pinal County, Arizona, the price of electricity is estimated to increase from 7 mils per kilowatt hour in 1963 to 40 mils per kilowatt hour in 1980. The variable cost of pumping ground water in Pinal County for cotton and wheat is approximately 18 to 25 percent of the total variable cost of their production.

Table 1. Estimated Withdrawals of Fresh Water for 1975 and 1985 for Domestic and Commercial, Manufacturing, Irrigation, and Minerals in Five Western Regions.

| | Withdrawal, 1975 | | Withdrawal, 1985 | |
|---|---|---|---|---|
| | Acre-feet per Day | Percent of Total | Acre-feet per Day | Percent of Total |
| California | | | | |
| Domestic and Commercial | 3,388 | 8.7 | 3,809 | 9.6 |
| Manufacturing | 796 | 2 | 830 | 2.0 |
| Irrigation | 34,611 | 88.5 | 34,863 | 87.5 |
| Minerals | 297 | .7 | 359 | .9 |
| Lower Colorado (Arizona) | | | | |
| Domestic and Commercial | 498 | 5.7 | 612 | 7.4 |
| Manufacturing | 89 | 1 | 92 | 1.1 |
| Irrigation | 7,989 | 91.2 | 7,299 | 88.4 |
| Minerals | 184 | 2.1 | 252 | 3.1 |
| Rio Grande (New Mexico) | | | | |
| Domestic and Commercial | 327 | 5.2 | 352 | 5.8 |
| Manufacturing | 19 | .3 | 42 | .7 |
| Irrigation | 5,684 | 89.1 | 5,498 | 89.8 |
| Minerals | 190 | .3 | 221 | 3.6 |
| Upper Colorado (Colorado) | | | | |
| Domestic and Commercial | 80 | 1.2 | 86 | 1.1 |
| Manufacturing | 4 | 0.0 | 2 | 0.0 |
| Irrigation | 6,400 | 96.7 | 7,223 | 96.2 |
| Minerals | .32 | 2 | 195 | 2.6 |
| Texas-Gulf (Texas) | | | | |
| Domestic and Commercial | 1,490 | 9.3 | 1,697 | 11.5 |
| Manufacturing | 1,932 | 12.1 | 2,559 | 17.4 |
| Irrigation | 11,538 | 72.1 | 9,333 | 63.4 |
| Minerals | 1,044 | 6.5 | 1,133 | 7.3 |

Source: United States Water Resources Council, 1978.


Figure 1. Five Western Water Resource Regions.

Source: U. S. Resources Council, 1978.

Many alternative irrigation practices may be employed to decrease the cost of irrigation and conserve water. But the profitability of these practices, and hence the likelihood that they will be adopted by farmers, depends directly upon the underlying crop-water response function. The yield response to water quantity and scheduling will affect farm profits, crop production, and water use. These impacts are of importance to both individual farmers and to those who formulate water and energy policy.

In spite of the importance of the underlying crop-water production relationships, little empirical knowledge of them exists. This is true for the response of cotton and wheat to water quantity and scheduling in Arizona, the crops upon which this research focuses.

The importance of cotton and wheat in Arizona agriculture (and in the agriculture of the arid Southwest) may be seen in Tables 2 and 3. In terms of total crop value and total quantity of water used, cotton and wheat are very important and have been so over time.

## Objectives of the Research

The specific objectives of this research are:

1. To determine the physical response of cotton and wheat produced on specific soil textures in Arizona to various irrigation quantity and scheduling practices.
2. To estimate the profit maximizing quantity and scheduling of water and determine the sensitivity of the solution to alternative water and electricity prices, lift depths, and soil textures.

Table 2. Crop Value and Consumptive Water Use of Principal Irrigated Crops in Selected Western States

| State | Cotton | | Vegetables | | Hay | | Wheat | | Sorghum | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Value[a] | C.U.[b] | Value | C.U. | Value | C.U. | Value | C.U. | Value | C.U. |
| Arizona | 318 | 1.9 | 104 | .1 | 94 | 1.6 | 26 | .3 | 15 | .2 |
| California | 733 | 3.6 | 1,515 | 2.2 | 456 | 7.0 | 119 | .6 | 23 | .3 |
| Colorado | | | 29 | .0 | 157 | 2.5 | 120 | .1 | 14 | .1 |
| Texas | 1,302 | 6.0 | 245 | .31 | 231 | 5.5 | 264 | 3.5 | 438 | 2.8 |
| Total | 2,353 | 11.5 | 1,893 | 2.6 | 938 | 16.5 | 529 | 4.5 | 490 | 3.4 |

a. Value in millions of dollars. b. Consumptive Water use in millions of acre-feet.

Source: United States Department of Agriculture (1978).

Table 3. Water Requirement, Harvested Acreage, Total Revenue, and Percentage of Total Revenue of Principal Crops in Arizona in 1972, 1976, and 1977

| Crop | Year | Water Requirement (acre-feet)[a] | Harvested Acreage | Total Revenue (in $1000) | Percentage of Total Revenue (All Crops) |
|---|---|---|---|---|---|
| Cotton[b] | 1977 | 3,184,416 | 556,500 | 355,321 | 54 |
| | 1976 | 1,945,555 | 340,000 | 318,067 | 44 |
| | 1972 | 1,780,755 | 311,200 | 111,574 | 35 |
| Vegetables[c] | 1977 | 176,755 | 65,600 | 124,421 | 19 |
| | 1976 | 171,366 | 63,600 | 118,781 | 16 |
| | 1972 | 215,555 | 80,000 | 84,467 | 27 |
| Hay (Alfalfa) | 1977 | 2,167,083 | 210,000 | 94,965 | 14 |
| | 1976 | 2,167,083 | 210,000 | 105,764 | 14 |
| | 1972 | 2,218,680 | 215,000 | 48,020 | 15 |
| Citrus | 1977 | 374,618 | 56,310 | 35,841 | 5 |
| | 1976 | 389,254 | 58,510 | 30,986 | 4 |
| | 1972 | 418,480 | 62,903 | 31,160 | 9 |
| Wheat | 1977 | 495,833 | 140,000 | 26,514 | 4 |
| | 1976 | 1,526,458 | 431,000 | 126,497 | 18 |
| | 1972 | 602,083 | 170,000 | 18,680 | 6 |
| Grain Sorghum | 1977 | 275,000 | 90,000 | 16,344 | 2 |
| | 1976 | 278,055 | 91,000 | 15,943 | 2 |
| | 1972 | 326,944 | 107,000 | 18,246 | 6 |

Source: Arizona Crop and Livestock Reporting Service, 1978.

a. A crop's water requirement is based upon its estimated consumptive use per acre and an irrigation delivery efficiency of 60 percent.

b. Total revenue from cotton includes the value of both cotton fiber and seed, and assumes 1.65 pounds of seed for each pound of fiber.

c. The water requirement for vegetables is based upon the average consumptive use of 19.4 inches per acre for eight vegetables and an irrigation delivery efficiency of 60 percent.

3. To estimate the elasticity of demand for water on a per acre basis in the production of wheat and cotton on specific soil textures.
4. To evaluate alternative water quantity and scheduling recommendations and practices of public agencies and individual producers relative to the results obtained in Objective 2.
5. To estimate the change in returns over total variable costs for wheat and cotton production should water use be cut to 90 and 80 percent of the profit maximizing level.
6. To draw policy implications for farm management, water conservation policy, and research.

## Organization

The thesis is divided into six chapters. Chapter 2 reviews the literature related to key physical and economic models of crop response to irrigation. Chapter 3 discusses economic theory, statistical methods, and data. Empirical results derived from the crop response models are presented in Chapter 4. Chapter 5 gives the empirical results of the economic models, the elasticity of demand for water in the production of wheat and cotton, and compares the empirical results to current recommendations and practices. Policy implications are provided in Chapter 6.

# CHAPTER 2

# LITERATURE REVIEW

The literature cited described (1) the physical response of crops to total water applied, (2) the physical response of crops to water scheduling, and (3) economic models of crop response to irrigation.

## Physical Response to Total Water Applied

Slayter (1967) discussed the importance of water to plant growth processes. Water contributes to the structural composition of biological molecules which constitute plant cells and tissues. Translocation of foodstuffs and minerals throughout the plant organism is conducted in a water-based medium. Water combined with carbon dioxide forms the initial substances for photosynthesis. Glucose, the product of plant respiration, is composed of water, starch, and related compounds.

Evapotranspiration is the process of water transfer into the atmosphere from soil-water evaporation and plant transpiration (Arkin, 1978). Brix's (1962) research indicated that transpiration and photosynthesis are closely related. Photosynthesis is the plant process that converts the sun's energy to carbohydrates for plant dry weight gain. Evaporation around a plant, stimulated by low humidity, high temperatures, and high winds, increase water loss through transpiration. Evapotranspiration in excess of root absorption causes a negative moisture balance. If water is not replenished through rainfall or irrigation, plants lose turgidity, wilt, and die.

Research to estimate evapotranspiration from climatic and meteorological data has been done by Blaney-Morin (1942), Thornwaite and Holzman (1942), Jensen and Haise (1963), Beringer (1961), Fleming (1964), Moore (1961), and Stewart, Hagan, and Pruitt (1974, 1977). Plant growth is a function of the parameters associated with plant moisture stress. The rate of moisture intake by the plant roots from the soil, and the rate of moisture loss from the plant leaves to the atmosphere are the most relevant parameters. Beringer (1961) developed the Integrated Moisture Index which aggregated the moisture deficiency over the growing season. Plant growth and yield may be estimated by determining the relationship between the potential evapotranspiration and actual evapotranspiration according to Stewart et al. (1977). Moore (1961) felt plant growth and yield could be reduced before the available soil moisture fell below the permanent wilting point.

Hexem and Heady (1978) derived crop-water production functions for cotton, sugar beets, wheat, corn, and corn silage in several Western States. The research sought to measure the productivity of water in terms of crop yields for different soils and climatic conditions. Irrigation treatments were based upon a predetermined available soil moisture depletion level. Timing or scheduling of irrigations and methods of application were not considered in their analysis. Graphic analysis of the estimated functions shows a declining total physical product to high water applications (a third stage of production), but graphs are projected beyond the range of the data. Climatic variables are not induced in their site models. And, finally, little economic analysis or comparison of experimental results with field situations is given.

## Physical Response to Water Scheduling

Crop response to water scheduling is discussed in terms of (1) general models, (2) water scheduling and wheat growth, and (3) water scheduling and cotton growth.

### General Models

Numerous research efforts have emphasized the importance of water applications in particular stages of plant growth. Focusing solely on the total quantity applied throughout the season can be misleading. Moore (1961) indicates that irrigation decisions should be primarily based upon plant needs in specific growth stages.

Black and Hay (1978) described the general relationship between water and plant growth at specific growth stages. Moisture stress during the plant's reproductive stage prevents or reduces pollination and retards kernel formation. Water stress prior to the reproductive stage decreases plant size. Late stress reduces filling out of the seed.

Dudley, Howell, and Musgrave (1971) determined the optimal timing of irrigations over a season in an uncertain environment. A plant growth-soil moisture simulation model is incorporated into a two-state variable stochastic dynamic programming model to determine an intraseasonal allocation pattern for irrigation water in a variable environment.

Anderson, Yaron, and Young (1977) developed mathematical models to predict yield response to soil moisture stress at different growth stages. The models depict outcomes when limited water is applied throughout the growing season.

Yaron and Strateener (1973) detailed the reduction in crop yield resulting from water stress at particular growth stages based upon critical days. A "critical day" occurs when the available soil moisture falls below a predetermined level. A critical day during the tassle stage will reduce corn yield an estimated 2 to 2.5 percent. Critical days before or after tassling will reduce yield by only .75 to 1.0 percent.

Hanks (cited in Stewart et al., 1977) examined variations in plant growth and yield resulting from water deficiencies in specific growth stages of corn in four Western states. Hanks estimated plant water loss in each growth stage on transpiration data.

Stewart et al. (1977), in the identical four-state project, focused upon the importance of conditioning. They determined that plants stressed in an early growth stage would be less sensitive to stress at later growth stages.

Jensen (1969), with data from southern Idaho from 1966-1970, developed irrigation scheduling models designed to prevent plant growth stress. Daily evapotranspiration was derived from climatic data to estimate the rate of soil-water depletion. Jensen's model sought to predict the optimum time for the next irrigation. Kincaid and Heerman (1974) modified the model to fit small desk calculators. Heerman, Haise, and Nickelson (1976) adapted the model to fit center pivot irrigation systems. The Salt River Project in Arizona used Jensen's irrigation scheduling program for three years.

The United States Bureau of Reclamation, collaborating with the Idaho State Extension Service, provided Idaho farmers with the Irrigation Management Service. Weekly estimates of evapotranspiration for numerous crops were provided (Buchheim and Ploss, 1977). Agricultural producers were able to estimate the available soil moisture in their fields with this service. The objective was to improve their irrigation allocations.

## Water Scheduling and Wheat Growth

Dennis et al. (1978) discussed irrigation application categories for wheat production in Arizona during preplant, first irrigation, and midseason irrigations.

A preplant or emergence irrigation in November is necessary to wet the soil profile to a depth of 5 to 6 feet. One application of 12 inches of water per acre will satisfy the preplant irrigation requirements in dry or heavy soils. Sandy soils receive 12 inches of water divided into two applications.

The first irrigation should be applied by early March. Cool temperatures and minimal plant growth in the early season generate minimal evapotranspiration and water loss. An average rainfall in Arizona of 3 inches in this period supplements the preplant irrigation. Variances in rainfall, temperature, and planting dates affect the timing of the first irrigation. A 6-inch application for the first irrigation refills most soil profiles.

The second through the final irrigations are spaced closer together to accommodate increased crop needs stimulated by additional plant foliage and higher temperatures. The quantity and timing of the water application depends upon the available water holding capacity of the soil, the depth of the plant root system, and the adequacy of the irrigation system. Moisture stress should be avoided to ensure normal seed development through the dough stage.

Erie, Bucks, and French (1973) and Halderman (1975) provided graphs of daily, semi-monthly, and cumulative water consumption of high-yielding wheat varieties in Arizona (Figures 2 and 3). Their graphs are based upon experiments in which enough water was applied to prevent plant stress and thereby maximize yield. Midseason irrigations can be planned by accounting for the date of the first and last irrigation and knowledge of the crop's consumptive use. For example, if the first irrigation occurs on March 1, and the final irrigation on April 25, 54 days transpired. Subtracting a preplant irrigation of 6 inches from 22 Erie et al.'s (1973) consumptive use figure between March 1 and April 25 equals 16 inches. Figure 3 shows that four applications will provide adequate water to maximize crop yield.

Dennis et al. (1976) indicated which irrigations should be foregone if water is restricted. The ordering of foregone irrigations is (1) the last, (2) the second, and (3) the second to last.

## Water Scheduling and Cotton Growth

Grimes and Dickens (1977) discussed water applied to cotton in terms of the preplant irrigation, the first irrigation, the scheduled

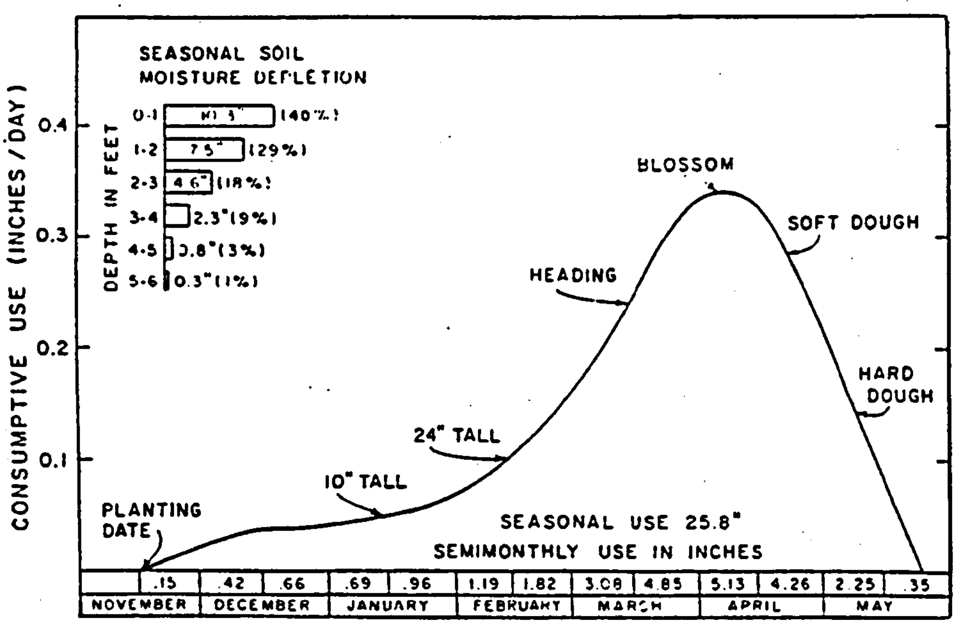


Figure 2. Daily and Semi-monthly Consumptive Water Use,
Four High-yielding Wheats, Mesa, Arizona.

Source: Erie et al., 1973.

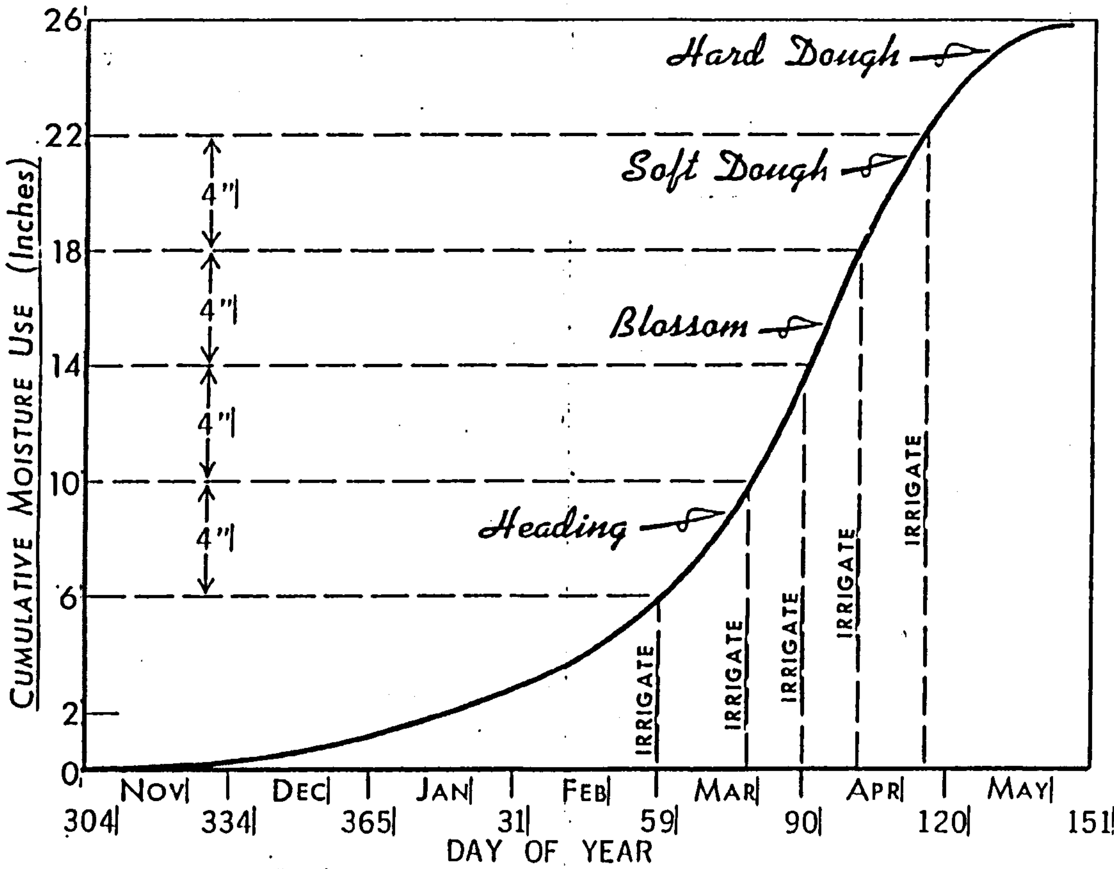


Figure 3. Cumulative Consumptive Water Use, Four High-yielding Wheats, Mesa, Arizona

Source: Halderman, 1975.

irrigations, and the final irrigation. Preplant irrigations are essential to ensure proper germination. The soil profile is saturated to field capacity. Residual soil salts are leached below the plant's root zone by the preplant irrigation. Erie, French, and Harris (1965) estimated the consumptive use of water for cotton prior to the first irrigation in mid-June to be 4.4 inches. Water demands early in the season are low because of cool temperatures and minimal plant foliage.

Farmers can be flexible in selecting the date of the first irrigation. Light, sandy soil may require an irrigation the last week in May. Heavy, clay soils may not require an irrigation until mid-June. By delaying the first irrigation, causing stress, the irrigator can "condition" the plant to withstand future water shortages. Insect damage is reduced when plants undergo water stress. Other researchers disagree with "conditioning" a plant and recommend providing sufficient water throughout the season (Grimes and Dickens, 1977).

The second through the final irrigations often involve following a set schedule designed to prevent water stress and maximize crop yield. Set schedules assist the planning efforts of farm irrigators and regional allocators of water.

Erie et al. (1965) and Halderman (1973) gave daily, semimonthly, and cumulative water use for cotton (Figures 4 and 5), again under no stress conditions. Figure 4 shows that from mid-June until the final irrigation on Agusut 31, the consumptive use is 25.09 inches (Erie et al., 1965). As the season progresses, additional plant growth combined with rising temperatures cause increased evapotranspiration and water loss.

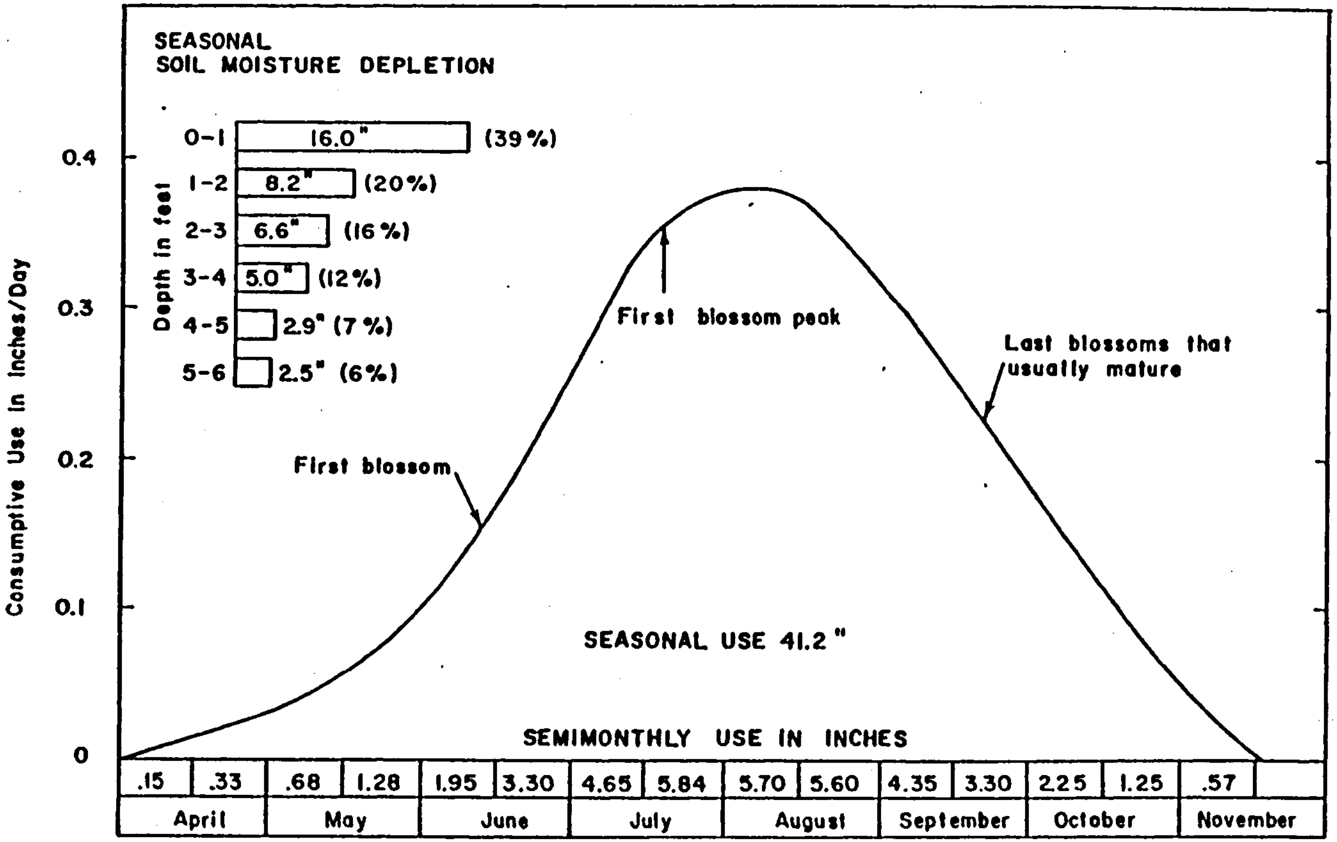


Figure 4. Daily and Seasonal Consumptive Use, Cotton, Mesa and Tempe, Arizona, 1954-1962.

Source: Erie et al., 1965.

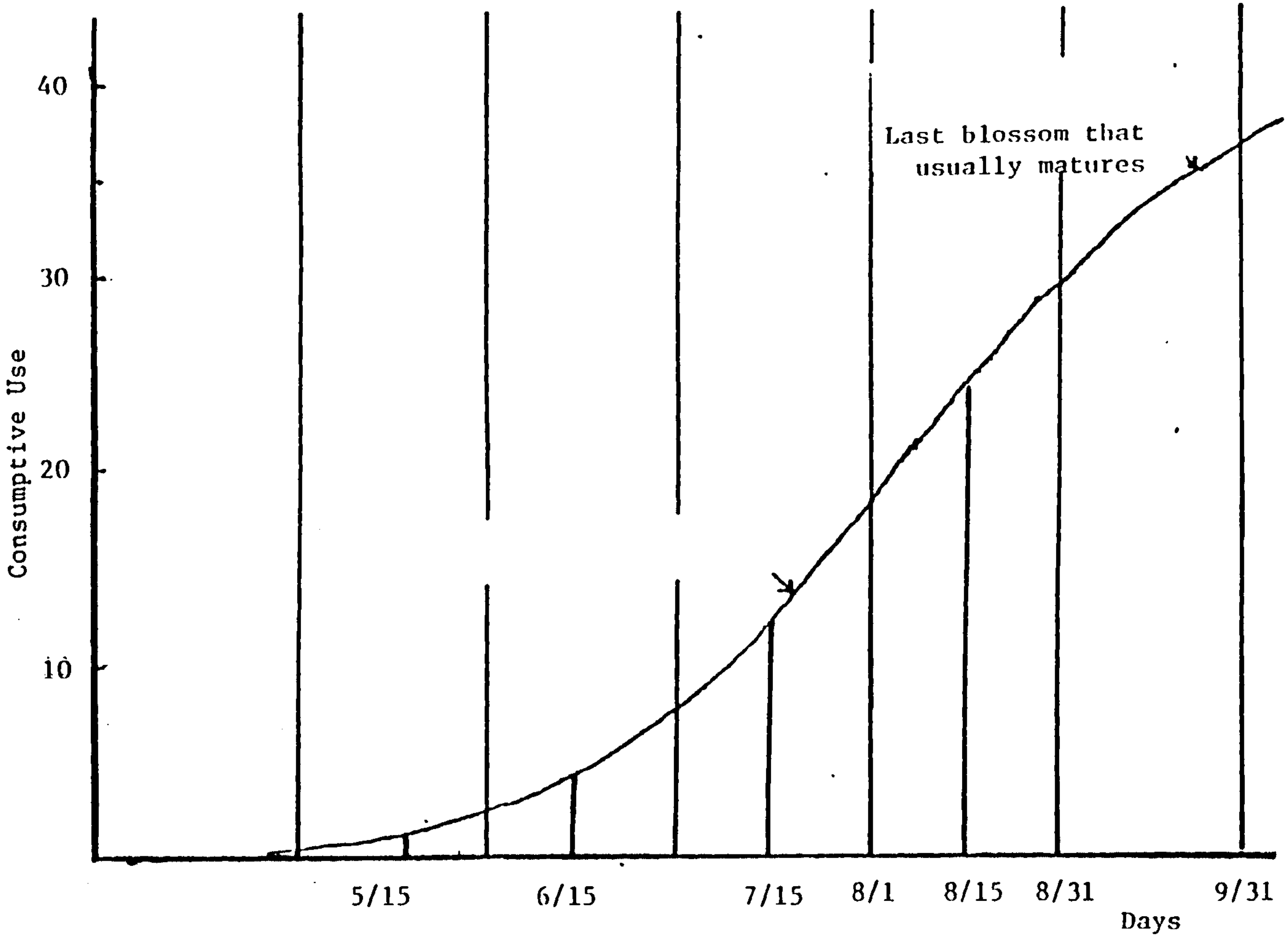


Figure 5. Cumulative Consumptive Use, Cotton, Mesa and Tempe, Arizona, 1954-1962.

Source: Halderman, 1973.

The date of the final irrigation affects the cotton harvest. In Arizona, if the last irrigation is made on August 15, the harvest date will fall within the first week of October. Delaying the last irrigation to September 1 will push the appropriate harvest date back to the first week in November. Cooler temperatures late in the growing season reduce plant growth and lessen the demand for water. Figure 4 depicts the consumptive use from September 1 until harvest to be 11.72 inches.

Early termination of the final irrigation is considered the best way to allocate water when the total water available is limited. Kittock at the Cotton Research Laboratory in Phoenix, Arizona, has attempted to quantify the effect on yield of early irrigation termination.

## Economic Models of Crop Response to Irrigation

An extensive review of economic models of crop response to irrigation was conducted by Ayer (1978). His review of basic production function models and models that account for the timing of water applications are summarized here.

Since 1972, basic production function work has been conducted by Delaney (1978); Dyke (1977); Hexem and Heady (1978); Holloway and Stevens (1973); Hogg and Vieth (1977); Wu and Liang (1972), and Yaron (n.d.). Crop yield is postulated to be a function of water quantity, quality, and non-water inputs. The underlying production function is estimated by regression analysis with the units of observation being experimental plots, farm fields, or counties. The yield response may be described by estimating the total response curve, or by taking the average yield at particular application levels. The marginal value product (MVP) is equated to water price, utilizing the regression production function. The optimum quantity of water to apply is estimated.

Basic production functions are most useful in regional analysis. Aggregated crop water production functions may be used to determine the impacts of water pricing policy on yields and input use. The marginal value product of output for the region can be calculated and compared to the price of providing additional irrigation water. The absence of irrigation scheduling, multicrop situations, and risk, weaken the reliability of basic production functions for farm level decisions.

Dudley et al. (1971), Flinn and Musgrave (1976), Hall and Butcher (1968), Minhas, Parikh, and Srinivasan (1961), Moore (1961), Moore, Snyder, and Sun (1974), and Stewart et al. (1974, 1977) estimated economic models based upon dated crop-water production functions. Dated production functions account for a plant's water demand in different growth stages. Identical quantities of total water applied will result in different yields, if the timing of application varies among vegetative, pollination, and maturation stages. Stewart et al. (1977) included "conditioning" effects in their recent work.

Derivation of dated production functions is more complex than for basic production functions. Water applied or evapotranspiration (ET) per growth period represent the independent variable. Other variables are held constant. Production functions are estimated by regression analysis from experimental data. Economic optimums are computed by setting the marginal value product (MVP) of water per growth period equal to the marginal factor cost of supplying water during that period. To handle the intertemporal nature of scheduling water, dynamic programming has been employed. Water quantity restrictions and prices per period are key consideration.

Dated production functions possess inherent weaknesses. Most models fail to acknowledge the interdependence of growth stages and the riskiness of crop production. Omission of climatic, soil, and other factors restricts transferability among fields. On farm application of dated production functions are limited, despite their improvements over basic production functions.

The research reported here focuses on the estimation and economic analysis of undated crop-water production functions for cotton and wheat on various soil textures in Arizona. Additional years of data from agronomic sites in Arizona will supplement data generated by Hexem and Heady's (1978) earlier efforts. Pan evaporation data is included in the modeling effort. Scheduling is not directly considered in the production function estimates, but is considered in side calculations.

## CHAPTER 3

## THEORY, METHODS, AND DATA

The economic theory, statistical technique of analysis, and data sources and descriptions are summarized here.

### Economic Theory

A production function indicates the relationship between alternative amounts of an input and the resulting output if inputs are applied in a technically efficient way. Curve OA of Figure 6 depicts a hypothetical production function with crop yield shown to vary with the level of input X.

The added output from each additional unit of input is the marginal physical product (MPP), and in Figure 6 is shown as curve MN. By multiplying the MPP times the price of the product, the marginal value product (MVP) is derived, and indicates the added value of output for each additional unit of input. Profit maximization with a single variable input takes place where the MVP equals the price of the input (and the value of the average physical product [AVP] is declining). Figure 7 depicts the MVP, AVP, and input price line. Point X is the profit maximizing level of input use.

When more than one input is variable and some factors of production are fixed, the production function may be expressed in functional notation as:

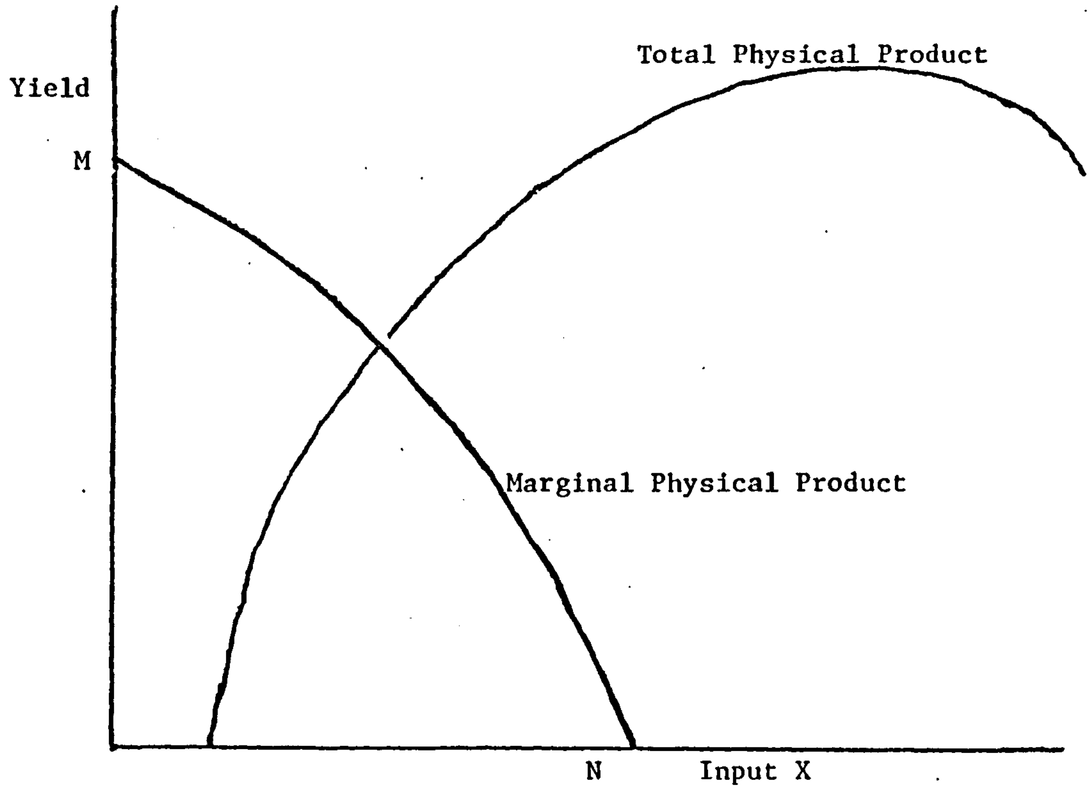


Figure 6. Hypothetical Production and Marginal Physical Product Functions

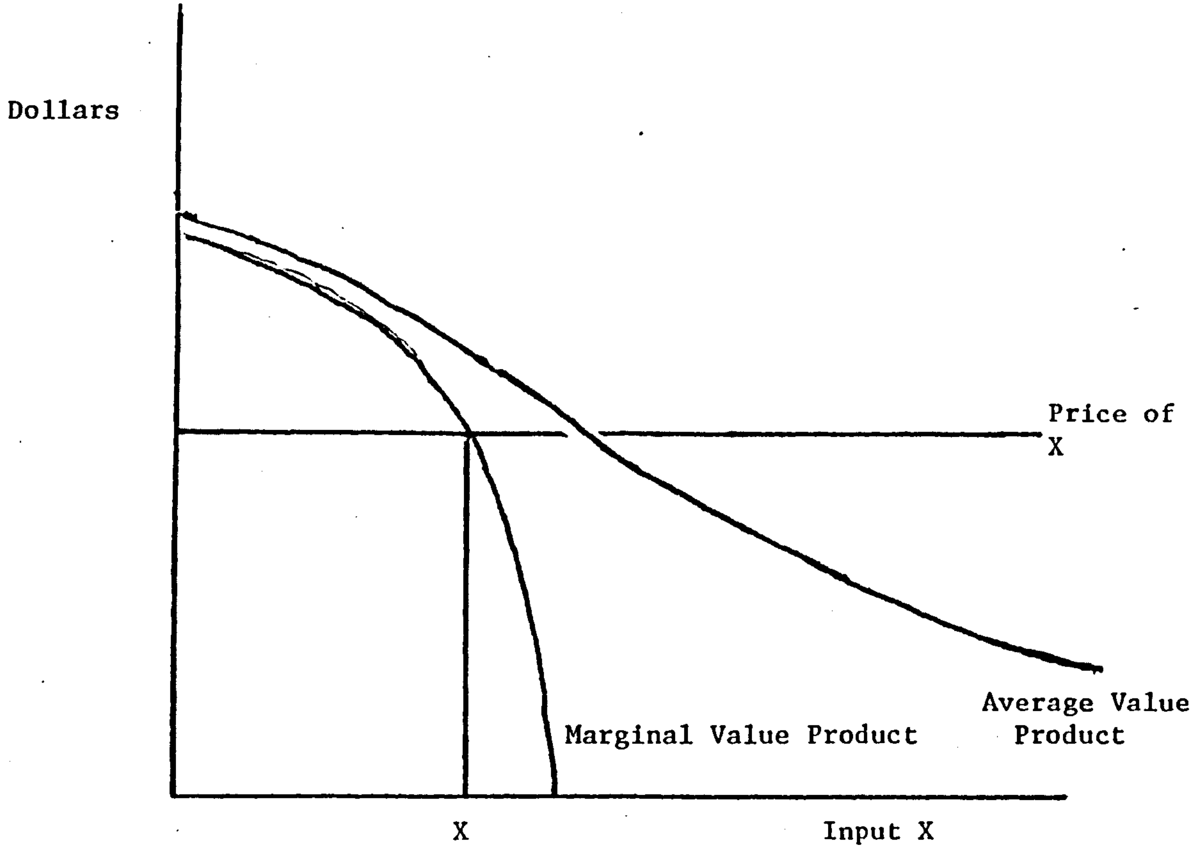


Figure 7. Marginal Value and Average Value Products

$$Y = f(X_1, X_2, X_3 \; . \; . \; . \; X_n S_{n+1}, \; . \; . \; . \; X_z)$$

where

$Y$ = yield

$X_1 \; . \; . \; . \; X_n$ = variable inputs

$X_{n+1} \; . \; . \; . \; X_t$ = fixed factors of production

Profits are expressed as

$$\pi = PyY = (P_x X_1 + P_x X_2 + P_x X_{nt} + \; . \; . \; . + P_x X_n) - FC$$

where

$\pi$ = profits

$Py$ = price of product $Y$

$Y$ = yield

$P_{x_i}$ = price of input $x_i$, $i = 1$ to $n$

$FC$ = fixed costs of inputs $X_{n+1} \; . \; . \; . \; X_t$.

Profits are maximized when the derivative of profits, with respect to all variable inputs, are equal to zero ( and the value of the average products are declining):

$$\frac{\partial \pi}{\partial X_1} = Py \frac{\partial y}{\partial X_1} - P_{x1} = 0$$

$$\frac{\partial \pi}{\partial X_2} = Py \frac{\partial y}{\partial X_2} - P_{x2} = 0$$

$$\frac{\partial \pi}{\partial X_3} = Py \frac{\partial y}{\partial X_3} - P_{x3} = 0$$

$$\vdots$$

$$\frac{\partial \pi}{\partial X_n} = Py \frac{\partial y}{\partial X_n} - P_{xn} = 0$$

And since $Py \frac{\partial y}{\partial X_i}$ is the $MVP_{x_i}$, each set of equations indicates that at profit maximization the $MVP_{x_i}$ must equal the price of $X_i$, as was true the single variable input case.

Solution of this system of "n" equations yields the profit maximizing level of input use. Substitution of the input levels into the response and objective functions, respectively, provides the level of output and profit under profit maximization.

The form of the production function equation affects the estimated profit maximizing quantity of water to apply. Quadratic, square-root, and three halves equations will be discussed.

The quadratic function ($Y = b_o + b_1X_1 + b_3X_2 + b_sX_1X_2$) permits the yield response surface to curve downward, displaying negative marginal products at high levels of input use (water, fertilizer, etc.). The marginal product curve is linear with the quadratic equation. The quadratic equation is attractive because it accounts for declining marginal yields as water applications increase and for declining crop yields resulting from excessive applications of water, fertilizer, or other inputs.

The square-root function ($Y = b_o + b_1X_1 + b_2X_1^{.5} + b_3X_2 + b_4X_2^{.5} + b_5X_1X_2$) has properties comparable to the quadratic. The marginal product curve for each input variable declines at a decreasing rate. This feature is consistent with known agronomic relationships.

The three halves function ($Y = b_o + b_1X;\ + b_2X_1^{1.5} + b_3X^2 + b_yX_2^{1.5} + b_5X_1X_2$) has several properties similar to the square-root, however, the marginal product curve of the input ($X_i$) declines at an increasing rate.

The marginal value product ($MVP_{x_i}$) function is also the demand function for input $X_i$, because the MVP curve indicates, as shown above, the amount of input which will be used at different prices of the input. From the demand curve, the elasticity of demand is derived. Elasticity of demand is the percentage change in quantity demanded with 1 percent change in input price. Elasticity of demand may be computed either as arc or point elasticity. Arc elasticity is:

$$\text{Arc } E_d = \left| \frac{\dfrac{X_b - X_a}{X_b + X_a}}{\dfrac{P_{x_b} - P_{x_a}}{P_{x_b} + P_{x_a}}} \right|$$

Where a and b are the limits of the arc for the quantity and price. Point elasticity is:

$$\text{Point } E_d = \left| \frac{\partial X}{\partial P_x} \cdot \frac{Px}{X} \right|$$

Elasticity of demand may be elastic, inelastic, or unitary. If the elasticity of demand is greater than one, demand is elastic, and the percentage change in quantity demanded is greater than the percentage change in its price. Inelastic demand, when elasticity is less than one, means that the percentage change in quantity demanded is less than the percentage change in price. Unitary elasticity, when the elasticity equals one, means the percentage change in quantity demanded is equal to the percentage change in price.

## Statistical Technique

Regression analysis is used to estimate the production functions. Regression is a descriptive tool that may be used to (1) find the best linear prediction equation, (2) evaluate prediction accuracy, (3) control for other confounding factors to evaluate the contribution of a specific variable or set of variables, and (4) find structural relationships and provide explanations for complex multivariant relationships.

Ordinary least-squares regression is a statistical technique to estimate the intercept and slope of a line from observations of the levels of an independent variable(s) and the associated levels of the dependent variable. The intercept and slope are estimated by finding the intercept and slope that minimizes the sum of the squared differences between the actual observations and the regression line.

Several tests of the statistical reliability of the estimated equation can be made with regression analysis. The coefficient of determination, $R^2$, denotes the variation in the dependent variable explained by the independent variables. The t test indicates the level of significance of individual intercept and slope coefficients.

## Data

Discussion of the data focuses on crop-water data for Arizona wheat and cotton, and the prices of water, wheat, and cotton.

### Crop-Water Data for Arizona Wheat and Cotton

An exhaustive search was conducted to collect all agronomic data that related crop response to water for major crops in Arizona.

Because of differing agronomic objectives and associated experimental design, much of the available data failed to provide the necessary information for derivation of crop-water response functions.
One major crop-water research effort did exist, providing sufficient data for this research.

In a study sponsored by the Bureau of Reclamation, Hexem and Heady (1978) designed, administered, and analyzed crop-water experiments for major and minor crops in the western United States. In Arizona, experiments were conducted on cotton, wheat, beets, and corn. Cotton data analyzed by Hexem and Heady (1978) are from the experiment stations located at Yuma Mesa, Yuma Valley, Tempe, and Safford, and for experiments conducted in 1971. The current study uses this same cotton data, additional data from Phoenix for 1975 and 1976, plus additional data on pan evaporation. Wheat data analyzed by Hexem and Heady are from experiment stations located at Yuma Mesa, Yuma Valley, Mesa, and Safford for experiments done in 1971 and 1972. These same data, additional data from Mesa from 1973 through 1975, and data on pan evaporation are used to analyze the impact of water on wheat yield.

Variation among the soil and climatic conditions for the Arizona field stations are depicted in Table 4. Yuma Valley, with a "fine" soil texture, has the highest available water holding capacity (AWHC) at 9.9 inches. Yuma Mesa, with a coarse soil texture, records and lowest AWHC 3.1 inches. Both Yuma sites are hotter and dryer than Mesa or Tempe. The electrical conductivity, although high in Yuma Valley, does not adversely affect yield because of the high salt tolerance of wheat and cotton.

Table 4. Selected Soil and Climatic Data for Five Experimental Sites in Arizona

| Site | Soil Texture | Available Water Holding Capacity (in./ft) | Hydrologic Conductivity (in/h) | Electrical Conductivity (millimhos per cm at 25°C) | pH Alkalinity-acidity Ratio | Average Annual Temperature (°F) | Average Annual Precipitation (in.) |
|---|---|---|---|---|---|---|---|
| Yuma Valley | Fine | 9.9 | .18 | 3.55 | 7.81 | 87.8 | 2.37 |
| Yuma Mesa | Coarse | 3.1 | 2.9 | 1.5 | 7.97 | 87.1 | 3.38 |
| Mesa | Medium | 7.3 | .64 | 1.22 | 8.03 | 84.6 | 8.06 |
| Tempe | Medium | 5.6 | .9 | 2.41 | 7.84 | 84.8 | 7.66 |
| Safford | Fine | 7.5 | .47 | 5.65 | 8.01 | 80.3 | 8.95 |

Source: Hexem and Heady (1978, Appendix, Table 2).

The agronomic experiments employed the incomplete block design involving factorial treatments. The factorial arrangement, referring to the specification and distribution of various treatment combinations, was selected for two reasons. First, this design allows estimation of coefficients for second order polynomial square root and other polynomial forms of production functions. Second, sufficient points are provided for a balanced goodness of fit test. Treatment combinations were randomly assigned to specific plots. Most experiments incorporated two blocks, each containing 22 experimental plots.

Irrigation quantity and timing was based upon the level of soil moisture tension as measured by neutron probe tubes and/or moisture blocks. Water was applied when the available soil moisture reached a predetermined level for each site in the top 4 feet of soil. Adequate water was applied to restore the soil moisture to field capacity with each irrigation. The quantity of water applied to each plot was metered at the plot's entry point. Borders, constructed after germination, prevented irrigation runoff. Rainfall in excess of one-quarter inch was included in the total water applied amount.

## Prices

The price of pump irrigation water is the cost of energy, repairs, maintenance, and lubrication to pump an acre foot of water. These costs may vary with lift depth, pump efficiency, the price of electricity (or other fuel), and the field irrigation efficiency. The price per acre-foot of pump irrigated water applied is:

$$P_{H_2O} = \frac{\dfrac{\text{KWH to lift one acre-foot}}{\text{overall pump efficiency}} * \text{power cost per KWH including sales tax} + (\text{R} * \text{lift depth in feet})}{\text{irrigation delivery efficiency}}$$

where:

R = Cost of plant repairs, maintenance, lubrication, and attendance per acre-foot per foot of lift.

Prices for water cost computations are from Hathorn's 1979 Arizona Field Crop Budgets (Hathorn and Armstrong, 1979; Hathorn and Cluff, 1979; Hathorn and Farr, 1979; Hathorn, Howell, and Hazlitt, 1979). Surface water costs are from the same publication. Pump efficiency, as per Hathorn, is assumed to be 60 percent, and the delivery efficiency is assumed to be 60 percent for flood irrigation.

Three water sources at three prices are examined in the sensitivity analysis. Surface water, pumping at 300 feet and at 600 feet, serve as the water sources. Expected costs for 1979, a 50 and 100 percent increase in the cost of electricity are the price levels. Surface water prices are increased 50 and 100 percent.

Three cotton prices are examined in the sensitivity analysis. Cottonseed and cotton lint are combined to provide a composite value per pound of cotton lint. There are 1.65 pounds of cottonseed per pound of lint. Review of 10 years of historical data showed an annual low cotton lint price of $.234 per pound in 1969. The historical (1976) high cotton lint price is identical to the estimated high price of $.66 per pound forecast for 1979. The medium range value for cotton lint is $.54 per pound.

Three values of cotton seed, $.055, $.05, and $.045 per pound are used. Marketing specialists from Arizona Producers forecast no greater than a 10 percent positive or negative change in the current $.05 per pound price of cottonseed for the next 5 years in Arizona. The aflatoxin situation causes Arizona producers to receive a lower value for cottonseed than cotton producers in other regions.

The composite cotton lint and cottonseed values are:

$.234 per pound + 1.65 * .045 per pound = $.31 per pound (low)

.54 per pound + 1.65 * .05 per pound = .62 per pound (medium)

.66 per pound + 1.65 * .055 per pound = .75 per pound (high)

Three output prices are examined in the sensitivity analysis on wheat. Review of 10 years of historical data showed the lowest price for wheat to be $.0235 per pound ($47/ton) in 1970. The high wheat price was $.065 per pound ($130/ton) in 1976. The 1979 expected price is $.0525 per pound ($105/ton). The output values used in the sensitivity analysis are a low or $.0235, a medium of $.0525, and a high of $.065 per pound.

## Scheduling

The agronomic experiments from which data for the production functions are taken were not designed to evaluate the impact of water scheduling on yield. Rather, some "optimum" scheduling was used. Supplemental agronomic information is used here to indicate the number of irrigations and something about the scheduling. Gravity irrigation, which accounts for nearly 95 percent of all irrigation in Arizona, is assumed. On fine- and medium-textured soils preplant irrigations generally total about 12 inches to bring soil moisture to field capacity. A total of 10 inches is usually sufficient for preplant irrigations on coarse soils. Each remaining irrigation usually applies 6 inches of water on fine- and medium-soil textures and 5 or less inches on coarse soils to wet the soil to root zone. Applications should be applied at particular times based on soil moisture and vegetative conditions.

## Summary

In summary, data from agonomic experiment stations are used in regression analysis to estimate crop-water production functions for cotton and wheat in Arizona. In the economic analysis, the profit maximizing level of water is estimated. The sensitivity of the profit maximizing level of water to soil textures, cotton fiber and seed prices, wheat prices, and three water sources (surface, 300-foot lift, and 600-foot lift) and water prices is also examined. The scheduling of water is not considered directly in the productin function estimates but is recognized through the use of supplemental agronomic information. The demand and elasticity of demand for water are estimated from the underlying production functions for each soil type.

CHAPTER 4

# EMPIRICAL ANALYSIS--CROP RESPONSE MODELS

Production functions for wheat are derived for (1) evaporatranspiration models similar to those of Stewart et al. (1977), Minhas et al. (1974), and Blank (1975); (2) a square-root function; (3) a Cobb Douglas function; (4) a quadratic functions; and (5) the "best" crop water functions for fine, medium and coarse soil textures in Arizona. Empirical results for cotton are derived for (1) a Cobb Douglas function; (2) a quadratic function; and (3) the "best" crop-water functions for fine, medium, and coarse soil textures in Arizona. Detailed equation results are given for the "best" functions for each soil type, but for brevity, only the highlights of other production functions are described.

## Evapotranspiration Models Applied to Wheat

### Stewart

Stewart et al. (1977) offered two evapotranspiration models for use in crop-water analysis. Both were applied to aggregate wheat data from Mesa for 1973, 1974, and 1975. Their S-1 model can be utilized when the amount of vegetative growth, temperature, and solar radiation associated with each crop growth period is not of practical significance. The model predicts crop yield as a function of evapotranspiration without reference to individual growth stages.

Stewart et al.'s (1977) evapotranspiration model without growth stages is labeled model S-1 and is:

$$Y_A = Y_M - Y_M \beta_0 (ET_D / ET_M)$$

where:

$Y_A$ = Actual marketable yield in pounds per acre

$Y_M$ = Maximum yield (in pounds per acre) attainable according to the varietal genetics as modified by climate, soil, and management

$ET_D$ = Evapotranspiration deficit = $ET_M - ET_A$; seasonal total depth in inches per acre

$ET_M$ = Maximum evapotranspiration = the upper limit of $ET_A$ = ET required to maximize yield; a seasonal total depth in inches per acre

$ET_A$ = Actual ET = ET(ASWP) + ET(R) + ET(IRR); all as seasonal depths in inches per acre

ET(ASWP) = ET resulting from soil water already stored when roots reset the profile layers concerned; a seasonal depth in inches per acre

ET(R) = ET resulting from rainfall during the crop season; a seasonal depth in inches per acre

ET(IRR) = ET resulting from IRR: a seasonal depth in inches per acre

IRR = Depth of irrigation water applied in specified time period in inches per acre

0 = A dimensionless slope that relates the decline in $Y_A$ per unit decrease in $ET_A$.

Stewart et al.'s (1977) S-2 model shows yield to depend on evapotranspiration per growth stage:

$$Y_A = Y_M - Y_M\beta(ET_D/ET_M)$$

where:

$$\beta = (\beta_v ET_{D,v} + \beta_p ET_{D,p} + \beta_M ET_{p,M}) \;/\; ET_D$$

and subscripts v, p and M refer to the vegetative, pollination, and maturation periods, respectively.

$ET_{D,v}$; $ET_{D,p}$; $ET_{D,M}$, and $ET_D$ = ET deficits anticipated in each three growth states and their sum.

Stewart et al.'s (1977) models based upon total evapotranspiration (S-1) and evapotranspiration broken into growth stages (S-2) failed to provide usable functions with aggregated Mesa wheat data. The coefficients of determination are only near .20.

Stewart et al. based the two models on corn production. The model did not effectively transfer to Arizona wheat production.

Minhas

A crop response model by Minhas et al. (1974) is applied to aggregated wheat data from Yuma Valley, 1970-71 and 1971-72; Yuma Mesa, 1970-71 and 1971-72; and Mesa, 1970-71 through 1974-75.

Minhas' multiplication model is:

$$Y = a[1 - (1 - x_1)^2]^{b_1}[1 - (1 - x_2)^2]^{b_2} \ldots [1 - (1 - x_n)^2]^{b_n}$$

where:

$Y$ = crop yield in pounds per acre

$x_j$ = relative (i.e., fraction of maximum) ET in period j

a, $b_1$, . . . $b_n$ = coefficients.

The coefficient of determination is .735. Some of the coefficients are statistically significant at the 10 percent level but fail to show the expected sign.

Blank

Additive and multiplicative models by Blank (1975) are applied to aggretated wheat data from Yuma Mesa and Yuma Valley for 1970-71 and 1971-72; and Mesa for 1970-71 through 1974-75. Crop yield is a function of evapotranspiration in three growth stages.

Blank's additive model is:

$$\frac{Y}{Y_{max}} = A_1 \frac{ET_1}{ET_{max1}} + A_2 \frac{ET_2}{ET_{max2}} + A_3 \frac{ET_3}{EG_{max3}} + A_4$$

where:

$Y$ = actual crop yield in pounds per acre

$Y_{max}$ = maximum crop yield in pounds per acre

$ET_i$ = measured evapotranspiration (ET) in period i (1,2,3)

$ET_{max_i}$ = maximum evapotranspiration (ET) in period i (1,2,3)

$A_i$ = a constant.

The coefficient of determination is .31. The coefficient for the ratio of the actual to the maximum evapotranspiration in the first stage of growth ($A_1$) is statistically significant only at the

50 percent level and showed an unexpected sign. The two other coefficients are statistically significant at the 1 percent level.

Blank's (1975) multiplicative model is:

$$\frac{Y}{Y_{max}} = A \left(\frac{ET_1}{ET_{1max}}\right)^{\lambda_1} \left(\frac{ET_2}{ET_{2max}}\right)^{\lambda_2} \left(\frac{ET_3}{ET_{3max}}\right)^{\lambda_3} \left(\frac{ET_4}{ET_{4max}}\right)^{\lambda_4}$$

where:

$Y$ = actual crop yield in pounds per acre

$Y_{max}$ = maximum crop yield in pounds per acre

$ET_i$ = measured evapotranspiration (ET) in period (1,2,3,4) in inches

$ET_{max_i}$ = maximum evapotranspiration (ET) in period (1,2,3,4) in inches

$A$ = a constant

$\lambda_i$ = coefficients

The coefficient of determination is .25. The ET coefficients are not statistically significant or show unexpected signs.

## Other Models Applied to Wheat

### Square-root Model

Hexem and Heady (1978) recommended square-root functions for crop-water analysis. The square-root function employed is

$$y = b_o + b_1\,WT + b_2\,FERT + b_3\,AWHC + b_4\,EC + b_5\,PH + b_6\,EVAP + b_7\,WT^{.5} + b_8\,FERT^{.5}$$

where:

Y = yield in pounds per acre

WT = total water applied to the crop in inches per acre

FERT = nitrogen applied in pounds per acre

AWHC = available water holding capacity in inches per foot of soil

EC = electrical conductivity in milli inches per cm at 25°C

PH = alkalinity/acidity ratio of the soil

EVAP = total pan evaporation for the season

$b_o$ through $b_8$ = coefficients.

Wheat data for Yuma Valley for 1970-71 and 1971-72, Yuma Mesa for 1970-71 and 1971-72, and Mesa for 1970-71 through 1974-75 were aggregated for analysis with the square-root function. With soil factors included, the square-root function provided a coefficient of determination of .76. Total water applied failed to show the expected sign and was statistically significant at the 10 percent level. Other variables are statistically significant with expected signs.

Cobb Douglas Model

The Cobb Douglas functional form is applied to aggregated wheat data from Yuma Valley for 1970-71 and 1971-72, Yuma Mesa for 1970-71 and 1971-72, and Mesa for 1970-71 through 1974-75.

The Cobb Douglas function is:

$$Y = b_0 W1^{b_1}\ W2^{b_2}\ W3^{b_3}\ EVAP^{b_4}\ AWHC^{b_5}\ FERT^{b_6}$$

where:

Y = crop yield in pounds per acre

W1 = water applied in the first stage in inches per acre

W2 = water applied in the second stage in inches per acre

W3 = water applied in the third stage in inches per acre

AWHC = available water holding capacity in inches per foot of soil

EVAP = total pan evaporation for the season in inches per acre

FERT = nitrogen applied in pounds per acre

$b_0$-$b_6$ = coefficients.

The coefficient of determination is .68 with the log of total evaporation not significant at the 10 percent level. Other variables are statistically significant at the 10 percent level and exhibit expected signs.

## Quadratic Models

A quadratic production function is used to evaluate wheat data from Yuma Valley for 1970-71 and 1971-72, Yuma Mesa for 1970-71 and 1971-72, and Mesa for 1970-71 through 1974-75. Both squared and interaction terms are in the equation. The interaction terms included water applied in each stage interacting with (1) evaporation in that stage, (2) water applied in another growth stage, and (3) total fertilizer applied.

The equation is:

$$Y = b_0 + b_1W1 + b_2W2 + b_3W3 + b_4FERT + b_5X1 + b_6X2 = b_7X3$$
$$= b_8X4 + b_9X5 + b_{10}X6 + b_{11}X7 + b_{12}X8 + b_{13}X9 + b_{14}X10$$
$$+ b_{15}EVAP1 + b_{16}EVAP2 + b_{17}EVAP3 + b_{18}PH + b_{19}EC + b_{20}AWHC$$

where:

Y = crop yield in pounds per acre

W1 = water applied in stage 1 in inches per acre

W2 = water applied in stage 2 in inches per acre

W3 = water applied in stage 3 in inches per acre

FERT = nitrogen applied in pounds per acre

EVAP1 = pan evaporation in stage 1 in inches per acre

EVAP2 = pan evaporation in stage 2 in inches per acre

EVAP3 = pan evaporation in stage 3 in inches per acre

AWHC = available water holding capacity of the soil in inches

EC = electrical conductivity of the soil in millimhos per cm at 25°C.

PH = acidity/alkalinity ratio of the soil

X1 = W1*W1

X2 = W2*W2

X3 = W3*W3

X4 = FERT*FERT

X5 = W1*EVAP1

X6 = W2*EVAP2

X7 = W3*EVAP3

X8 = W1*FERT

X9 = W2*FERT

X10 = W3*FERT

$b_0$-$b_{20}$ = coefficients.

For wheat, equations with the interaction terms provided a coefficient of determination of .83, and all variables show the expected sign. Coefficients for AWHC, X3, X4, X7, W3, are statistically significant at the 1 percent level. Evaporation in the third stage (EVAP3), is statistically significant at the 5 percent level. Water applied in the second stage, W2, is statistically significant at the 10 percent level. All other coefficients are not statistically significant at the 10 percent level.

A quadratic equation is applied to Arizona wheat data from Mesa for 1970-71 through 1974-75 and Yuma Mesa and Yuma Valley for 1970-71 and 1971-72.

The equation is:

$$Y = b_0 + b_1W + b_2N + b_3EVAP + b_4AWHC + b_5NIRR + b_6W^2 + b_7N^2$$

where:

Y = crop yield in pounds per acre

N = nitrogen applied in pounds per acre

W = total water applied to the crop in inches per acre

EVAP = total pan evaporation over the season in inches per acre

AWHC = available water holding capacity in inches

NIRR = number of irrigations applied to the crop

$b_0$-$b_7$ = coefficients

The coefficient of determination is .48. The number of irrigations is correlated with water (r = .46) and available water holding capacity (r = .63). Coefficients not statistically significant at the

10 percent level include water, the number of irrigations, and water squared. The number of irrigations failed to show the expected sign.

A quadratic function is derived from aggregated Arizona wheat data from Mesa for 1970-71 through 1974-75 and Yuma, Mesa, and Yuma Valley for 1970-71 and 1971-72. The equation is:

$$Y = b_0 + b_1W + b_2W^2 + b_3N + b_4N^2 + b_5PH + b_6HC + b_7EVAP$$

where:

Y = crop yield in pounds in wheat per acre

W = acre-inches of water applied and effective rainfall from preplant irrigation until harvest

N = nitrogen applied in pounds per acre

AWHC = available water holding capacity of soil in inches

HC = hydraulic conductivity of soil in inches per hour

EC = electrical conductivity of soil in millimhos per centimeter at 25° C.

EVAP = total pan evaporation for the season in inches

PH = ratio of alkalinity to acidity in the soil

$b_0$-$b_7$ = coefficients

The coefficient of determination is a respectable .77 with no variables displaying unexpected signs. Several variables are not significant at usually accepted levels.

The best aggregated production function for wheat is:

$$Y = \underset{(6152.3)}{\overset{***}{-74912.94}} + \underset{(52.2)}{\overset{**}{116.99W}} - \underset{(.9)}{1.17W^2} + \underset{(2.0)}{\overset{***}{15.2N}} = \underset{(.006)}{\overset{***}{.03N^2}} + \underset{(812.8)}{\overset{***}{10204.37PH}}$$

$$\underset{(63.7)}{\overset{***}{-1246.12HC}} - \underset{(22.4)}{\overset{***}{100.8EVAP}}$$

where:

Y = crop yield in pounds per acre

W = acre inches of water applied and effective rainfall from preplant irrigation until harvest

N = nitrogen fertilizer applied in pounds per acre

AWHC = available water holding capacity of soil in inches

HC = hydraulic conductivity of soil in inches per hour

EC = electrical conductivity of soil in millimhos per centimeter at 25°C.

EVAP = total pan evaporation for the season in inches

PH = ratio of alkalinity to acidity in the soil

*** = coefficient is statistically significant at the 1 percent level

** = coefficient is statistically significant at the 5 percent level

* = coefficient is statistically significant at the 10 percent level,

and numbers in parentheses are standard errors of the estimates.

The coefficient of determination is .77 with no variable displaying unexpected signs.

## The Best Crop-Water Production Functions for Wheat

Because of the lack of fit, multicollinearity, and other problems associated with most of the previous attempts to estimate production functions from data aggregated over sites, functions were developed for each of three soil textures (fine, medium, and coarse) found at the experimental sites. Overall these disaggregated production functions are the best, and are used in the later economic analysis. The best regression equations are presented below for each soil class. Standard errors are below the respective coefficients.

Fine-textured Soils

Data from Yuma Valley (1971 and 1972) and Safford (1972), where fine-textured soils are found, is aggregated. The quadratic equation shown below was judged the best of all investigated in terms of coefficient of determination, expected signs, statistical significance, and provision of logical estimates.

$$Y = \underset{(558.9)}{\overset{**}{-1265.7}} + \underset{(26.8)}{\overset{***}{387.0W}} - \underset{(.25)}{\overset{***}{3.7W^2}} + \underset{(2.0)}{\overset{**}{5.8N}} - \underset{(.01)}{\overset{**}{.02N^2}} - \underset{(7.9)}{\overset{***}{80.4EVAP}}$$

where:

Y = crop yield in pounds of wheat per acre

W = acre inches of water applied and effective rainfall from preplant irrigation until harvest

N = nitrogen applied in pounds per acre

EVAP = total pan evaporation for the season in inches

*** = coefficient is statistically significant at the 1 percent level

** = coefficient is statistically significant at the 5 percent level

* = coefficient is statistically significant at the 10 percent level.

The coefficient of determination ($R^2$) is .769. The coefficient for nitrogen squared is statistically significant at the 5 percent level. All other coefficients are statistically significant at the 1 percent level. All coefficients show the expected sign.

Medium-textured Soils

Yield-water data for wheat for 1973 through 1975, from the medium-textured soil area of Mesa, are fitted with a quadratic equation. The equation is:

$$Y = \underset{(2953.85)}{1656.785} + \underset{(186.27)}{\overset{**}{431.793W}} - \underset{(3.22)}{\overset{*}{6.358W^2}} + \underset{(5.08)}{\overset{***}{18.488N}} - \underset{(.01)}{\overset{**}{.031N^2}} - \underset{(38.58)}{29.904EVAP}$$

where:

Y = crop yield in pounds of wheat per acre

W = acre inches of water applied and effective rainfall from preplant irrigation until harvest

N = nitrogen applied in pounds per acre

EVAP = total pan evaporation for the season in inches

*** = coefficient is statistically significant at the 1 percent level

** = coefficient is statistically significant at the 5 percent level

* = coefficient is statistically significant at the 10 percent level.

The coefficient of determination ($R^2$) is .67. The coefficient for nitrogen is statistically significant at the 1 percent level. The coefficients for water and nitrogen squared are statistically significant at the 5 percent level. The coefficient for water squared is statistically significant at the 10 percent level. The coefficient for pan evaporation is statistically significant at the 50 percent level. All coefficients show the expected sign.

Coarse-textured Soils

Yield-water data for wheat for 1971 and 1972, from the coarse-textured soil area of Yuma Mesa, are best fitted with a three halves or 1.5 polynomial equation. The equation is:

$$Y = \underset{(1826.44)}{\overset{***}{12803.008}} + \underset{(143.98)}{\overset{**}{372.87W}} - \underset{(19.06)}{\overset{**}{44.014W^{1.5}}} + \underset{(5.47)}{\overset{***}{15.237N}} - \underset{(.32)}{\overset{***}{1.368N^{1.5}}}$$
$$+ \underset{(.11)}{\overset{***}{.571WN}} - \underset{(51.09)}{\overset{***}{424.168EVAP}}$$

where:

Y = crop yield in pounds of wheat per acre

W = acre inches of water applied and effective rainfall from preplant irrigation until harvest

N = nitrogen applied in pounds per acre

EVAP = total pan evaporation for the season in inches

WN = water applied times nitrogen applied

*** = coefficient is statistically significant at the 1 percent level

** = coefficient is statistically significant at the 5 percent level

* = coefficient is statistically significant at the 10 percent level.

The coefficient of determination ($R^2$) is .77. The coefficients for water applied and water to the three halves are statistically significant at the 5 percent level. All variables show the expected sign.

## Evapotranspiration Models Applied to Cotton

Evapotranspiration models are not used in analysis of the cotton data. Climatic data, necessary inputs to the models, are not available for both Yuma Mesa and Yuma Valley, two of the three sites, despite obvious climatic differences. The small sample size of 3 site-years (compared to 9 with the wheat experiments) accentuated the difficulty of estimation.

## Other Models Applied to Cotton

### Cobb Douglas Model

The Cobb Douglas model uses aggregated data from Yuma Valley, Yuma Mesa, and Tempe for 1970-71. The coefficient of determination is .66, but only one independent variable is statistically significant at the 10 percent level or better.

### Quadratic Models

Various quadratic models, similar to the quadratic models of wheat production in form and independent variables, were estimated from the aggregated wheat data. Although the coefficients of determination tended to be high, often around .85, many key variables were not statistically significant, or had unexpected signs. In many cases high multicollinearity appeared to cause statistical problems.

## The Best Crop-Water Production Functions for Cotton

Again multicolliniarity and other problems suggested that separarate equations be run for each of the three soil types--fine, medium, and coarse. Equation results follow.

### Fine-textured Soils

Yield-water data for cotton for 1971 from the fine-textured soil areas of Yuma Valley and Safford are fitted with a three halves equation:

$$Y = \underset{(380.05)}{\overset{***}{-1313.961}} + \underset{(19.12)}{\overset{***}{77.641}}W - \underset{(2.08)}{\overset{***}{6.437}}W^{1.5} + \underset{(.8)}{\overset{***}{3.785}}N - \underset{(.05)}{\overset{***}{.203}}N^{1.5} + \underset{(5.5)}{\overset{**}{13.25}}EVAP$$

where:

Y = crop yield in pounds of cotton lint per acre

W = acre inches of water applied and effective rainfall from preplant irrigation until harvest

N = nitrogen applied in pounds per acre

EVAP = total pan evaporation for the season in inches

*** = coefficient is statistically significant at the 1 percent level

** = coefficient is statistically significant at the 5 percent level

* = coefficient is statistically significant at the 10 percent level.

The coefficient of determination ($R^2$) is .94. The coefficient for evaporation is statistically significant at the 5 percent level. The coefficients for all other variables are statistically significant at the 1 percent level. All coefficients show the expected sign.

Medium-textured Soils

Yield-water data for cotton from Phoenix (1975 and 1976) and Tempe (1971), areas of medium-textured soils, are fitted with a quadratic equation.

$$Y = \underset{(467.04)}{\overset{***}{2845.254}} + \underset{(13.9)}{\overset{***}{74.468W}} - \underset{(.17)}{\overset{***}{.587W^2}} - \underset{(5.40)}{\overset{***}{40.95EVAP}}$$

where:

Y = crop yield in pounds of cotton lint per acre

W = acre inches of water applied and effective rainfall from preplant irrigation until harvest

N = nitrogen applied in pounds per acre

EVAP = total pan evaporation for the season in inches

*** = coefficient is statistically significant at the 1 percent level

** = coefficient is statistically significant at the 5 percent level

* = coefficient is statistically significant at the 10 percent level.

The coefficient of determination ($R^2$) is .85. The coefficients for all of the variables are statistically significant at the 1 percent level. All coefficients show the expected sign.

Coarse-textured Soils

Yield-water data for cotton for 1971 from the coarse-textured soil area of Yuma Mesa are fitted to a square root equation:

$$Y = \underset{(2532.92)}{\overset{**}{7209.473}} - \underset{(40.91)}{\overset{***}{135.807W}} + \underset{(651.97)}{\overset{***}{2006.207W^{.5}}} - \underset{(1.72)}{\overset{***}{5.341N}} + \underset{(51.17)}{\overset{*}{106.818N^{.5}}} + \underset{(.11)}{\overset{***}{.04WN}}$$

where:

Y = crop yield of cotton ling in pounds per acre

W = acre inches of water applied and effective rainfall from preplant irrigation until harvest

N = nitrogen applied in pounds per acre

EVAP = total pan evaporation for the season in inches

*** = coefficient is statistically significant at the 1 percent level

** = coefficient is statistically significant at the 5 percent level

* = coefficient is statistically significant at the 10 percent level.

The coefficient of determination ($R^2$) is .66. The coefficient for the square root of nitrogen is statistically significant at the 10 percent level. All other coefficients were statistically significant at the 1 percent level. All coefficients show the expected sign.

# CHAPTER 5

## EMPIRICAL RESULTS--ECONOMIC ANALYSIS

The "best" production functions of the previous chapter are used to estimate first the profit maximizing quantity of water and, second, the demand and elasticity of demand for water for each crop and each soil type. Four comparisons of the profit maximizing level of water, estimated from the soil specific production functions, are made. First, they are compared with similar estimates based upon the "best" aggregate (over time and location) production functions. Second, profit maximizing levels of water are compared to the most common level of water application as indicated by Arizona extension agents. Third, they are compared to the yield maximizing level of water application. Fourth, they are compared to predictions of site specific and aggregate (over sites) models of Hexem and Heady (1978). The yield maximizing level of water application is of particular interest because most irrigation management services, including government agencies, base their recommendations upon yield maximizing criteria. Typically, recommendations are to irrigate enough in all stages of plant growth to avoid stress.

The sensitivity of profit maximizing water levels and elasticities to the sources of water (300- and 600-feet well lift depths and surface water), water price (current, 50 percent and 100 percent above current), and crop prices (expected low, medium, and high) is also estimated.

Estimates of the profits maximizing level and number of irrigations is a two-step process. First, the profit maximizing level of water is estimated by equating the MVP of water to its price. The number of irrigations is then determined from outside agronomic information as discussed in the previous chapter.

## Wheat

### Profit Maximizing Quantity and Number of Irrigations

The profit maximizing levels of water and number of irrigations, by water source, water price, and wheat price are shown for fine-, medium-, and coarse-textured soils in Tables 5, 6, and 7. Estimates are based on the soil texture models previously presented. Notable features of the estimates may be summarized. (1) For all soil types, a combination of low product prices and high water prices (50-100 percent increase in the price of electricity for the 600-foot lift) results in wheat going out of production. (2) For all soil types, the profit maximizing level of water appears to decrease fairly substantially as the price of water increases substantially among water sources. For example, on fine-textured soils at a 1979 price of surface water of $.46/acre-inch, the profit maximizing level of water is 49 acre-inches, but at 1979 electricity prices and a 600-foot pump lift, the optimum level of water is only 20 acre-inches. (3) For all soil types and for surface water situations, the price of water is so low that even doubling its price has almost no impact on the profit maximizing amount

Table 5. Profit-maximizing Quantity of Water and Number of Irrigations at Different Wheat and Water Prices for Wheat Raised on Fine-textured Soil

| Water Source and Price Situation | Price of Water | Wheat Prices: Low ($.0235/lb) | | Medium ($.0525/lb) | | High (.065/lb) | |
|---|---|---|---|---|---|---|---|
| | $/acre-in. | --acre-in. | (number of irrigations)-- | | | | |
| Surface | | | | | | | |
| Expected 1979 price | $0.46 | 49 | (7) | 50 | (7) | 51 | (7) |
| 50% increase | .69 | 48 | (7) | 49 | (7) | 50 | (7) |
| 100% increase | .92 | 46 | (7) | 49 | (7) | 50 | (7) |
| 300-foot Lift | | | | | | | |
| Expected 1979 price | 2.77 | 36 | (5) | 45 | (6) | 46 | (7) |
| 50% increase in price of electricity | 4.06 | 29 | (4) | 41 | (6) | 43 | (6) |
| 100% increase in price of electricity | 5.35 | 21 | (3) | 38 | (5) | 41 | (6) |
| 600-foot Lift | | | | | | | |
| Expected 1979 price | 5.52 | 20 | (2) | 38 | (5) | 40 | (6) |
| 50% increase in price of electricity | 8.08 | 6 | (0) | 31 | (4) | 35 | (5) |
| 100% increase in price of electricity | 10.65 | 0 | (0) | 24 | (3) | 30 | (4) |

Table 6. Profit-maximizing Quantity of Water and Number of Irrigations at Different Wheat and Water Prices for Wheat Raised on Medium-textured soil

| Water Source and Water Price situatin | Price of Water $/acre-inch | Price of Wheat ($/lb) Low ($.0235/lb) | | Medium ($.0525/lb) | | High ($.065/lb) | |
|---|---|---|---|---|---|---|---|
| | | --acre-in | (number of irrigations)-- | | | | |
| Surface | | | | | | | |
| Expected 1979 price | .46 | 32 | (4) | 33 | (5) | 33 | (5) |
| 50% increase | .69 | 32 | (4) | 33 | (4) | 33 | (5) |
| 100% | .92 | 31 | (4) | 33 | (4) | 33 | (4) |
| 300-foot Lift | | | | | | | |
| Expected 1979 price | 2.77 | 25 | (3) | 30 | (4) | 31 | (4) |
| 50% increase in price of elictricty | 4.06 | 20 | (2) | 28 | (4) | 29 | (4) |
| 100% increase in price of electricity | 5.35 | 16 | (2) | 26 | (3) | 28 | (4) |
| 600-foot Lift | | | | | | | |
| Expected 1979 price | 5.52 | 16 | (2) | 26 | (4) | 27 | (4) |
| 50% increase in price of electricity | 8.08 | 7 | (0) | 22 | (3) | 24 | (3) |
| 100% increase in price of electricity | 10.65 | 0 | (0) | 18 | (2) | 21 | (3) |

Table 7. Profit-maximizing Quantity of Water and Number of Irrigations at Different Wheat and Water Prices for Wheat Raised on Coarse-textured Soil

| Water Source and Price Situation | Price of Water | Wheat Prices: Low ($.0235/lb) | | Medium ($.0525/lb) | | High ($.065/lb) | |
|---|---|---|---|---|---|---|---|
| | $/acre-in | --acre-in(number of irrigations)-- | | | | | |
| Surface | | | | | | | |
| Expected 1979 price | .46 | 45 | (8) | 47 | (8) | 47 | (8) |
| 50% increase | .69 | 43 | (7) | 46 | (8) | 46 | (8) |
| 100% increase | .92 | 41 | (7) | 45 | (8) | 46 | (8) |
| 300-foot Lift | | | | | | | |
| Expected 1979 price | 2.77 | 27 | (4) | 38 | (7) | 40 | (7) |
| 50% increase in price of electricity | 4.06 | 19 | (3) | 34 | (6) | 36 | (6) |
| 100% increase in price of elcetricity | 5.35 | 12 | (1) | 29 | (5) | 33 | (6) |
| 600-foot Lift | | | | | | | |
| Expected 1979 price | 5.52 | 12 | (1) | 29 | (5) | 32 | (5) |
| 50% increase in price of electricity | 8.08 | 3 | (0) | 22 | (3) | 26 | (4) |
| 100% increase in price of electricity | 10.65 | 0 | (0) | 14 | (2) | 20 | (3) |

used--no matter the price of wheat. (4) For all soil types and for both pump lift depths, profit maximizing water use decreases by at least one-third as the price of electricity doubles, and (5) there is a very sizable difference in the optimum amount of water to apply depending on soil type.

Comparison of Soil Texture Models with Other Models

The profit maximizing level of water use under conditions of medium wheat prices and expected 1979 water prices shown in Tables 5, 6, and 7, are compared with water use projected by various other models. Comparisons are made with the profit maximizing level of water predicted by the aggregate (over soil types and time) wheat model, with the common practice amount of water applied, with a yield maximizing model, and with the profit maximizing level of water estimated from site specific and aggregate (over sites) models of Hexem and Heady. Comparisons are shown in Table 8.

Comparison with Aggregate Models. If the results for models of particular soils are nearly equal to those of the aggregate model, then the applicability of the generalized aggregate functions is verified: otherwise analysis for particular soil types should rely on production functions for those particular textures.

The profit maximizing level of water for each soil type, the medium wheat price, and for the expected 1979 price of surface, 300-foot lift and 600-foot lift water is shown in Table 8.

The aggregate model has approximately the same $R^2$ ($R^2$ = .77) as the soil texture models, but it fails to distinguish among soil types in

Table 8. Water Applications Implied by the Six Wheat "Models" for Soils of Different Texture, Medium Wheat Price

| Water Source and Model | Expected 1979 Price of Water | Soil Texture | | |
|---|---|---|---|---|
| | | Fine | Medium | Coarse |
| | $/acre-in. | -------- acre-in. | ---------- | |
| Surface | $0.46 | | | |
| Soil Texture | | 50 | 33 | 47 |
| Aggregate | | 47 | 47 | 47 |
| Common Practice | | 39-50 | 36-40 | 72-84[a] |
| Yield-maximizing | | 52 | 34 | 49 |
| Hexem and Heady Site[b] | | 32 | 26 | 44 |
| Hexem and Heady Aggregate[b] | | 148 | 198 | 148 |
| 300-foot Lift | 2.77 | | | |
| Soil Texture | | 45 | 30 | 38 |
| Aggregate | | 28 | 28 | 28 |
| Common Practice | | 39-50 | 36-40 | 72-84[a] |
| Yield-maximizing | | 52 | 34 | 49 |
| Hexem and Heady Site[b] | | 30 | 25 | 36 |
| Hexem and Heady Aggregate[b] | | 84 | 94 | 94 |
| 600-foot Lift | 5.52 | | | |
| Soil Texture | | 38 | 26 | 28 |
| Aggregate | | 5 | 5 | 5 |
| Common Practice | | 39-50 | 36-40 | 72-84[a] |
| Yield-maximizing | | 52 | 34 | 49 |
| Hexem and Heady Site[b] | | 28 | 23 | 26 |
| Hexem and Heady Aggregate[b] | | 46 | 46 | 46 |

a. Yuma Mesa is the only site in Arizona with coarse-textured soil, and almost no wheat has been grown on Yuma Mesa for the past 5 years. Hazlitt (1979) estimates 72-84 acre-inches of water are required to produce wheat.

b. Models used in computations are from Hexem and Heady (1978, pp. 106, 115, 116, 181, and 182).

profit maximizing computations. As shown in Table 8, there is frequently a very considerable difference between the profit maximizing levels of water projected from the soil texture model versus the aggregate model. Since agronomic information suggests that soil texture does affect wheat yield, the better of the models are the soil texture models.

Comparison with Common Practice. The most common level of water application in the county represented by each soil texture is given in Table 8. The common practice levels are based upon estimates of county extension specialists who survey farmers (Hathorn and Armstrong, 1979; Hathorn and Cluff, 1979; Hathorn and Farr, 1979; Hathorn et al., 1979; and Hathorn, Liddle, and Stedman, 1979)

For the fine-textured soils, such as those found in the Yuma Valley and Safford areas, common practice may not be greatly different, at low and medium water prices, than the profit maximizing level projected from the soil texture model. At higher water prices, however, the spread widens. For the other two soil textures, there is often a considerable difference between common practice and the level of water suggested by the soil texture model. The difference is often more than 6 inches, an amount which would account for at least one irrigation.

Comparison with Yield Maximizing Models. Several agencies of the U. S. Government, including the Bureau of Reclamation, the Salt River Project, and the Extension Service, plus various private firms, offer irrigation management services. In general, their recommendations are designed to avoid plant stress and thereby maximize yield. Considerable literature exists that details the consumptive use of particular crops under particular soil and climatic conditions when water is readily available. Most irrigation management services then try to match the actual water consumption to potential water consumption of the plants.

Estimates of the yield maximizing amount of water which irrigation management services, using usual criteria, would recommend may be made from the soil specific production functions. These estimates are given in Table 8. The estimates show that the profit maximizing and yield maximizing levels of water are nearly the same at the very low water price, but at expected 1979 water prices for both the 300- and 600- foot lifts, there is generally a 6-inch or greater difference. For the medium and expensive water then, the results suggest that at least one irrigation could often be avoided if attention is paid to the profit maximizing versus yield maximizing level.

Comparison with Hexem-Heady Models. Much of the data used in the current analysis is taken from the agronomic experiments originally organized and analyzed by Hexem and Heady (1978) and reported in their book and other publications. The current study differs from theirs in that additional years of data are obtained from some of the experimental sites, separate models are estimated based upon soil texture, which provides a better representation of the data than Hexem and Heady's aggregate models, and alternative functional forms and variable specifications are investigated.

For the fine textured soil, the profit maximizing level of water predicted with the Hexem and Heady site specific model is considerably lower than the soil texture model. For the medium and coarse texture soils, results from the two models are not greatly different. The aggregate model (over sites) of Hexem and Heady does not provide realistic estimates for any soil type.

Demand and Elasticity of Demand for Water

Normative demand curves for water and associated elasticities help illustrate the effect of rising water prices on irrigation water use. Although the demand relationship is implicit in the profit tables given earlier, actual demand schedules and computed elasticities of demand provide a sharper portrayal of the effect of price changes on water use. Of course, projections of actual changes in water use must be hedged, because the demand equations are normative in the sense that they predict what the water use will be if farmers maximize profits and if only a single crop is considered.

The demand schedules, derived from the production functions by soil type, are shown in Figure 8. For illustration, the schedules have been constructed for the 600-foot lift and a medium price of wheat. Given the assumptions, the demand schedule indicates the amount of water used per acre of wheat as the price of water changes. Figure 8 shows, for example, that if the price of water is $5.52 per acre inch, approximately 38 acre inches of water will be applied per acre on fine-textured soil planted to wheat.

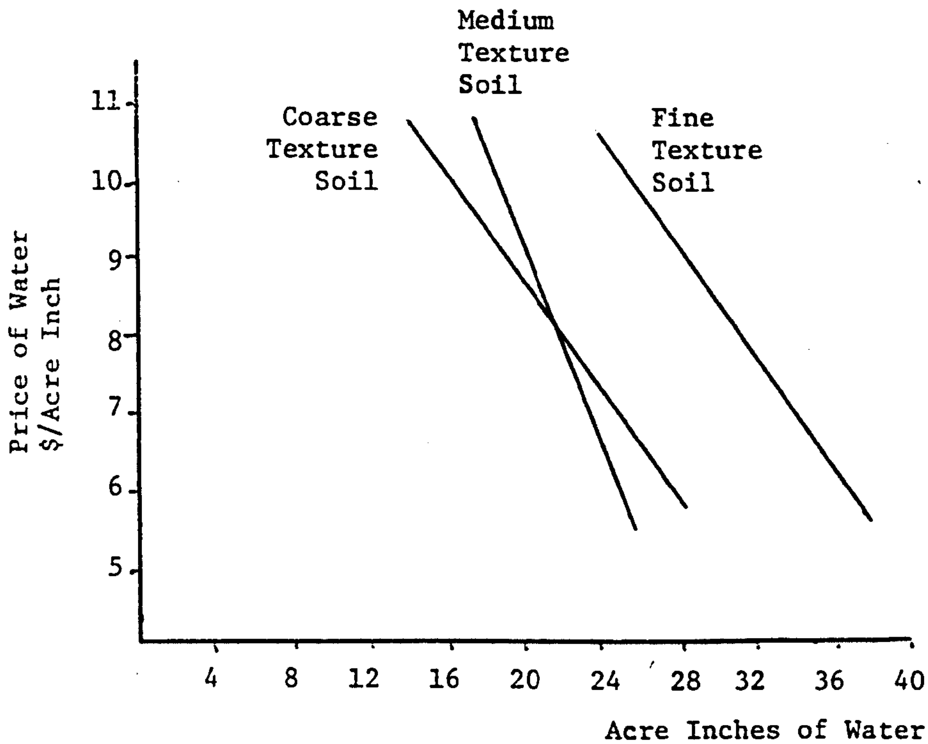


Figure 8. Short-run Normative Demand Curves for Water in the Production of Wheat by Soil Type, 600-foot lift; Price of Output, $.0525/lb.

The responsiveness of the quantity of water demanded to changes in water price is perhaps best shown through elasticities. Elasticities show the percentage change in quantity demanded with a 1 percent change in price. Demand is said to be elastic if the elasticity is greater than one, of unitary elasticity if equal to one, and inelastic if less than one. Table 9 shows the arc and point elasticity of demand for water in the production of wheat by water source, water price, output price, and soil texture.

For each water source, the arc elasticities are computed over the demand schedule from the 1979 expected price to a price which reflects a 100 percent increase in the price of electricity or, in the case of surface water, a 100 percent increase in its price. As an example, the arc elasticity of demand for surface water on fine soils is computed over the price range of $.46 per acre inch to $.92 per acre-inch on fine soils. The elasticity of .09 for surface water and low wheat prices indicates that on average, a 1 percent change in the price of water will result in only a .09 percent change in quantity demanded. That is, demand under these conditions is very inelastic.

The estimates indicate that for all soil types, for all product price levels, and for both surface and water pumped from 300 feet, the demand for water is very inelastic. Only at the deep lift depths is the demand for water substantially affected by price rises--and even in this case the effect may be exaggerated because a large price increase (100 percent) is assumed from an already high base level ($5.52 per acre-inch). The point elasticity of demand at $5.52 per acre-inch of water for the three soil types and for each output price level is greater than one at the low output price on all 3 soil textures.

Table 9. Arc and Point Elasticity of Demand for Water in the Production of Wheat

| Soil Texture and Water Source | Price Range ($/acre-in.) | Price of Wheat: Low ($.0235/lb) | Medium ($.0525/lb) | High ($.065/lb) |
|---|---|---|---|---|
| | | **Arc Elasticity** | | |
| **Fine** | | | | |
| Surface | $0.46-$0.92 | 0.09 | 0.03 | 0.03 |
| 300-foot Lift | $2.77- 5.35 | .82 | .26 | .18 |
| 600-foot Lift | $5.52-$10.65 | 3.22 | .73 | .46 |
| **Medium** | | | | |
| Surface | $0.46-$.92 | .05 | .03 | .00 |
| 300-foot Lift | $2.77-$5.35 | .69 | .22 | .16 |
| 600-foot Lift | $5.52-$10.65 | 4.03 | .59 | .40 |
| **Coarse** | | | | |
| Surface | $0.46-$0.92 | .14 | .06 | .03 |
| 300-foot Lift | $2.77-$5.35 | 1.20 | .42 | .30 |
| 600-foot Lift | $5.52-$10.65 | 3.20 | 1.12 | .74 |
| | | **Point Elasticity** | | |
| **Fine** | | | | |
| 600-foot Lift | $5.25 | 1.60 | .38 | .28 |
| **Medium** | | | | |
| 600-foot Lift | $5.25 | 1.19 | .32 | .24 |
| **Coarse** | | | | |
| 600-foot Lift | $5.25 | 2.09 | .61 | .45 |

Water Quantity Restrictions

Water policy may call for restricted water use. The soil texture models are here used to estimate the change in returns over total variable cost for wheat production should water use be cut to 90 and 80 percent of the profit maximizing level. For brevity, a medium price of wheat is assumed. The estimates are shown in Table 10.

The most notable findings are: (1) Variable costs are greater than returns for all soil types and for all water applications at a 600-foot lift. (2) If fixed costs are assumed to be $90 per acre, a reasonable figure, then in the long run only wheat irrigated with surface water is economically viable. And (3), for surface water situations, assuming fixed costs of $90 per acre, profits (returns to management and risk) are cut from 20 to 100 percent as water is decreased to 80 percent of the profit maximizing level.

## Cotton

Profit Maximizing Quantity and Number of Irrigation-Cotton

Tables 11, 12, and 13 show the profit maximizing level of water to apply by fine, medium, and coarse soil texture, respectively. Again, estimates are based on the soil texture models presented earlier. Levels are also shown to depend on the source and price of water, and upon the price of cotton.

The most notable results are as follows:

1. For all soil types, as the price of water increases greatly between surface and 600-foot lift situation, and when product

Table 10. Water Restrictions and Change in Returns over Total Variable Costs for Wheat, Water Cut to 90 and 80 Percent of Profit Maximum Level, Medium Price of Wheat[a]

| Water Source and Restrictions | Price of Water ($/acre-in.) | Soil Texture | | |
|---|---|---|---|---|
| | | Fine | Medium | Coarse |
| Surface | $0.46 | | | |
| Returns over TVC at profit maximum | | $197 | $102 | $147 |
| Change in returns over TVC at water cut to 90% of profit maximum level | | - 6 | - 5 | - 3 |
| Change in returns over TVC at water cut to 80% of profit maximum level | | - 22 | - 16 | - 10 |
| 300-foot Lift | $2.27 | | | |
| Returns over TVC at profit maximum | | $108 | 43 | 67 |
| Change in returns over TVC at water cut to 90% of profit maximum level | | - 5 | - 4 | - 4 |
| Change in returns over TVC at water cut to 80% of profit maximum level | | - 19 | - 14 | - 12 |
| 600-foot Lift | $5.52 | | | |
| Returns over TVC at profit maximum | | - 27 | - 49 | - 44 |
| Change in returns over TVC at water cut to 90% of profit maximum level | | - 2 | - 2 | - 2 |
| Changes in returns over TVC at water cut to 80% of profit maximum level | | - 10 | - 8 | - 13 |

a. A rough estimate of fixed costs (including those for machinery, well depreciation, general farm maintenance, taxes on land, and interest on land) for a wheat farm in Graham County, Arizona, 1979, are $90 per acre (Hathorn and Cluff, 1979).

Table 11. Profit-maximizing Quantity of Water and Number of Irrigations at Different Cotton and Water Prices for Cotton Raised on Medium-textured Soil.

| Water Source and Price Situation | Price of Water | Cotton Prices: Low ($.31/lb) | | Medium ($.62/lb) | | High ($.75/lb) | |
|---|---|---|---|---|---|---|---|
| | $/acre-in | --acre-in. (number of irrigations) | | | | | |
| Surface | | | | | | | |
| Expected 1979 price | .46 | 62 | (9) | 63 | (10) | 63 | (10) |
| 50% increase | .69 | 51 | (9) | 63 | (10) | 63 | (10) |
| 100% increase | .92 | 60 | (9) | 62 | (9) | 62 | (9) |
| 300-foot Lift | | | | | | | |
| Expected 1979 price | 2.77 | 51 | (7) | 57 | (9) | 59 | (9) |
| 50% increase in price of electricity | 4.06 | 45 | (6) | 54 | (8) | 55 | (8) |
| 100% increase in price of electricity | 5.35 | 39 | (6) | 51 | (8) | 53 | (8) |
| 600-foot Lift | | | | | | | |
| Expected 1979 price | 5.52 | 38 | (5) | 51 | (7) | 53 | (8) |
| 50% increas in price of electricity | 8.08 | 29 | (4) | 45 | (6) | 48 | (7) |
| 100% increase in price of electricity | 10.65 | 20 | (2) | 39 | (6) | 43 | (6) |

Table 12. Profit-maximizing Quantity of Water and Number of Irrigations at Different Cotton and Water Prices for Cotton Raised on Medium-textured Soil.

| Water Source and Price Situation | Price of Water | Cotton Prices: Low ($.31/lb) | | Medium ($.62/lb) | | High ($.75/lb) | |
|---|---|---|---|---|---|---|---|
| | $/acre-in | --Acre in.(Number of irrigations) | | | | | |
| Surface | | | | | | | |
| Expected 1979 price | .46 | 62 | (9) | 63 | (9) | 62 | (9) |
| 50% increase | .69 | 62 | (9) | 63 | (9) | 62 | (9) |
| 100% increase | .92 | 61 | (9) | 62 | (9) | 62 | (9) |
| 300-foot Lift | | | | | | | |
| Expected 1979 price | 2.77 | 56 | (8) | 60 | (9) | 60 | (9) |
| 50% increase in price of electricity | 4.06 | 52 | (8) | 58 | (9) | 59 | (9) |
| 100% increase in price of electricity | 5.35 | 49 | (7) | 56 | (8) | 57 | (9) |
| 600-foot Lift | | | | | | | |
| Expected 1979 price | 5.52 | 48 | (7) | 56 | (8) | 57 | (9) |
| 50% increase in price of electricity | 8.08 | 41 | 96) | 52 | (8) | 54 | (8) |
| 100% increase in price of electricity | 10.65 | 34 | (5) | 49 | (7) | 51 | (8) |

Table 13. Profit-maximizing Quantity of Water and Number of Irrigations at Different Cotton and Water Prices for Cotton Raised on Coarse-textured Soil.

| Water Source and Price Situation | Price of Water | Cotton Prices: Low ($.31/lb) | | Medium ($.62/lb) | | High ($.75/lb) | |
|---|---|---|---|---|---|---|---|
| | $/acre in. | --acre-in. (number of irrigations) | | | | | |
| Surface | | | | | | | |
| Expected 1979 price | .46 | 64 | (12) | 65 | (12) | 65 | (12) |
| 50% increase | .69 | 64 | (12) | 65 | (12) | 65 | (12) |
| 100% increase | .92 | 63 | (12) | 64 | (12) | 65 | (12) |
| 300-foot Lift | | | | | | | |
| Expected 1979 price | 2.77 | 57 | (10) | 61 | (11) | 62 | (11) |
| 50% increase in price of electricity | 4.06 | 54 | (10) | 60 | (11) | 60 | (11) |
| 100% increase in price of electricity | 5.35 | 51 | (9) | 58 | (11) | 59 | (11) |
| 600-foot Lift | | | | | | | |
| Expected 1979 price | 5.52 | 50 | (9) | 57 | (10) | 39 | (11) |
| 50% increase in price of electricity | 8.08 | 45 | (8) | 54 | (10) | 56 | (10) |
| 100% increase in the price of electricity | 10.65 | 40 | (7) | 40 | ( 9) | 53 | (10) |

prices are low to medium, there is a large difference in the optimum aount of water to apply. In general, there is a decrease of two or more irrigations. At high product prices, the profit maximizing levels of water tend to show much smaller differences between low and high priced water.

2. For all soil types and using surface water, there is virtually no difference in the profit maximizing level of water to apply, no matter the price of cotton, the percentage increase in the price of water, or soil type. The amount of water to apply is simply 62-65 acre inches, although the number of irrigation is dependent upon soil type.

3. Increases in the price of electricity from 50 to 100 percent, and hence in the price of pumped water, results in varying degrees of water use adjustment. In these pumping cases, both soil type and product price have a significant effect on the amount of adjustment.

Comparison of Soil Texture Models with Other Models

The profit maximizing level of water, as predicted from the soil texture models and given in Tables 11, 12, and 13. are compared with water application suggested by the aggregate model, common practice, the yield maximizing model, and two Hexem and Heady (1978) models. Predictions assume a medium price for cotton ($.62 total value if lint and seed per pound of lint), and the 1979 expected price of water for each source. Comparisons of water application by model, soil type, and water source are shown in Table 14.

Table 14. Water Applications Implied by Six Cotton "Models" for Soils of Different Texture, Medium Cotton Price

| Water Source and Model | Expected 1979 Price of Water | Soil Texture: Fine | Medium | Coarse |
|---|---|---|---|---|
| | $/acre-in. | ---------- acre-in. | | ---------- |
| **Surface** | $0.46 | | | |
| Soil Texture | | 63 | 63 | 65 |
| Aggregate | | 66 | 66 | 66 |
| Common Practice | | 48-60 | 42-60 | 72-84[a] |
| Yield-maximizing | | 65 | 64 | 66 |
| Hexem and Heady Site[b] | | 60 | 37 | 58 |
| Hexem and Heady Aggregate[b] | | 74 | 74 | 74 |
| **300-foot Lift** | 2.27 | | | |
| Soil Texture | | 57 | 60 | 62 |
| Aggregate | | 61 | 61 | 61 |
| Common Practice | | 48-60 | 42-60 | 72-84[a] |
| Yield-maximizing | | 65 | 64 | 66 |
| Hexem and Heady Site[b] | | 57 | 37 | 56 |
| Hexem and Heady Aggregate[b] | | 65 | 65 | 65 |
| **600-foot Lift** | 5.52 | | | |
| Soil Texture | | 51 | 56 | 59 |
| Aggregate | | 55 | 55 | 55 |
| Common Practice | | 48-60 | 42-60 | 72-84[a] |
| Yield-maximizing | | 65 | 64 | 66 |
| Hexem and Heady Site[b] | | 52 | 37 | 51 |
| Hexem and Heady Aggregate[b] | | 55 | 37 | 55 |

a. Yuma Mesa is the only site in Arizona with coarse-textured soil, and almost no cotton has been grown on Yuma Mesa for the past 5 years. Hazlitt (1979) estimates 72-84 acre-inches of water are required to produce cotton.

b. Models used in the computations are from Hexem and Heady (1978, pp. 134, 135, and 182).

Comparison with the Aggregate Model. The "best" aggregate equation, given earlier, had an $R^2$ of .85. For each soil type and each water source-price situation, the profit maximizing levels of water, as estimated from the two models, are within 4 acre inches of each other. For cotton then, the aggregate model appears to work well across soil types.

Comparison with Common Practice. In general, the commonly applied amounts are not greatly different than the profit maximizing levels.

Comparison with Yield Maximizing Models. Only at the highest water price, i.e., that for the 600-foot lift, is there a notable difference between the profit maximizing and yield maximizing quantity of water to apply.

Comparison with Hexem-Heady Models. For fine soils, the soil texture model and the Hexem-Heady model gave very similar results. For the medium-textured soil, the Hexem-Heady model is greatly different and projections from their models are unreasonable. For coarse soils, the results are similar although the Hexem-Heady model estimates about a 6-inch lower amount of water to maximize profits. Their aggregate model predicts nearly a foot more surface water, but similar amounts of pump water for profit maximization.

## Demand and Elasticity of Demand for Water

Normative demand schedules for cotton produced on fine, medium, and coarse soils, with all the assumptions attendant to the demand equation for wheat, are shown in Figure 9. The curves indicate that there is not a great deal of difference among soil types in the demand for water as the price of water increases.

Arc elasticities of demand by water source, water price, output price, and soil texture are given in Table 15. Arc elasticities for each water source are again computed for the range between the 1979 expected price and the price when energy costs increase 100 percent.

The estimates indicate that for all soil types, all output prices, and all water sources, except one, demand for water is inelastic. Only for a situation of low cotton price and deep water lifts is the elasticity of demand at one. Similar to wheat, this arc elasticity is taken over a range of very high water prices. The point elasticity at the 1979 expected price of water for the 600-foot lift is between .02 and .83, depending on soil type.

Water Quantity Restrictions

The effect on profits of cutting water applications to 90 and 80 percent of the profit maximizing level is shown in Table 16. The estimates indicate that with a posited fixed cost of $230 per acre, profits (returns to management and risk) are very high for fine and medium soils for all water source situations. However, for all soils and all water sources, a reduction in water availability to 80 percent of the profit maximizing level reduces profits by $20 to $55 per acre--a rather substantial amount.

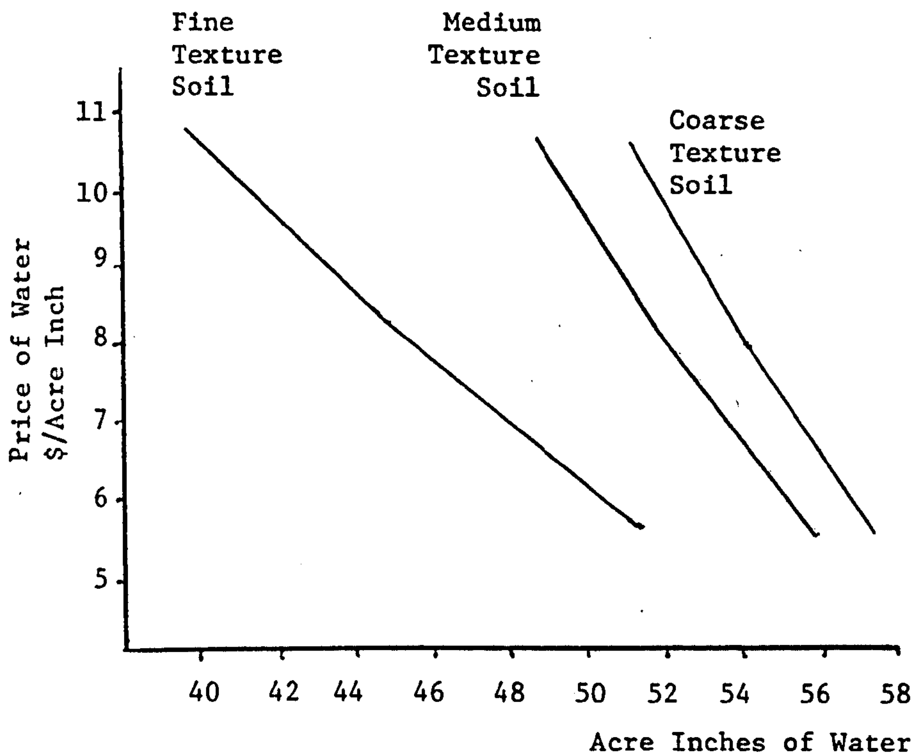


Figure 9. Short-run Normative Demand Curves for Water in the Production of Cotton by Soil Type, 600-foot lift, Price of Output, $.62/lb. of Lint

Table 15. Arc and Point Elasticities of Demand for Water in the Production of Cotton, by Water Source, Water Price, Output Price, and Soil Textures.

| Soil Texture | Water Source | Price Range $/acre-inch | Price of Cotton: Low ($.30/lb) | Medium ($.62/lb) | High ($.75/lb) |
|---|---|---|---|---|---|
| Fine: | | | | | |
| | Arc Elasticity | | | | |
| | Surface | 0.46- 0.92 | .05 | .02 | .02 |
| | 300-foot Lift | 2.77- 5.35 | .42 | .17 | .17 |
| | 600-foot Lift | 5.52-10.65 | 1.00 | .43 | .34 |
| | Point Elasticity for 600-foot Lift at | 5.52 | .59 | .26 | .22 |
| Medium: | | | | | |
| | Arc Elasticity | | | | |
| | Surface | 0.46- 0.92 | .02 | .02 | .00 |
| | 300-foot Lift | 2.77- 5.35 | .21 | .11 | .08 |
| | 600-foot Lift | 5.52-10.65 | .55 | .21 | .18 |
| | Point Elasticity for 660-foot Lift at | 5.52 | .31 | .14 | .11 |
| Coarse: | | | | | |
| | Arc Elasticity | | | | |
| | Surface | 0.46- 0.92 | .02 | .02 | .00 |
| | 300-foot Lift | 2.77- 5.35 | .17 | .08 | .08 |
| | 600-foot Lift | 5.52-10.65 | .36 | .18 | .17 |
| | Point Elasticity for 600-foot Lift at | 5.52 | .24 | .13 | .11 |

Table 16 Water Restrictions and Change in Returns over Total Variable Costs for Cotton, Water Cut to 90 and 80 Percent of Profit Maximum Level, Medium Price of Cotton[a]

| Water Source and Restrictions | Price of Water ($/acre-in.) | Soil Texture | | |
|---|---|---|---|---|
| | | Fine | Medium | Coarse |
| Surface | $0.46 | | | |
| Returns over TVC at profit maximum | | $603 | $610 | $284 |
| Change in returns over TVC at water cut to 90% of profit maximum level | | - 8 | - 16 | - 14 |
| Change in returns over TVC at water cut to 80% of profit maximum level | | - 34 | - 58 | - 55 |
| 300-foot Lift | $2.27 | | | |
| Returns over TVC at profit maximum | | 489 | 495 | 170 |
| Change in returns over TVC at water cut to 90% of profit maximum level | | - 11 | - 15 | - 13 |
| Change in returns over TVC at water cut to 80% of profit maximum level | | - 32 | - 55 | - 55 |
| 600-foot Lift | $5.52 | | | |
| Returns over TVC at profit maximum | | 312 | 306 | - 25 |
| Change in returns over TVC at water cut to 90% of profit maximum level | | - 5 | - 11 | - 5 |
| Change in returns over TVC at water cut to 80% of profit maximum level | | - 20 | - 44 | - 33 |

a. A rough estimate of fixed costs (including those for machinery, well depreciation, general farm maintenance, taxes on land, and interest on land) for a cotton farm in Graham County, Arizona, 1979, are $230 per acre (Hathorn and Cluff, 1979).

# CHAPTER 6

# IMPLICATIONS

The results of the previous chapter are used here to draw implications for farm level irrigation management, government policy with respect to water conservation, and needed irrigation research.

## Farm Management

Several farm level implications may be summarized. For wheat production, (1) there is a significant difference in the profit maximizing level of water to apply as the price of water goes from the lowest (surface water) to the highest (600-foot lift) price. (2) It is not profitable to produce wheat in deep lift areas. This conclusion corresponds to an observed sharp decrease in wheat production in deep lift areas of the state. (3) In surface water areas, even doubling the price of water will not change the profits maximizing level of water use by any significant (6 inches or more) amount. And (4) there is a great difference in the profit maximizing level of water to apply depending upon soil type.

For cotton production, the principle management implications are that (1) there is a significantly large difference (6 inches or more) in the profit maximizing level of water to apply between the lowest and highest priced water (except in the case of very high product prices). However, (2) only at the highest water prices is there a notable difference between the profit and yield maximizing levels of water case. (3) Even doubling the price of surface water does not significantly alter the optimal amount of water to apply. And, (4) a 50-100 percent increase in the price of electricity results in varying degrees of water use adjustment, depending on both soil type and product prices.

## Water Conservation Policy

Water conservation is an important policy goal by several levels of government. Results from the economic analysis may be used to draw implications for water conservation policy. For wheat production, (1) the demand for water tends to be very inelastic, and therefore marginal changes in the institutional price of water will not significantly decrease water use. (2) The price of water on several irrigation projects administered by government agencies is so low that even doubling the price of water will not lead to meaningful (6 inches or more) decreases in water use. Water prices would need to increase several-fold to significantly reduce water applications on wheat. (3) There is a significant difference between the profit maximizing and yield maximizing level of water to apply for medium and high priced water. Government agencies which provide irrigation management services to farmers should recognize this difference, and base water recommendations on economic rather than traditional yield maximizing criteria. And (4) should government policy restrict the quantity of water used to 90-80 percent of the profit maximizing level, profits per acre of wheat will be cut 20 to 100 percent, depending on the magnitude of the restriction and soil type.

For cotton production, (1) the demand for water is very inelastic, and therefore meaningful water savings will be difficult to obtain via the price mechanism. Large price increases would be required to conserve water used in cotton production. (2) Water prices set by government agencies for surface water is so low that even doubling its price will not cut water applications on cotton by a meaningful amount. Only a several-fold price increase would conserve water. (3) If the quantity of water used on cotton is cut to 80 percent of the profit maximizing level, cotton profits are cut a substantial $20-$55 per acre.

## Research

Related research is needed in several areas. (1) Crop-water response functions are needed for other crops and other regions of the arid southwest. (2) The economic analysis of crop response to alternative irrigation quantities needs to be expanded to a multi-crop analysis where optimization among crop mix and input levels is simultaneously determined. (3) Risk should be incorporated into the analysis. The current analysis was based upon profit maximizing criteria, but many people argue that farmers respond not only to expected profits, but also the riskiness of obtaining particular profit levels. (4) Alternative irrigation technologies should be included to analyze their impact on water conservation, farm profit, crop output and other factors. Part of this analysis may be simply incorporated into the profit computations of the current research by altering the effective price of water. Further analysis may require programming models of various sorts to account for lumpy investments and the time dimension of investments.

(5) Finally, more basic agronomic research on crop response to low levels of water and alternative levels at difference plant growth stages needs to be conducted. For years agronomic research has focused on measuring the amount of water lost through evapotranspiration when water is applied to avoid plant stress. This extensive research has resulted in recommendations for irrigation which avoid plant stress and thereby maximize plant yield. As demonstrated in the current research, profits can often be maximized and water conserved by applying a lessor amount of water.

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