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Estimation of Derived Demand for Surface Water on Two Rice Irrigation Districts in the Lower Colorado River Basin, Texas

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Chapter 1
Summary of Results

Introduction

Property rights in surface water ensure that water is adequately distributed throughout a river basin. In addition, the assignment of private property rights to common property resources can lead to economic benefits by reducing investment risks. However, when water supplies become limiting and water is inefficiently allocated among users there are suboptimal economic returns. Agricultural interests have had and continue to have preferential access to water supplies. In the process of promoting agricultural development by the assignment of water rights, the state has failed to ensure that agricultural interests develop water-saving technologies in response to water shortages. As a result, the economic returns from limited supplies of water have not reached their potential.

This paper analyzes the allocation of water within the Lower Colorado River Basin and measures the economic impact of water rights. This is accomplished by estimating the derived demand for water on two rice irrigation districts that account for most water diversions. The demand for water and the value of water in its assigned use are determined through farm budget analysis and linear programming methods common in agricultural economics. The benefits of agricultural water use are then assessed against the cost of obtaining alternative supplies of water within the river basin. Results show an economic cost associated with the allocation of water.

The approach used to evaluate the allocation of water is to measure the benefits of water used on the irrigation districts against what less-senior owners of water rights are willing to pay for water. The reallocation of water for storage in the Highland Lakes is not considered itself to be a productive use of run-of-river water that is not diverted by the irrigation districts. The economic rationale for reduced downstream consumption of Highland Lakes water is that if water is reallocated from the irrigation districts, and reduces the cost of stored water for less-senior water rights holders, the benefits to the basin could exceed the costs. Although there may be various environmental benefits associated with reducing water diversions on the irrigation districts, the assumption is that these are satisfied by existing institutional constraints.

If water is not a limiting resource, there is no need to allocate it among users and there are no costs or subsidies associated with its use. Once water is allocated by water rights, and market transfers of water that would occur in a competitive market do not occur, the allocation of water becomes inefficient. Market efficiency is defined as the condition in which water is freely traded among parties so that the productive output of water is maximized. Inefficiencies arise when water rights and state regulations obstruct price signals between buyers and sellers that indicate water might be more productive in another use.

This paper considers whether economic principles could support a transfer of water, and not how a transfer should take place. In the absence of market mechanisms, an efficient transfer of resources is still possible. Efficient transfers meet the conditions of Pareto efficiency. That is, a trade occurs such that one party is better off, and the other party is at least no worse off. In the case that a transfer of resources represents a tradeoff between the well being of two parties, there is yet another indicator of whether or not that transfer is efficient. The Kaldor-Hicks standard of efficiency assesses whether or not those who gain from the transfer **could** compensate those who lose from the transfer.

Diversions of water for irrigation account for the vast majority of consumptive water diversions from the lower Colorado River (Table 1.1). Agricultural water diversions, in particular those for rice irrigation, dominate all other uses. Although agriculture is an important part of the regional economy, the allocation of a substantial portion of the regional water resources to agriculture has a significant burden on the economy as whole. This allocation of water increases the cost of water to other users. Others who seek to divert run-of-river water under their own water rights, but cannot do so, must purchase relatively expensive stored water supplies from the Highland Lakes. An economic argument to reallocate run-of-river water to other uses can be made if the value of water in irrigation is less than the value of water in alternative uses.

Table 1.1
Water Consumption, Lower Colorado River, Texas, 1980 - 1989
(Acre-Feet)

Year	Municipal	Industrial	Mining	Irrigation	Total
1980	90,005	38,844	2,242	605,075	736,166
1981	84,935	24,070	2,123	573,732	684,860
1982	97,243	26,524	2,082	607,873	733,722
1983	91,874	49,710	1,571	410,779	553,934
1984	114,106	41,600	1,893	580,497	738,096
1985	116,248	82,381	2,035	447,677	648,348
1986	118,497	38,419	1,795	441,265	599,984
1987	114,101	26,362	1,576	432,590	574,637
1988	122,300	89,293	3,800	568,971	784,372
1989	138,527	105,816	2,519	488,415	735,277

Source: Texas Water Commission (TWC). 1993. "Reported Surface Water Use For Colorado River Basin, All Rights and Claims," Austin, Texas. (Computer Printout.)

Note: Does not include non-consumptive diversions for recreational uses, industrial uses, or hydro-electric power generation. Irrigation water uses include agricultural and non-agricultural water diversions.

Chapter 2 presents a normative framework for evaluating the allocation of water in a river basin. The results of this project are interpreted in terms of the economic efficiency criteria established in that section of the paper. Economic efficiency is not and should not be the only basis for evaluating the allocation of water. Social or non-economic policy goals may indicate that an uneconomical allocation of water is a legitimate or a preferred outcome. Chapter 2 also discusses the use of crop production functions and farm budget analysis to estimate the marginal benefit of water in crop production. In competitive markets, resources are allocated according to the value of their marginal product.

It is not possible to determine the demand for water directly because no competitive market for water exists. Derived demand is a method of estimating the value of water based on the demand for farm outputs. One complication with this approach is that there is an artificial demand for farm output. The market for rice is subsidized through Agricultural Stabilization and Conservation Service (ASCS) farm programs. Therefore, the demand for farm outputs is not an entirely accurate measure of the value of farm outputs.

Chapter 3 systematizes information about the irrigation districts so that farm budget methods and linear programming may be applied to estimate the value of water. Chapter 4 assesses the potential for water conservation in rice irrigation. This is an application of data envelopment analysis to data collected at sample farms during the Texas A&M University's Less Water-More Rice research project. Chapter 5 follows with a description of the linear program and a discussion of model assumptions. Model results are presented and interpreted in Chapter 6.

Research Results

Research results include:

- a model for predicting district rice acreage in the upcoming season based on ASCS program parameters;
- a model for estimating reductions in per-acre on-farm water use in response to LCRA's introduction of volumetric pricing;
- an estimate of the crop-water production frontier;
- derived demand functions for irrigation water.

Predicting district rice acreage in the upcoming season based on ASCS program parameters:

Chapter 3 presents a regression model for forecasting each districts' rice acreage in the upcoming season using information about ASCS program parameters. The model predicts rice acreage on the basis of historical acreage levels, maximum planting rates, and advance deficiency payment rates. ASCS program parameters for an upcoming crop season are made public in January. Rice acreage and crop prices affect estimates of the value of water. Using these acreage estimates in the linear programmming model incorporates these factors into derived demand estimates and makes the model more suitable as a planning tool.

Formerly, LCRA required information on farmers planting intentions to forecast rice acreage. This information is not available until just before planting begins in March. This regression model lengthens LCRA's planning horizon by approximately three months because estimates are available beginning in January.

Estimating reductions in per-acre on-farm water use in response to volumetric pricing:

Chapter 3 also discusses a model for estimating decreases in on-farm water use that resulted from LCRA's introduction of volumetric water pricing in the 1993 crop season. Results are interpreted in terms of on-farm water savings during the first crop period in Chapter 3 and short-run elasticity estimates in Chapter 6.

Estimating the crop-water-production frontier:

Chapter 4 applies data envelopment analysis to estimate the production frontier for irrigation water as an input in the production process. Data envelopment analysis (DEA) is a non-parametric method of estimating a technically efficient level of input use. Model results could be used to establish field-specific irrigation water standards, and to estimate the potential water savings associated with on-farm water conservation programs. These results suggest more analysis is needed to develop a uniform irrigation standard.

DEA results reveal a significant water savings potential associated with on-farm water conservation that are distinct from efforts such as canal improvement and volumetric pricing. On-farm water conservation programs emphasize the introduction of water-saving technologies in rice farming. The potential water savings associated with an on-farm water conservation program during the first crop period on Lakeside District is 24 percent of 1993 irrigation inflows during that period. Similarly, the potential water savings is 51 percent of 1993 first crop irrigation inflows on Gulf Coast District.

Estimating and using derived demand functions for irrigation water:

Chapter 5 presents the linear program and discusses model assumptions. Chapter 6 presents and interprets derived demand functions based on linear program and farm budget analysis results. Derived demand functions may be interpreted to estimate the:

- collective value of water delivered to the farm gate;
- short-run average value of water delivered to the farm gate;
- short-run average value of land during the crop season;
- marginal value of successive units of water on the districts;
- value of the subsidy to farmers associated with LCRA's irrigation district water right;
- cost to others associated LCRA's irrigation district water right;
- equilibrium price for water under an average cost per acre-foot pricing strategy;
- decrease in rice acreage resulting from implementation of an average cost pricing strategy.

Linear program results should be interpreted with a knowledge of the limits of the linear programming model. In general, the linear programming method requires a rigid specification of conditions on the irrigation districts and the results will be sensitive to year-to-year changes in these conditions. For example, changes in crop price and farm acreage will affect estimates. On the other hand, this model is easily updated to reflect changing conditions. This report presents a detailed review these assumptions.

The collective value of water delivered to the farm gate:

The total value represents that portion of profit on the irrigation districts specifically associated with farmer's access to irrigation water. It is a collective value of water based on agricultural markets, alternative crops, farming costs, on-farm water use and water prices during the 1993 crop season. On Lakeside Irrigation District, the collective value of on-farm water deliveries to 26,221 acres at an effective price of $11.11 is approximately $4.133 million. On Gulf Coast Irrigation District, the value of on-farm water deliveries to 25,371 acres at an effective price of $6.55 is $4.198 million. For reasons discussed later in this report, these are modelled acreage values, not actual acreage values. Total values will be sensitive to the acreage assumptions used in the linear program. As rice acreage and water deliveries increase, so will the total value of water.

The value of water will decrease as the price of water increases. The effective price used in making these estimates represents the expected price of one acre-foot of water on the district plus the expected cost of stored water. The districts also charge farmers on a per-acre basis. To account for this cost, payments made by farmers to the LCRA have been subtracted from estimates of the total value.

The short-run average value of water delivered to the farm gate

When the collective value of water is averaged over the volume of water delivered to farmers, the result is an average value per acre-foot. Individual farmers might place more or less value on the water they use depending upon their range of crop alternatives and their farming practices. Unlike collective values described above, average values are not sensitive to acreage assumptions.

Estimates of the average value of water are short-run values. They represent the value of water during the 1993 crop season only. Short-run estimates are based on variable costs of farming. Long-run values are a function of the farmer's perception about the market for irrigated crops in the future, and both the capital cost and the variable cost of farming. Economic theory suggests that long-run values are generally lower than short-run values. Estimates represent the value of water, not the value of water rights. The rationale for this approach is those who use the water rights on these districts do not own them and therefore have no right to sell them.

The short-run average value of one-acre foot of water represents the price that the average farmer would be willing to sell his right to *use* one acre-foot of water if that farmer stopped raising irrigated crops, switched to dryland farming where possible, and sold *all* of his water. Table 1.2 presents estimates of the short-run average value of water. The average value of water over the full crop season (first and second crop periods combined) is $37.95 on Lakeside District and $32.80 on Gulf Coast District.

In general, the value of water will be higher during the first crop period than the second crop period because yields are higher. In 1993 the short-run value of one acre-foot of water delivered to fields on Lakeside District was $61.44 during the first crop period, and $7.41 during the second crop period. On Gulf Cost District, the average values are $41.47 and $13.15 for first and second crop periods respectively.

The short-run average value of land during the crop season:

It has been suggested that transfer payments might be used to reduce rice acreage by paying farmers to farm non-irrigated crops. Table 1.2 presents estimates of the value of one irrigated acre used in rice production. This may be interpreted as the expected cost of paying the average farmer to raise a non-irrigated crop during the 1993 crop season. For example, on Lakeside District, the average value of one irrigated acre is $144.26. The average value of one second crop acre is $13.38. The total cost of such a program, $1.22 million, can be estimated by multiplying first crop acreage by the value of second crop acreage.

The marginal value of successive units of water on the districts:

This paper also estimates the marginal value of successive units of water on the irrigation districts. Marginal values are more useful in allocating water between users, but are of little use without comparable information on the marginal value of water in alternative uses. No estimates are presented for instream values because reliable estimates of canal losses are unavailable. Because canal losses are part of the cost of transferring water from the river to the farm gate, instream values would be lower.

The value of the subsidy to farmers associated with LCRA's irrigation district water right:

Estimates of the value of water developed in this paper suggest that the current allocation of water in the Lower Colorado River Basin is inefficient. Model results show that the volume of water inefficiently allocated is 49,929 acre-feet on Lakeside District and 42,122 acre-feet on Gulf Coast District. This inefficiency may be characterized as a cost to those who must purchase alternative supplies of water in the Highland Lakes, or as a benefit to those who have access to the water. The approach used in this paper is to characterize the inefficiency as a benefit.

The benefit is an indirect subsidy. It arises from farmers' access to water that would not be available if water were allocated on the basis of economic efficiency criteria. The indirect subsidy to farmers on Lakeside District is approximately $395,249. The indirect subsidy to farmers on Gulf Coast District is approximately $561,895. Results of the model in Chapter 6 indicate that the value of the indirect subsidy to farmers and the cost associated with the current allocation of water rights are a function of second crop acreage. One assumption implicit in these estimates is that other users that currently purchase water from the Highland Lakes would use all of the water the districts did not divert.

The cost to others associated LCRA's irrigation district water right:

Although the benefit farmers receive is small, the cost to others who must obtain alternative supplies of water may be much larger. The cost to others can be estimated as farmers' cost of replacing the volume of water that is inefficiently allocated with stored water from the Highland Lakes. Farmers could not afford to do this, but if they did, the cost on Lakeside District would be $2,521,380 and the cost on Gulf Coast District would be $2,127,208. Thus, the total cost associated with LCRA's ownership of water rights on the irrigation districts in 1993 was approximately $4.65 million.

The equilibrium price for water under an average cost per acre-foot pricing strategy:
Estimates of the value of water are followed by a review of the potential for average cost pricing. Average cost pricing is the practice of pricing water so that LCRA's cost of operating and maintaining the irrigation districts is fully recovered. Until 1993, LCRA averaged its cost over acreage and charged farmers only for the number of acres irrigated, not the volume of water used. Under that system there was no cost associated with water and no incentive for farmers to reduce water use.

Economic theory suggests that if the marginal cost of water is high, farmers will use less water. This concept is reflected in the price elasticity of water demand, the percent change in on-farm water use relative to a percent change in price. Implementation of an average cost per acre-foot price requires an understanding of how much less water farmers would use as the price increases. If not, there is a risk LCRA would not recover its cost of supplying water. This report evaluates the elasticity estimates implicit in the linear programming model. Assumptions used in developing the model may have resulted in artificially low elasticity estimates. Relaxing these assumptions provides a maximum elasticity value. Chapter 6 provides details of this aspect of the study.

Table 1.2
Short-Run Average Value of Water on LCRA Irrigation Districts in 1993

Description		**Lakeside District**	**Gulf Coast District**
Average Value of Water:			
(Value per acre-foot)	Full Crop*	$37.95	$32.80
	First Crop	61.44	41.47
	Second Crop	7.41	13.15
Average Value of Irrigated Land:			
(Value per-acre)	First Crop	$144.26	$145.16
	Second Crop	13.38	33.85

Source: Calculated by the author based on data generated by the linear program using XA Software.

Note: Values based on 1993 agricultural markets, farming costs, and on-farm water use. (*) The average value during the full crop period is the average value of water in the first and second crop periods combined.

The decrease in rice acreage resulting from implementation of an average cost pricing strategy:
Linear programming results show that average cost pricing would not substantially reduce first crop acreage, and would have only a small effect on first crop water diversions. Under an average cost pricing system, the price of one acre-foot of water on Lakeside District would be approximately $36.42. First crop acreage would decrease 220 acres and all second crop acreage would go out of production. Similarly, on Gulf Coast District the price of one acre-foot would be approximately $26.05. First crop acreage would decrease 1,848 acres and all second crop acreage would go out of production.

How These Results May be Used by Affected Agencies

Results contained in this report have many applications for the planning and management of water resources. Some of these have already been discussed. Results may be directly applied within the Lower Colorado River Basin to:

- evaluate water conservation benefits;
- evaluate water conservation program alternatives;
- establish water conservation targets;
- evaluate costs and benefits of water rights;
- evaluate economic impacts of alternative drought management policies;
- establish volumetric water prices in accordance with state law.

This report demonstrates how results can be obtained using derived demand functions developed in this paper. Any agency interested in pursuing an evaluation of water conservation benefits on the LCRA districts may adapt the models accordingly. Cost and benefit estimates will be specific to 1993 unless the model is updated. However, exact estimates may not be as important as the magnitude and sign of model results. For example, the exact estimate of costs associated with LCRA irrigation district water rights within the basin will vary from year to year, but the magnitude of costs will not likely change much. This demonstration of cost should be sufficient to evaluate policy options unless specific decisions require more exact estimates.

Throughout this paper, there are discussions of the potential water savings associated with price increases and on-farm water conservation. On-farm water savings might occur when farmers voluntarily adjust technology and input ratios in response to volumetric pricing. Extension efforts can also educate farmers and encourage them to adopt water-saving technologies. Regulations can produce water savings by either prohibiting certain practices or requiring farmers to adopt specific technologies as a condition of service. This report reveals substantial on-farm water savings that are yet un-tapped on the LCRA districts.

Water conservation estimates are not additive. For example, it would not be reasonable to implement an on-farm water conservation program and increase the variable price of water with the goal of achieving the maximum potential savings associated with each of these programs individually. Finally, all estimates are made under the assumption that there is no change in the conditions on which the model is based. Despite this sensitivity of results, these models provide insights into irrigation district water rights and tangible lessons for regional water policy that are not available elsewhere.

This report develops a methodology for addressing each of these tasks and demonstrates how conclusions can be drawn from the linear programming models. The report also demonstrates how management and policy alternatives may be evaluated using this information. The methods can be applied in other areas of the state as well, but adjustments may be needed to accomodate differences in the availability of data and local conditions. The emphasis this report places on clarification and validation of model assumptions should be useful to any agency interested in applying linear programming and farm budget analysis to specific problems.

Chapter 2
Methods Estimating the Value of Water

Economic theory provides a window through which to view and understand issues associated with the allocation of water in a river basin. The assignment of water rights has caused an inefficient distribution of water among users and a net economic cost in the river basin. The cost is increasing as the demand for water increases due to population pressures and economic growth. The purpose of this chapter is to present a normative theoretical framework for interpreting the effect of LCRA irrigation district water rights on the economy in the Lower Colorado River Basin, and to present analytical methods for evaluating that effect. This analysis also provides a tool for estimating the subsidy associated with the allocation of water rights and for determining an appropriate price for water on the LCRA irrigation districts.

Water has been the subject of much theoretical and applied research because its availability can make or break a regional economy. Economic theory of perfectly competitive markets suggests the most efficient allocation of water occurs when those willing to pay the most have access to water. If economic efficiency is a goal, knowledge of water's value indicates how to distribute access to limited water supplies. For example, this information could be used to determine the optimum placement of water development projects. Knowledge of the value of water also provides information on how much to charge those who use the water, and whether or not water development projects are cost effective.

The Value of Water in Competitive Markets

Consumptive uses of water are often allocated according to the category of use. Typical categories include municipal, commercial, industrial, agricultural, and environmental uses. With the exception of environmental uses, the value of water is equal to the consumer's willingness to pay. In municipal uses, water is an end product from which consumers derive direct utility. The value of a unit of water in municipal uses is equal to the utility consumers derive from the use of that unit of water. In commercial, industrial and agricultural uses, water is a factor in the production process. The value of a unit of water is equal to the marginal contribution of that unit of water in production. The value of water in environmental uses is more difficult to evaluate, although several methods exist (Gibbons, 1986). For the purposes of this paper, water allocated to environmental uses is considered unavailable. This is consistent with previous studies which focus only on the portion of water which regulations allow to be allocated among users (Yaron, 1967; Gisser, 1970).

If water is a commodity, the value of water is equal to the consumers willingness to pay, and each consumer is willing to pay more for the first unit of water than for additional units. This pattern of diminishing marginal value of water exists in all categories of water use. A marginal value product curve describes the change in consumers willingness to pay for water. Figure 2.1 provides an example of what hypothetical marginal value product curves might look like in a typical river basin. Any point along the line of the curve represents the maximum amount that any user in that category would be willing to pay for that water. Figure 2.1 also displays an aggregate marginal value product curve. This is the horizontal sum of all three category-specific curves. For example, if the marginal value of water is MV2, and if Q2 units of water are available, municipal users will value Q1 units of water more highly than industrial users. Industrial users will value Q2 - Q1 units of water more highly than the remaining municipal users. Therefore, municipal users will get Q1 units of water, and industrial users will get Q2 - Q1 units of water. Agricultural users do not value water at a level above MV3, and therefore receive no water. In a competitive market, these curves relate directly to the value of any one unit of water.

Figure 2.1 describes how water might be allocated in a competitive market. Other investigators have documented that municipal users place the highest value on the first few units of water (Gibbons, 1986). One reason may be that water is a life requisite, no other activities are possible without it. Agricultural users of water place the lowest value on their first few units of water. The reason is that the economic returns from water are lower in agriculture than in commercial and industrial uses (Kelso *et al.*, 1973). Figure 2.2 displays the aggregate demand curve for water in the same hypothetical river basin. P1, P2, and P3 are possible prices of water. Given a price of P1, industrial and agricultural users would not purchase water because the marginal value product of water in those uses is less than its value in domestic use. Similarly, at price P2, some industrial and most agricultural users would still not purchase water. At price P3, most possible uses are satisfied.

In a perfect market, the equilibrium price is a function of the availability of water and the cost of supplying that water to users. Price will equal the marginal value product of the last unit of water used in each category. The value of water is given by the area above the price line and below the demand curve.

Figure 2.2 shows that if water price in a competitive market is equal to P2, then the value of Q2 - Q1 units of water is equal to the shaded area beneath the demand curve and above the price line. Another perspective can reveal the value of water in a particular use. If water price is P3, and the maximum volume of water available to all users of water is Q3, then the value of water in agricultural uses is equal to the crosshatched area beneath the demand curve and above the price line.

If the price of water rises due to competition among users during a water shortage, marginal users would be the first to loose access to water. In their study of the economic impact of water shortage in Arizona, Kelso *et al.* (1973) found that marginal users in the agricultural category were most critical because, in relation to other users, the volume of water they use is large and the marginal productivity of water is low. In many cases, it is possible to focus an analysis of regional water demand exclusively on this marginal user group because a reallocation of water among users will occur in this portion of the demand curve.

A normative demand function reveals problems associated with the allocation and management of surface water in practice. Price serves as a mechanism for allocating resources to their highest valued use. When surface water is allocated among end users through non-market mechanisms, the allocation is potentially inefficient. When water rights specify the use, the point of diversion, the location of use, and the priority of right, they create a barrier through which price signals cannot travel. As long as sufficient quantities of water are available to satisfy all water rights, no inefficiency exists.

There is a cost associated with any inefficient allocation of water. This may be characterized as either a subsidy to those who use the water in ways that are less productive than the market value of the water, or a cost to others who would have used the water but were deprived of that use. The value of a subsidy is equal to the difference between the price of water in a perfect market, and the productivity of that unit of water. The cost is equal to the difference between the water price and either the potential productivity of a unit of water, or the cost of obtaining alternative supplies of water.

There can be only one efficient price for a certain quantity of water. This price is equal to the marginal value of the last available unit of that water in any category of use. If some users are granted access to water at an artificially low price, they receive an indirect subsidy. Figure 2.3 shows how to evaluate this subsidy. The demand function for water in agriculture has a positive slope rather than a negative slope. This is accomplished by expressing the quantity of run-of-river water available to group 2 as a function of the quantity of water available in the river basin that is not allocated to group 1. Suppose the maximum quantity of run-of-river water available to those that own water rights is Qmax. If all run-of-river water is available, Qmax = (Q1 + Q2), and Q2 = (Qmax - Q1). The variables Q1 and Q2 represent the volume of water allocated to group 1 and group 2 respectively.

Maximum willingness to pay is a function of the quantity of water available. Suppose that group 1 consists of municipal, commercial, and industrial users of water. Their maximum willingness to pay is P = f(Qmax - Q2) = f(Q1). Group 2 consists of agricultural interests. Their maximum willingness to pay is P = f(Qmax - Q1) = f(Q2). At the price P*, water will be allocated so that group 1 receives Q* units of water and group 2 receives (Qmax - Q*) units of water. P* is the efficient price at which the two groups' maximum willingness to pay is equal. The maximum price each group is willing to pay is a function of both the amount of water available and competing demands.

The price P* is the market clearing price for water. At this price, all water in the river basin is allocated to its most highly valued use. However, if agricultural interests have preferential access to water at some below market price, there will be an inefficient allocation of water. The degree of inefficiency will be a function of the marginal cost of diverting that water for irrigation, Pa. Agricultural interests will demand (Qmax - Q1) units of water, and their maximum willingness to pay, Pa, will equal the cost of diverting water. The result is a net loss to the economy in the river basin, and an indirect subsidy to agricultural interests.

The economic cost is given by the shaded area D that is associated with the lost productivity of water. The indirect subsidy to agriculture is given by the sum of the shaded areas A and B. The shaded area A is associated with the benefit of access to an additional (Q* - Q1) units of water that would have been allocated to others in a competitive water market. The shaded area B is the benefit to farmers associated with paying less than the competitive market price for water that would have been used for agricultural purposes anyway.

Inefficiencies can still occur if both groups of users pay only their individual costs of diverting water. For example, if group 2 has a senior water right that allows it to divert water first, and the cost of diverting water is Pa, then the group will divert (Qmax - Q1) units of water. Water users in group 1 will use the remaining Q1 units of water and the preceding evaluation of inefficiencies is still valid. If group 1 has access to stored water supplies at a price above P*, it can be shown that stored water supplies mitigate the inefficiency represented by area D that is associated with group 2's preferential access to water. However, if the cost of the stored water is above the market clearing price P*, there will still be a net loss to the economy in the river basin.

Figure 2.4 displays the demand curve for on-farm irrigation water on a hypothetical irrigation district where farmers have no individual water rights. Suppose this public irrigation district possesses a senior water right within a river basin where river flows are limiting. Also suppose that this irrigation district determines its price on a cost of service basis. P3 is the unit price of water, and Q3 is the quantity of water farmers currently use. P2 represents the highest price farmers would be willing to pay for an additional unit of water at Q2. It is the price they would be willing to pay if they adopted irrigation technologies that increased the value of water in response to local water shortages. For example, if water were distributed among farmers on the irrigation district on the basis of their willingness to pay, rather than the cost of service, farmers would adopt technologies and find substitutes in response to the localized scarcity of water. The point P1 is the highest price that municipal and industrial water consumers would be willing to pay the irrigation district not to divert water under its water rights, therefore making Q1 units of water available for themselves.

When the allocation of water encourages technological inefficiency, the subsidy to irrigators can be divided into two parts. Shaded areas in the Cartesian plane reflect key values of subsidies associated with irrigation district water rights. The sum of shaded area represents the total indirect subsidy to farmers as a result of the current system of water rights and district pricing strategies. The gray shaded portion of the subsidy is due specifically to district ownership of water rights. The crosshatched portion of the subsidy is due specifically to a price for water which is less than the maximum willingness to pay if the quantity of water available were restricted to Q2. As water becomes increasingly scarce this area increases and the total value of the subsidy increases. Similarly, if the price of water on the irrigation district decreases, the area within the crosshatched portion of the subsidy increases; therefore, the value of the subsidy to farmers increases.

Economic Inefficiencies Related to Water Markets in Practice

In practice, the State of Texas does not allocate water rights and water development projects on the basis of economic criteria. With certain exceptions, the state allocates water administratively on a first-come, first-serve basis. To understand how this allocation can be economically inefficient, it is first necessary to understand how the state manages its water resources.

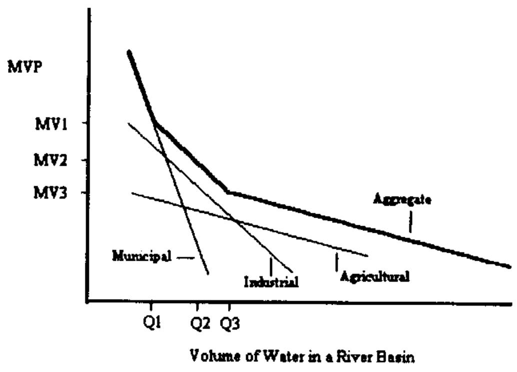
In Texas, water is a commodity. Water rights and water itself may be bought and sold. Water rights allow an owner to divert surface water from a stream, subject to limitations on the volume, the rate of diversion, the purpose, and the location of use. For that individual, the cost of a unit of water is the cost of delivering it to the point of use. Those who do not own water rights must purchase their water from those who own water rights. For these individuals, the cost of a unit of water is the rental rate of that portion of the water right, plus the cost of delivering it to the point of use. In Texas, the Texas Natural Resource Conservation Commission (TNRCC) administers water rights, and monitors the transfer of water rights between individuals. Because the transfer of water rights can have negative impacts on other water rights owners, the TNRCC must approve all market transfers (Griffin and Boadu, 1992).

Access to water under a water right is restricted by the prior appropriation doctrine. This doctrine states that owners of water rights may divert water only if the needs all other water rights owners with a more senior (earlier) priority date have been satisfied. The priority date is the date on which the state granted those water rights. When water is scarce, those users who would apply water to more highly valued uses might be required to defer to those applying water to less valued uses, if the latter user has an earlier priority date.

As a rule of thumb, the State of Texas grants water rights when the flow of water at the point of diversion is sufficient to supply the applicant with at least 75 percent of the volume he requests at least 75 percent of the time (Evans, Interview, January 20, 1994). It follows that if the state has allocated all of the water rights within a river basin, 25 percent of those who own water rights will not have access to water 25 percent of the time. During drought periods, when river flows are lower than normal, those with less-senior water rights will have even less access to surface water. Storage facilities can help alleviate this problem by making water available when it is needed. However, water rights do not typically extend to stored water supplies, and water rights owners must purchase stored water just like those users without water rights.

It is important to distinguish between water rights and water itself. A water right is a capital good that guarantees access to water when it is available. Because in theory a water right is valid in perpetuity, it may be valued in either the short or the long run. When the use of water diverted under those rights is specified, it is possible to calculate and compare the long-run value of water rights in a river basin. However, water rights are not a substitute for water in municipal, industrial, or agricultural uses. When the value of water in environmental uses is excluded from the analysis, water that is not diverted from the stream has no value. Unless a unit of water is stored for future use, its value is a short-run value because any unit of water is only available temporarily as it flows downstream.

Figure 2.1
Hypothetical Marginal Value Product Curves in a Typical River Basin



Note: MVP is the marginal value product of water.

Figure 2.2
Hypothetical Demand Curve for Water in a Typical River Basin

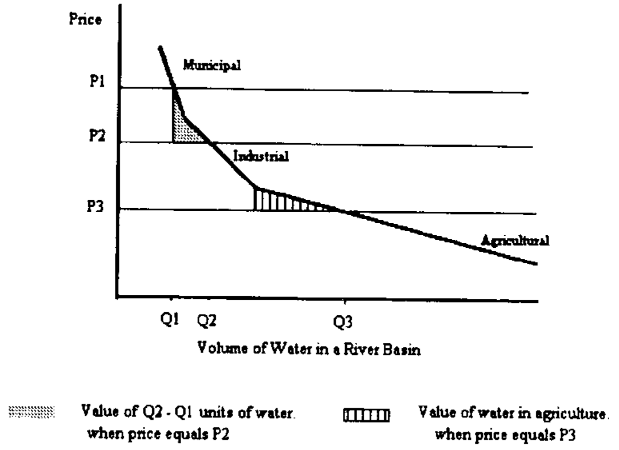


Figure 2.3
Value of a Subsidy in an Efficient Water Market

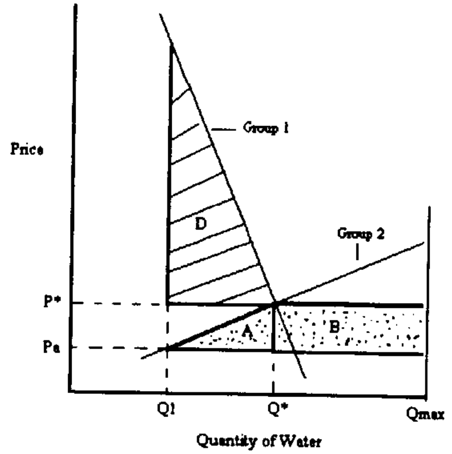
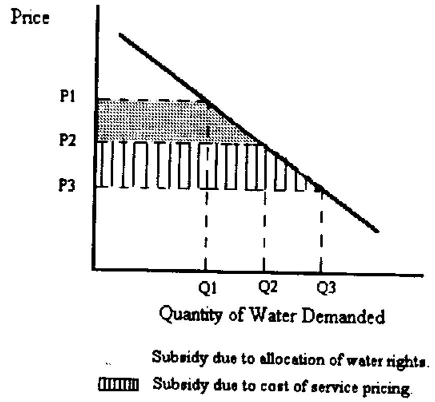


Figure 2.4
Hypothetical Demand Curve for Water on a Public Irrigation District



Methods of Estimating the Value of Water

Gibbons (1986) provides a good summary of techniques for determining the value of water and water demand in municipal, industrial, agricultural, and environmental settings. This discussion will focus on methods of determining the value of water in agricultural uses, and deriving water demand functions from non-market sources.

There are two methods of deriving the demand for irrigation water from non-market sources. Crop-water production functions measure the contribution of water to agricultural production. Farm budget analysis measures the farmers willingness to pay for water. Table 2.1 provides a brief outline of the advantages and disadvantages of each method. Estimates of the value of water may be either average or marginal values, and may be estimated in the short-run or the long-run. In general, those studies which resort to the use of the average value of water do so in response to a lack of information. Marginal values provide more information on how best to allocate water among users. The decision whether or not to calculate short- or long-run values of water is slightly more complex. In the context of a farmer's irrigation and planting decision, short-run values provide a more meaningful measure of the value of water in any one crop year. When making long-term decisions about how to allocate water rights among municipal, industrial, and agricultural uses in the future, or where to construct reservoirs and pipelines, long-run values are more meaningful.

Demand curves appear to provide a simple mechanism for determining the quantity of water farmers in an irrigation area would use at any particular water price. In planning water projects, public agencies and private suppliers of irrigation water can ensure that water sales will cover project costs. Private water suppliers can adjust their prices to maximize profits and state agencies charged with funding irrigation projects can allocate their funds more efficiently if they know the relationship between inter-regional water values.

Several caveats accompany the conceptual simplicity of these models. There is rarely good information on how consumers respond to different water prices because competitive markets for water are uncommon. In the context of agricultural production, water is an intermediate good. As such, its value may only be derived in terms of its marginal value product which is a function of the crop price (Young and Gray, 1982, p.1820). Whether or not the estimated value of water is derived through a crop production function or through farm budget analysis, the value of water and the elasticity of demand will change in response to changing crop prices.

Farmers subjective estimates of what crop prices will be in the future will usually differ from those specified in the model. In addition, farmers will differ in their decisions about what proportion of inputs to use in production, and each farmer will achieve different levels of production. These factors will result in deviations from the projected demand in any one crop season (Flinn, 1969, p.140). Projections of the demand for water are also susceptible to changes in technology, environmental conditions, and institutional factors. These changes will result in year to year deviations from the projected demand.

Within a given season, the demand for irrigation water may be nearly inelastic because farmers have already made their planting decisions. In the face of increasing water prices, farmers will be reluctant to make large adjustments in irrigation intensity or abandon their crops. Therefore, demand models based on crop production functions or farm budgets may be more useful in predicting the effect of changes in the price of water on short-run planting decisions, or on changes in the year-to-year demand for water.

Table 2.1
Methods of Estimating Derived Demand: Advantages and Disadvantages

Model	Advantage	Disadvantage
Production Functions		
Quadratic specification	Models the relationship between water input and yield as determined in experimental fields.	Requires experimental or field data on water inputs and crop yields. Regression line underestimates the production frontier. Underestimates the elasticity of water demand when crop alternatives are present.
Product method	Models the relationship between water input and yield as determined in experimental fields. Incorporates additional information on the sensitivity of yields to the timing of irrigation.	Requires experimental or field data on water inputs and crop yields. Underestimates the elasticity of water demand when crop alternatives are present.
Cobb-Douglas specification	Gives the partial elasticity of output with respect to farm inputs directly and allows calculation of the returns to scale. May be applied to data on either physical farm inputs or on farm production costs. May be applied to individual fields, individual farms, or to farming regions.	Form is inconsistent with the negative marginal product of water observed at high irrigation intensities in experimental settings. Underestimates the elasticity of water demand when crop alternatives are present. Regression line underestimates the production frontier.
Farm Budget Analysis		
Static budget valuation	Computationally simple method of estimating the average value of water.	The crop water requirement is fixed in the farm budget. Provides only a static average value.
Linear programming	Provides a means of estimating either average or marginal values of water. Crop water requirements and water prices need not be fixed in the budget. Incorporates information about crop alternatives, risk, and farmer's reactions to changing farm input or output prices.	Requires detailed knowledge about the irrigation area. Provides marginal values of water on individual farms, but not by crop type if there is more than one irrigated crop on the farm.

There are several examples of attempts to estimate the long-run value of water using derived demand curves (Gisser, 1970; Shumway, 1973; Kulshreshtha and Tewari, 1991). However, there is not much conceptual support for concluding that a static derived demand curve based on a rigid input-output model can adequately capture future changes in technology, input prices, crop prices, environmental conditions, or institutional factors. The fact that many farmers actually make their planting decisions on the basis of anticipated crop prices provides an additional argument for interpreting these models on a short-run basis.

The most reliable interpretation is in the short-run, during which all conditions are relatively predictable. However, even in the short-run, derived demand models may not be useful in predicting farmers immediate reactions to abrupt changes in the price of water or abrupt changes in crop price. In any one year, farmers subjective estimates and farming decisions may be different from those specified in the model. In recognition of this problem, Moore and Hedges (1963, p.131) conclude that, over a longer time span, farmers will adjust to what they should do according to a short-run model as long as the model parameters remain constant. Lacewell and Condra (1976, p.16) came to the same conclusion in their work on the Texas High Plains.

Estimates of the demand for water are location specific. Environmental conditions vary between sites and farmers have different crop alternatives. As a result, farmers' planting decisions and crop production levels will vary, even within a small geographic boundary. Choosing the size of the area under analysis is perhaps more important when using farm budget methods than crop production functions. In general, farm budget methods include assumptions about a larger number of variables, and attempt to model the behavior of farmers on individual farms. Crop production functions only reflect the biological demand for water in relation to crop productivity.

Crop Water Production Functions

Both marginal and average values of water may be measured in terms of water's contribution to crop production. Because these functions are not related to the economics of production, but to the physical demands of the plant, they may not be defined in terms of the short- or the long-run (Gibbons, 1986, p.28). In dryland farming, plants depend on soil moisture and rainfall to meet their evapotranspiration requirements. When these two factors are limiting, the plant suffers from water stress which in turn reduces crop production. Irrigation can boosts production by satiating this demand. For many years, agricultural scientists assumed that each plant's water requirement was fixed (Flinn, 1969, p.128). But small amounts of water stress may have only a negligible impact on yields, and at near optimum levels of irrigation, the demand for water may be near perfectly elastic. As the supply of water decreases, the demand for water becomes increasingly inelastic.

Production functions can assist the farmer in achieving both economic efficiency and irrigation efficiency, but efficiency is a complex variable that consists of several economic and technical factors. Moreover, statistically derived production functions and most derived demand functions do not adequately account for these factors. Therefore, the results have limited usefulness in terms of improving the on-farm irrigation efficiency on either a technical or an economic basis.

When estimating the crop water production frontier from sample farms, the implicit assumption is that farmers *operate* on the production frontier, and that farmers are acting rationally (maximizing profits) with complete information. However, most farms are inefficient and therefore do not operate on the production frontier (McGuckin *et al.*, 1992). Figure 2.5 shows a production frontier and describes each of these inefficiencies. A farm is technically inefficient if the combination of inputs does not achieve the appropriate production level on the frontier.

In Figure 2.5, farm A is both technically inefficient and price inefficient. However, given a technical inefficiency constraint, farm A can still maximize its profits if it meets price efficiency criteria. The farmer must adjust his use of water so that the marginal product of water equals a ratio of water prices to other input prices. He must also produce at a marginal cost that is equal to the crop price. These conditions are referred to as allocative efficiency and scale efficiency respectively. In Figure 2.5, farm B is price efficient, but remains technically inefficient. Farm C is technically efficient because its yields are precisely on the production frontier, but it is economically inefficient. Farm D is both technically and economically efficient.

According to this analysis, the optimum use of water is not the volume of water that maximizes yield, but rather the volume of water that produces a marginal benefit equal to the marginal cost of supplying that water. For the purposes of modelling irrigation water demand, most researchers assume that farmers internalize this condition as a constraint in making their irrigation water management decisions.

Experimental evidence has been used to argue that, within a region, the slope of the crop-water production function is constant across experimental fields with different levels of soil fertility, and across years with different environmental conditions, including weather and pest infestation. Within a region, quadratic production functions will vary in their elevation on the y-axis (crop production), but not in the slope of the parameter estimates (Yaron, 1967). This stable parameter simplification allows farmers to optimize production if they know how much water is needed, and use the appropriate combination of farm inputs. Given an optimum volume of water, production across farms will still vary as a result of differences in the input mix.

Marginal values of successive units of water plotted against volume is a demand curve for water. However, deriving the demand function from the production function directly assumes that farmers have no crop alternatives. The existence of crop alternatives will increase the elasticity of demand within a region. If the existing crop mix is known, the appropriate production functions may be weighted and added to represent the on-farm demand for irrigation water for that growing season.

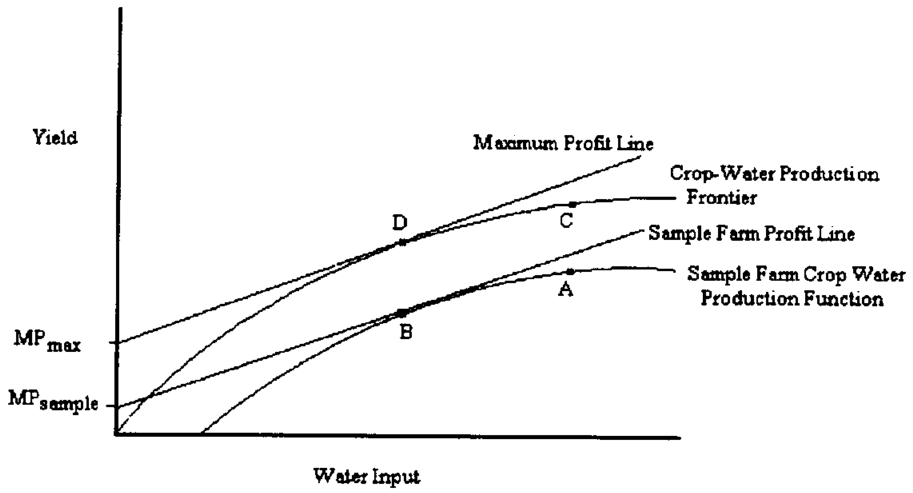
Equation 2.1 presents a simple crop water production function. The model states that yield (crop production per acre of land under cultivation) is a function of the amount of water the farmer applies to the field:

$$Y_k = \beta_0 + \beta_1 W_k + \beta_2 W_k^2 \qquad \textbf{(Eq. 2.1)}$$

Y	expected yield
W	crop water requirement
k	an index of crop type
β	parameters estimated by regression

In practice, the variable W represents either actual evapotranspiration divided by potential evapotranspiration or the total volume of water used in production. In many cases, these functions include other variables related to plant growth such as fertilization and weather. Those equations based solely on evaporation ignore the concept of irrigation efficiency and are therefore less useful in estimating water values (Gibbons, 1986).

Figure 2.5
The Relationship Between Economic and Technical Efficiency on Hypothetical Farms



A	Technically and economically inefficient
B	Technically inefficient
C	Economically inefficient
D	Technically and economically efficient

MPmax	Maximum marginal product
MPsample	Sample farm marginal product

Since the timing of water applications is often a critical factor in production, more sophisticated analyses incorporate information on both the time and volume of water applied relative to growth stages. Equation 2.2 presents a Jensen growth-stage production function in which a shortage of water in one period can have differential effects on production (Water Resources Management Incorporated, 1992). The model states that yield is a product of the ratio of actual evapotranspiration to potential evapotranspiration in defined growth stages.

$$\frac{Y}{Y_m} = \prod_{i=1}^{s} \left(\frac{W_i}{W_{m\,i}} \right)^{\lambda_i} \tag{Eq. 2.2}$$

Y	the total yield for all growth stages
Y_m	the maximum yield under full irrigation
W_i	water applied in growth stage i
W_m	the water requirement under full irrigation in growth stage i
i	an index of growth stage
s	the number of growth stages
λ_i	an empirical water-response sensitivity coefficient specific to growth stage i

One drawback to the quadratic and product methods is that both require data from experimental or field observations. These data are rarely available. Some researchers have resorted to estimates of the ratio of actual to potential evapotranspiration to explain the ratio of actual to potential yields. Kulshreshtha and Tewari (1991) used the sum of residual soil moisture and the volume of irrigation water applied to estimate actual evapotranspiration. However, the authors used these estimates to establish the optimum volume of water required by crops, not as a means of imputing the marginal value of water directly. Nevertheless, the use of non-experimental data to estimate yields using crop water production functions reduces both the validity and the reliability of these estimates.

The Cobb-Douglas production function is an alternative to quadratic and product methods. The independent variables in the Cobb-Douglas equation are some substitutable combination of farm inputs. From the economist's perspective, this is a more intuitively satisfying alternative because it recognizes that water does more than satisfy evapotranspiration requirements. Water can serve as a substitute for other farm inputs, and this may be more efficient if the cost of the water is less than the alternative input. The Cobb Douglas production function is particularly useful because it provides information on the partial elasticity of yield with respect to individual farm inputs.

Ruttan (1965) modelled the demand for irrigated acreage for agricultural regions in an attempt to project future irrigation water demands in regions within the United States. Equation 2.3 presents his specification of the Cobb-Douglas production function. The equation states that irrigated crop yield within a region is equal to the area of land under irrigation times the operating expenses for farms in that region.

$$Y = \beta_0 X_1^{\beta_1} X_2^{\beta_2} \tag{Eq. 2.3}$$

Y	value of farm products sold in the region
X_1	number of acres irrigated in the region
X_2	regional farm operating expenses
β	parameters estimated by regression

Equation 2.3 may be transformed to a linear equation and estimated by ordinary least squares regression. By themselves, the parameters β_1 and β_2 represent the partial elasticity of yield with respect to inputs. The sum of the parameter estimates β_1 and β_2 gives the total elasticity of yield with respect to all inputs. The elasticity of yield is the proportional change in yield with respect to a proportional change in inputs. A sum of parameter estimates greater than one suggests increasing returns to scale and a sum less than one suggests decreasing returns to scale.

Equation 2.4 shows how to derive the marginal physical product of inputs from equation 2.3 once the parameter estimates are known. The equation states that the marginal physical product of irrigated land is equal to the yield per-acre times the partial elasticity of yield with respect to acreage:

$$\lambda_L = \left(\frac{Y}{X_1}\right) \beta_1 \qquad \textbf{(Eq. 2.4)}$$

λ_L marginal physical product of irrigated land (unrelated to λ in Eq. 2.2)

In this model, the water requirement is fixed on each acre. The variable λ can be converted to the marginal physical product of water by substituting the total water requirement for the number of irrigated acres:

$$\lambda_W = \left(\frac{Y}{\psi X_1}\right) \beta_1 \qquad \textbf{(Eq. 2.5)}$$

λ_W marginal physical product of irrigation water
ψ crop water requirement on one acre

Ruttan's Cobb-Douglas model is appropriate if irrigation water is a strict complement to irrigated land, and the researcher assumes a fixed water requirement. However it provides no information on what might happen to crop yield if the level of irrigation intensity were altered. Economic theory and empirical field observations suggest that water has a diminishing marginal value in production. Because the model provides no indication of what an optimum level of irrigation intensity might be, and crop yields vary with irrigation intensity, the demand for water is a function of the demand for crop output, not the demand for land (Ruttan, 1965, p.73-5). Furthermore, this production function relies on financial data on farm production, and does not describe the physical relationship between farm inputs and farm outputs. Therefore, it requires assumptions about farmer behavior (Moore *et al.*, 1992, p.17).

Moore *et al.* (1992) developed an alternative Cobb-Douglas specification using cross-sectional data from the Department of Agriculture's Farm and Ranch Irrigation Survey. This model states that crop yield is a function of the amount of water applied, rainfall, cooling degree days, and the amount of land area under cultivation:

$$Y = \beta_0 X_1^{\alpha} X_2^{\beta_1} X_3^{\gamma} X_4^{\delta} e^{\sum_{i=1}^{n} \rho_i z_i + \epsilon_1} \qquad \textbf{(Eq. 2.6)}$$

Y output per-acre
X_1 volume of irrigation water used in production
X_2 rainfall per-acre of irrigated land

X_3	cooling degree days
X_4	area of land under irrigation
$\alpha, \beta, \delta, \gamma, \rho$	parameters estimated by regression

The equation is linear in the logarithms. The parameter β_0 is the y-intercept, α is the partial elasticity of yield with respect to irrigation water inflows, β_1 is the partial elasticity of yield with respect to rainfall, and γ is the partial elasticity of yield with respect to cooling degree days. The parameter estimate δ is the returns to scale with respect to farm size. The variable z_i in the exponential function is a vector of n qualitative variables representing irrigation technology, water management, farm structure, climate, and soil quality. It is accompanied by a vector of parameter estimates, ρ_i. Qualitative variables are specified as an exponential series because they are not variable inputs in the short-run context of this model. The value of the parameter estimate ρ_i indicates the marginal contribution of farm characteristic z_i on crop yield.

Because the per-acre specification is algebraically derived from farm-level data, the parameter estimate for land, δ, measures returns to scale rather than the partial elasticity of yield with respect to land, ϕ. By definition, returns to scale is equal to the sum of all partial elasticities:

$$1 + \delta = \alpha + \beta_1 + \gamma + \phi \qquad \textbf{(Eq. 2.7)}$$

ϕ	partial output elasticity of land

All other parameters are as previously defined. From this it can be seen that the output elasticity of land is contained in the returns to scale term. The output elasticity may be isolated by rearranging equation 2.7 so it expresses the output elasticity of land (Moore *et al.*, 1992, p.18):

$$\phi = -\alpha - \beta_1 - \gamma + 1 + \delta \qquad \textbf{(Eq. 2.8)}$$

The Cobb-Douglas specification is useful because it provides information on both returns to scale and output elasticities of farm inputs. The authors note that for most crops the returns to scale, δ, are consistently close to 1.0. These conclusions support the use of a constant returns to scale assumption in many econometric models of irrigation water demand. Knowledge of the output elasticities of different farm products enables the researcher to calculate the marginal rate of technical substitution (MRTS) between farm inputs.

Equation 2.9 defines the MRTS between land and water. Farmers may optimize their combination of farm inputs if the prices are known. Equation 2.9 states that the tradeoff between the water land is equal to the irrigation intensity (acre-feet of water per-acre of land) times a ratio of the output elasticities:

$$\mathrm{MRTS} = \left(\frac{-\phi}{\alpha}\right)\left(\frac{X_1}{X_4}\right) \qquad \textbf{(Eq. 2.9)}$$

MRTS	marginal rate of technical substitution
ϕ	output elasticity of land
α	output elasticity of water
X_1	amount of water used in irrigation
X_4	amount of land irrigated

When specified on a per-acre basis, equation 2.6 describes how much additional land a farmer would need to cultivate in order to maintain his total yield if he were required to reduce his irrigation intensity.

Despite its advantages, the Cobb-Douglas specification does not fully describe agricultural principles of irrigation. Unlike the quadratic specification, the Cobb-Douglas never reaches a maximum, and there is no negative marginal product for irrigation water. This is important because experimental evidence shows too much water can reduce yields. However, when the researcher's objective is to evaluate economic rather than biological parameters, and the assumption is that farmers maximize profits, this problem is irrelevant because maximum profits will not occur in the range of negative marginal product (Moore *et al.*, 1992, p.27). For example, Figure 2.5 shows a stylized quadratic production function. All farmers could apply more water to their crops. However, this would cause them to move along the production function and away from the point of tangency with the profit line. As the amount of water applied to the field increases, yield decreases. No rational farmer would apply water to a crop if it would reduce yield.

Farm Budget Analysis

When field data on the crop-water relationship are not available, farm budget analysis provides an alternative to statistical production functions. Farm budgets include information on the cost and combination of inputs required to achieve a certain level of production, and the returns from farming activities. Farm budgets are in essence a static production function. When all farm inputs other than water are valued at their marginal value product, the difference between variable production costs and farm revenue is a measure of the value of water applied (Young and Gray, 1985). This value is referred to as the farm budget residual, and may be used to calculate the average value of water when the quantity of water is known. The returns to farming activities represent the farmer's maximum ability to pay, and can be interpreted as willingness to pay. Linear programming methods, discussed below, provide a means of determining the marginal value of water from farm budgets.

Farm budgets may be used to determine short-run and long-run values of water. When the budgets include both variable and fixed costs, the estimate is a long-run value of water. The estimate is a short-run value when the budget includes only variable costs (Shumway, 1973; Kulshreshtha and Tewari 1991). Some authors regard short-run values as more appropriate in the context of estimating irrigation water demand because changing crop prices, irrigation technologies, and environmental conditions make statements about the future questionable (Flinn, 1969).

Farm budget estimates may overstate the value of water because they include no information on technical or economic efficiency (Kulshreshtha and Tewari, 1991). Young and Gray (1985) also caution that the residual method of valuing water may result in an overestimate of water's true value when the opportunity costs of unpriced factors of production such as labor and capital are excluded from farm budgets. Gisser (1970) suggests that excluding these costs from the analysis may be justified when estimating an extremely short-run value for water because the value of land in farming regions and the availability of alternative employment for farm managers is low.

Shulstad et al. (1982) used the farm budget residual to estimate the relative value of water among farming regions in Arkansas. They conclude that the difference between the residual for irrigated and dryland farming operations, divided by the amount of water used in irrigation, represents the average value of water. For crops such as rice dryland farming is not an alternative means of production. In these cases, profits from the most remunerative non-irrigated crop alternative to rice represent returns to dryland farming. The authors conclude that these estimates of water value may be used to allocate water among farming regions, evaluate the potential transfer of water from one region to another, and locate water development projects.

Linear programming methods estimate the static normative demand for irrigation water. The model is static because farm inputs are fixed in the model budgets, and is normative because the budgets reflect what farmers should do to maximize profits, not what they actually do. It expands on the concepts of the value of water by allowing the researcher to vary the price of water, and estimate water use under specified conditions. In contrast, Shulstad's average values discussed above say nothing about how farmers will alter water use in relation to changing water prices.

Linear programming methods optimize farm profit by adjusting crop mix subject to farming constraints. Given a single farm with fixed water requirements and fixed production levels for each crop, the quantity of water used is a function of crop mix. As the price of water increases, the farmer chooses an appropriate crop mix to maximize profits. Biological and economic considerations can be incorporated into the model by limiting the maximum acreage of individual crops within the farm.

The water requirement for each crop may be either fixed or variable. If the crop-water relationship is known, the model may incorporate crop response to different levels of irrigation intensity (Flinn, 1969). When this information is not available, the average value of water is fixed in the farm budget residual, and the volume of water and level of production remain constant for each crop. As the price of water increases, crops go out of production if more remunerative crop alternatives are available. The result is a stepped demand curve over a range of water volume. Each transition point is a corner on the demand schedule, and represents the highest possible water cost for an individual crop.

The constraints in the linear programming model should reflect the actual conditions in the study area. If a study area is homogenous, the model need not distinguish between farms and analysis can be done on an acre-by-acre basis (Gisser, 1970). Farms may vary in size, but will exhibit constant returns to scale and a fixed proportion of inputs for each crop.

Models of heterogenous farming areas are more complex and it is rarely feasible to analyze and model each individual farm within a diverse irrigation area. In this case, farms may be grouped into farm types by physical characteristics such as soil type, farm size, and preferred crop mix as well as characteristic differences such as cultural orientation and farming practices between farmers. For a heterogeneous farming region, demand schedules are estimated for each farm type and weighted in terms of the prevalence of that farm type in the region. The horizontal sum of all these demand schedules represents the demand schedule for the region as a whole.

Three sources of error can bias linear programming results. These are specification error, sampling error, and aggregation error (Flinn, 1969, p.130). Specification error results from problems in adequately describing the conditions faced by farmers in the region, the objectives of each farm firm, and the potential decisions of each farmer. Sampling error refers to problems in collecting information on the conditions faced by each farm firm in the region. Aggregation error refers to the difference in the horizontal sum of demand functions for individual farm units and the sum of demand functions for model farm types.

Aggregation error is probably the most difficult problem with respect to linear programming estimates because each farm faces a unique set of conditions, and each operator makes individual decisions about farm management. Flinn (1969, p.130) suggests two ways of minimizing aggregation error. First, farms should be grouped in terms of the most limiting resource in the production process, and second, farms with similar patterns of output response to price change should be grouped together.

Common assumptions of linear programming models are that the market for farm products is perfectly elastic, and that the factor input ratios do not change in response to changes in the price of water. A perfectly elastic market for farm products indicates that crop prices do not change as crop production decreases with acreage in response to increases in the price of water. This may not be an unreasonable assumption when working in small areas that serve much larger markets.

Constant factor input ratios reflect a much stronger assumption. Economic theory suggests that the input ratio will equal the ratio of the input prices. As the price of water increases, rational farmers should adjust by finding substitutes for water. However, input ratios are fixed in the budgets and farmers cannot adjust inputs within the model. If the price of farm inputs or farm products changes, the analysis may no longer be valid (Shumway, 1973; Lacewell *et al.*, 1974).

Applications of Linear Programming Techniques

Knowledge of irrigation water demand provides information on not only the economic efficiency of a particular water development project, but also on the viability of proposed water projects. From the variety of literature available, it is clear that many possible formulations of the problem exist, and such analyses may be either normative or positive. Moore and Hedges (1963) developed a linear programming model for irrigation water in Tulare County, California, to evaluate the feasibility of a proposed water development and to project revenues for the development. They also suggest that public and private water districts would find such a curve useful in establishing a variable price for water.

Yaron (1967) conducted a similar study in Israel in the attempt to estimate an efficient allocation of water which had not been previously assigned through water rights. He suggests that the larger the region under analysis, the more complex the objective function must be in order to meet the conditions of economic efficiency. He also stresses that, to be a useful tool, the analysis must focus only on that portion of the available water for which farmers actually compete. Institutional constraints, such as the prior allocation of water rights among farmers, must be incorporated in the model. Following the concept of diminishing marginal value of water, such considerations would result in lower estimates of the value of water, and perhaps even a tendency to allocate marginal water supplies among those farmers without existing water rights.

Flinn (1969) used linear programming procedures to estimate a demand function for the Yanco Irrigation Area in Australia. He notes that the crop water requirement varies over the growing season, and that the demand curve within a region will have different elasticities during different periods of the growing season. Accordingly, the author constructed separate demand curves for three periods during the growing season on each model farm. The horizontal sum of these curves represented the demand for water on that model farm over the entire growing season. The horizontal sum of seasonal demand for all farm models, when weighted appropriately, represents the demand for water in the region.

In his study of agriculture in the Pecos River Basin of New Mexico, Gisser (1970) used linear programming methods to estimate the future demand for imported water. His model incorporated the effects of both varying levels of irrigation intensity and water salinity on crop production. This study assisted policy-makers in determining the appropriate quantity of water to import and the appropriate price to charge while simultaneously maintaining efficient use of existing groundwater supplies.

Kelso *et al.* (1973) analyzed the effect of water shortage on the regional economy in Arizona by modelling agricultural water demand on irrigation districts within the state. Their primary assumption was that continued growth in the state's economy, and the difference in the marginal value of water between the non-agricultural and the agricultural sectors, would result in a transfer of water away from agriculture towards urban and industrial centers. Extensive research on the supply of water within the state, and the demand for water among different farms and farming regions provided the basis for estimating that impact.

Shumway (1973) estimated an optimum price for irrigation water on the west side of the San Joaquin Valley in California to meet regional crop production targets and reduce the total value of the state's subsidy to agricultural producers. In the Texas High Plains Region, Lacewell and Condra (1976) estimated the long-run demand for irrigation water. This analysis differs from others of its kind in that the authors considered the effect of projected changes in the price of agricultural inputs. Gisser et al. (1979) analyzed the effect of competition for water from hydro-electric power plants in New Mexico. Kulshreshtha and Tewari (1991) estimated both short-run and long-run values of irrigation water on an irrigation district in Saskatchewan, Canada, to assess the potential for future public investment in water development projects.

This project uses farm budget analysis and linear programming methods to derive the demand for irrigation water on two rice irrigation districts in the Texas Gulf Coast region. The objective is to estimate the subsidy to farmers which arises as a result of district ownership of senior water rights in the Lower Colorado River Basin. Since 1988, the Lower Colorado River Authority (LCRA) has implemented a water conservation program to reduce surface water diversions. Knowledge of the source of economic inefficiencies related to water diversions will assist LCRA in more efficiently distributing its water conservation effort between program components and in determining the benefits associated with its investment in water conservation. Knowledge of the demand for irrigation water on each district will also assist the LCRA in replacing its fixed per-acre irrigation rate with a volumetric rate structure. From the analysis presented in the following chapters, LCRA should be able to determine what price of water would both enable it to meet the fixed costs on the irrigation districts and encourage farmers to be conservative in their use of water.

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Chapter 3
LCRA Rice Irrigation Districts

This chapter describes the irrigation districts and factors that influence on-farm demand for water. The first section discusses the Lower Colorado River Authority and water management in the Lower Colorado River Basin. The following sections identify key factors that influence farm water requirements, and discuss the methods used to estimate their effect. Factors of water demand include climatological factors, physical factors, crop price, crop alternatives, water management practices, and second cropping rate. The data and estimates presented in this chapter are the parameters used in the linear programming model.

The Lower Colorado River Authority (LCRA) and county agents at Texas Agricultural Extension Service offices in Columbus, Wharton, and Bay City provided much of the data. Until 1992, LCRA collected information only on total water diversions, and first and second crop rice acreage on each district. In 1992, the LCRA also began collecting data on the volume of water deliveries to individual fields. This information provided data for calculating individual farm water requirements. The Texas Agricultural Extension Service (TAES), US Soil Conservation Service, and Texas A&M University provided the information needed to make statements about farm water requirements under different technological and economic conditions. Detailed information on the field characteristics, operations, and crop production on individual farms was not available for this study. However, TAES model farm budgets provided an approximation of farming operations and crop production in each county.

The Lower Colorado River Authority

LCRA is a state-owned river authority charged with managing land and water resources within the Lower Colorado River Basin, a ten county area in Central Texas. LCRA operates under the statutory authority of the Texas state administrative codes and the LCRA Act of 1934 which established the agency as a conservation and reclamation district. The agency manages a system of six reservoirs, the Highland Lakes, with a storage capacity of approximately 1.5 million acre-feet and a firm yield of approximately 445,000 acre-feet a year (LCRA, 1988). Although the LCRA receives revenues through stored water sales within the river basin, it depends mostly on revenues from its coal and hydroelectric power generation facilities that produce electricity for wholesale to other public utilities throughout Texas. Stored water supplies in the Highland Lakes are an important addition to the natural flow of the Lower Colorado River because the state has allocated all surface water rights within the basin, and run-of-river flows are not sufficient to meet municipal, industrial, and agricultural demands.

The LCRA owns and operates the Lakeside and Gulf Coast Irrigation Districts. The LCRA purchased the Lakeside District in 1983, and the Gulf Coast District in 1960. Both district own senior water rights to run-of-river water flows in the Lower Colorado River. The volume of Lakeside's water right is 131,250 acre-feet, and the volume of Gulf Coast District water rights is 262,500 acre-feet. The districts divert and sell water to farmers for rice irrigation. Each year, these two districts account for about half of all consumptive uses of surface water within the basin. Table 3.1 shows the total irrigation district diversions and the percent of total diversions within the river basin for each year since 1980. For example, in 1980, Lakeside District diverted 139,797 acre-feet of water from the river. This was 18.98 percent of all consumptive municipal, industrial, and agricultural water diversions from the river in 1980.

Lakeside and Gulf Coast Irrigation District water rights have priority dates of 1901 and 1900 respectively. Because their water rights possess a more senior priority date than most other water rights in the basin, the irrigation districts have preferential access to run-of-river water. When run-of-river flows cannot satisfy the total demand within the basin, those with less-senior water rights may not have access to run-of-river flows. Those who wish to divert water must purchase stored water from the Highland Lakes. For this reason, most major water rights owners maintain long-term firm water contracts with the LCRA. These contracts guarantee access to specified quantities of stored water supplies. In 1992, 76 percent of firm water supplies were committed under LCRA water contracts (Crittendon, Interview, January 25, 1993). The cost of maintaining these contracts is $50.50 per acre-foot per year, with an additional $50.50 for each acre foot which the contract holder actually diverts.

When the demand for water exceeds the run-of-river flow and the irrigation districts are unable to divert water under their own water rights, they also must purchase stored water from the Highland Lakes. However, the districts do not maintain firm-water contracts. Instead, each district has access to unspecified quantities of interruptible stored water with which to supplement water diverted under their own water rights. The districts purchase this water for $4.50 an acre-foot, which is LCRA's operational cost of supplying one acre-foot of interruptible water (Taylor, Interview, January 25, 1993). The cost of interruptible water is much less than firm water because LCRA does not guarantee its availability. During drought periods, when the level of water in the reservoirs drops below a certain point, the LCRA curtails its interruptible water sales.

The LCRA has operated under this system of firm water and stored water since 1989, but LCRA has never found it necessary to curtail the sale of interruptible water. As of 1993, LCRA only sells interruptible stored water for agricultural uses. While it is legally possible to deprive farmers of their long-established access to stored water during a drought period, the political difficulties associated with this decision might make implementation an unfeasible alternative for the LCRA board (McGarity, Interview, October 20, 1993). Therefore, it may not be possible to equate the discounted cost of interruptible water with the risk associated with its potential curtailment. Table 3.2 lists each irrigation districts' interruptible stored water diversions since 1989. For example, in 1989, Lakeside Irrigation District diverted 78,717 acre-feet of stored water. This was 59.4 percent of all surface water diversions on that district.

Although LCRA owns the irrigation districts and their water rights, those water rights do not include the authority to divert and use this water for non-agricultural purposes. In addition, LCRA may not market this water outside of the district boundaries. However, ownership of the districts gives LCRA the means to implement agricultural water conservation programs to increase the supply of water in the basin. Since 1988, LCRA has pursued a water conservation program to reduce the demand for water through education, canal rehabilitation, and water measurement. A 1993 study showed that, with the exception of canal rehabilitation on the Gulf Coast District, these efforts had not contributed to a measurable decrease in the total demand for water on the districts (Lyndon B. Johnson School of Public Affairs, 1995).

Operational water losses, leaks, and seepage of water from the unlined canal systems contribute to the total demand for water on the irrigation districts. Although both irrigation systems are about one-hundred years old, canal maintenance on Lakeside District has been more intensive than on Gulf Coast District. To address this problem on Gulf Coast District, LCRA began a canal rehabilitation program in 1988. Canal rehabilitation has succeeded in reducing the annual demand for water on Gulf Coast District by approximately 57,000 acre-feet (Lyndon B. Johnson School of Public Affairs, 1995).

Table 3.1
Total Water Diversions and Percent of Total Consumptive Uses

	Lakeside District Water Diversions		Gulf Coast District Water Diversions	
	(acre-feet)	(percent)*	(acre-feet)	(percent)*
Year				
1980	139,797	18.98%	236,801	32.17%
1981	116,735	17.05	302,364	44.15
1982	142,957	19.48	240,485	32.78
1983	108,019	19.50	186,389	33.65
1984	149,698	20.28	245,339	33.24
1985	109,809	16.94	179,766	27.73
1986	92,811	15.47	212,426	35.41
1987	115,825	20.15	187,657	32.66
1988	160,349	20.44	235,136	29.98
1989	133,186	18.11	199,522	27.14

Sources: Texas Water Commission. 1993. "Reported Surface Water Use for Colorado River Basin, All Rights and Claims," Austin, Texas. (Computer Printout.); and Lower Colorado River Authority. 1993. "Irrigation Water Diversions," Austin, Texas. (Photocopy.)

Note: (*) Percent of total consumptive uses of surface water in the Lower Colorado River Basin. Includes both run-of-river and stored water diversions.

Table 3.2
Interruptible Stored Water Diversions on LCRA Irrigation Districts

	Lakeside District Stored Water		Gulf Coast District Stored Water	
	(acre-feet)	(percent)*	(acre-feet)	(percent)*
Year				
1989	78,717	59.40%	71,920	36.15%
1990	64,163	43.18	71,229	45.83
1991	67,273	56.17	16,857	13.05
1992	15,748	11.61	0	0.00
1993	52,981	54.92	56,802	53.84

Source: Lower Colorado River Authority. 1993. "Total and Stored Water Diversions by Lakeside and Gulf Coast Irrigation Districts." Austin, Texas. (Computer Printout.)

Note: (*) Percent of total district diversions that are stored water.

Table 3.3
1993 Volumetric Irrigation Water Rates

	Lakeside District		Gulf Coast District	
	1993 Rate	**1992 Rate**	**1993 Rate**	**1992 Rate**
Variable Charges				
Volume Charge per acre-foot:	$9.25	-	$5.40	-
Stored Water Charge per acre-foot:	5.27	-	5.27	-
Fixed Charges				
Per-Acre Charge				
Irrigated Rice:	$42.50	$92.43	$49.50	$87.26
Irrigated Turf Grass:	N/A	N/A	22.20	29.30

Source: Lower Colorado River Authority. 1992. "Board Meeting Agenda." Austin, Texas. (December, 16.)

Under the water measurement program established in 1993, farmers must pay for both the volume of water they use and the number of acres they irrigate. Volumetric water pricing contrasts with the district's pre-1993 practice of charging farmers a fixed fee for irrigation based only on the amount of land they irrigate. LCRA designed the new rate structure on a cost-of-service basis. Table 3.3 displays the new rate structure for both districts. Farmers pay a diversion charge for each acre-foot of water that they use. This variable rate covers the marginal cost of supplying water. The difference in the volumetric rates between the two districts is due to the fact that Lakeside District must lift its water a second time in each of its main canals.

When farmers receive interruptible stored water from LCRA reservoirs, as determined by the LCRA's daily water allocation model, a $5.27 surcharge accompanies the diversion charge. The surcharge represents LCRA's standard interruptible stored water rate ($4.50) plus a cost factor of 17 percent of the interruptible stored water rate (Taylor, Interview, January 25, 1993). Operational water losses are those water losses which occur between the irrigation district's diversion point on the Colorado River and farm delivery structures. The 17 percent cost factor is not based on empirical estimates of canal efficiency, but rather, is LCRA's best estimate of canal efficiency.

The final element of LCRA's volumetric rate structure is a per-acre charge which, like the old rate, is based strictly on the number of acres a farmer irrigates. This charge reflects the fixed costs of operating the districts regardless of the actual amount of water delivered in any particular year. The lower per-acre charge on Lakeside District is due to the somewhat more efficient labor costs on that district.

LCRA does not calculate the stored water diversions until after the districts divert water from the river, and the irrigation districts charge farmers for stored water on the basis of the proportion of total diversions that LCRA determines are stored water. Because rainfall has a significant effect on the volume of run-of-river flows, the proportion of stored water which the districts divert varies from year to year. In addition, stored water diversions increase as the rice season progresses because run-of-river flows decline in response to decreases in the amount of rainfall between March and October. Because farmers make their water management decisions on the basis of the price of water, but do not know the actual volume of stored water they purchase, they must make their decisions on the basis of an anticipated water price. Historical data on the proportion of monthly diversions that LCRA determines are stored water provides a means of estimating the probability that a farmer will draw stored water.

Annual Rice Acreage Requirements

Rice is the principal crop on the irrigation districts, and is the only crop which farmers consistently irrigate. The standard practice among farmers is to rotate their rice crop among their fields on a three year basis. During the two year interim, farmers usually leave their rice fields fallow, but may also raise cattle on that land. Not all the land on the districts is used in rice production. Where possible, farmers also raise cattle, corn, cotton, sorghum, soybeans and, on Gulf Coast District, turf grass. With the exception of turf grass, these crops are normally grown under dryland conditions. Farmers choose to irrigate these crops only during extreme drought.

For farmers that participate in the Agricultural Stabilization and Conservation Service's (ASCS) price support programs, rice is the most remunerative crop alternative. Because rice prices fluctuate from year to year, farmers who do not participate in these programs take a considerable risk in terms of recovering the costs of production. In many cases, banks are reluctant to provide loans to farmers who do not participate (Humphrey, Interview, December 14, 1992). Farmers who participate in the programs are limited in the amount of land they can put into rice production by their base acreage allotments. ASCS establishes base acreage limitations on the basis of historical production records on the land.

Base acreage allotment are tied to specific land areas, not farming entities. In addition to base acreage allotments, the ASCS also uses mandatory and optional set-aside requirements to reduce the total area of land on which farmers plant rice. With limited exceptions, the variety of crops which farmers may plant on base acreage which they have set-aside is restricted by the ASCS. In choosing the proportion of their base acreage to set-aside, farmers respond primarily to the anticipated price of rice at the time of harvest relative to guaranteed deficiency payments from the ASCS (Engbrock, Interview, December 14, 1993).

Rice acreage on each irrigation district fluctuates because market prices and ASCS farm programs fluctuate. Therefore, it is not possible to make a year to year prediction of the exact rice acreage on each district. Table 3.4 lists the total amount of rice acreage planted on the irrigation districts in each year since 1968. For example, in 1968, farmers on Lakeside District irrigated 25.7 thousand acres of rice during the first crop period, and 23.4 thousand acres of rice during the second crop. The drop in rice acreage that occurred between 1980 and 1982 is the result of changes in ASCS farm programs.

Given the annual rice acreage on the districts in past years, and ASCS farm program parameters, ordinary least squares regression provides a means of estimating first crop acreage in the upcoming crop season. Estimates may be made in January when ASCS makes program parameters public. Equation 3.1 gives a time series model of first crop rice acreage on each district. The model states that first crop acreage is a function of the mandatory ASCS set-aside requirement and ASCS advance deficiency payments.

$$A_t = \beta_0 + \beta_1 Y_t + \beta_2 M_t + \beta_3 D_t \qquad \textbf{(Eq. 3.1)}$$

A	first crop acreage (thousand acres)
Y	a trend variable for crop year $Y = (1, 2, 3, ..., n)$
M	maximum fraction of base acreage allowed by ASCS in that year (a fraction)
D	advance deficiency payment that ASCS gives farmers at the time they state their planting intentions for the coming year (dollars per acre)
t	an index of crop year $t = (1, 2, 3, ..., n)$
β	coefficients estimated by ordinary least squares regression

For those years prior to 1982 when the current ASCS programs went into effect, the variable M equals 1 to indicate there was no limit on the acreage a farmer could plant, and the variable D equals zero, to indicate that farmers did not receive advance deficiency payments. Table 3.5 shows the regression results. Figures 3.1 and 3.2 graph the acreage predictions on Lakeside and Gulf Coast Districts respectively.

Table 3.4
Rice Acreage Irrigated with Surface Water on LCRA Districts
(Thousand Acres)

	Lakeside District		Gulf Coast District	
	First Crop	Second Crop	First Crop	Second Crop
Year				
1968	25.7	23.4	41.2	27.9
1969	25.7	23.2	38.8	34.7
1970	22.6	22.2	34.6	27.5
1971	24.0	22.2	35.0	30.2
1972	25.4	23.5	35.2	31.0
1973	26.1	15.7	42.5	22.8
1974	27.1	25.6	40.4	36.0
1975	26.1	24.9	41.6	38.5
1976	25.7	25.1	38.1	32.5
1977	26.2	25.4	36.2	30.1
1978	27.4	27.0	42.8	38.6
1979	26.7	24.7	40.9	35.2
1980	28.2	27.5	42.7	39.7
1981	28.3	27.2	41.7	40.8
1982	27.2	26.6	39.3	34.6
1983	21.0	20.2	21.7	16.1
1984	25.4	23.1	31.9	21.1
1985	23.3	17.0	24.4	8.4
1986	21.0	19.2	21.6	18.1
1987	18.6	18.1	21.1	16.2
1988	26.7	23.9	33.7	15.3
1989	25.1	23.2	25.8	16.9
1990	26.7	23.9	28.9	12.9
1991	26.7	26.0	28.2	9.3
1992	26.9	22.3	27.2	8.7
1993	21.3	12.7	21.7	4.2

Source: Lower Colorado River Authority. 1992. "LCRA Irrigation District Acreage and Water Use." Austin, Texas. (Computer File.); Lower Colorado River Authority. 1993. Irrigation District Water Accounting Database. Lakeside Irrigation District, Eagle Lake, Texas (Computer File.); Lower Colorado River Authority. 1993. Irrigation Water Accounting Database. Gulf Coast Irrigation District, Bay City, Texas. (Computer File.)

Parameter estimates measure the change in planted rice acreage associated with changes in ASCS program parameters. All else equal, first crop rice acreage is increasing on Lakeside District at a rate of 313 acres per year. An insignificant parameter estimate for the trend variable on Gulf Coast District indicates no long-term change in first crop acreage after controlling for ASCS program parameters. Interpretation of the parameter β_2 is that for every one percentage point increase in the maximum fraction of base acreage, planted acreage will increase 158.4 acres on Lakeside District, and 268.1 acres on Gulf Coast District. The smallest fraction of base acreage ASCS allowed in any one year was 0.65 between 1985 and 1987.

Parameter estimates for the advance payment variable are negative. Planted acreage decreases 638.1 acres on Gulf Coast District with every ten cent ($0.10) increase in the per-acre advance deficiency payment. This parameter estimate is insignificant on Lakeside District, suggesting advance deficiency payments have little effect on farmers planting decisions. The negative sign of this coefficient seems contrary to prior expectations of model results. However, advance deficiency payments may increase as anticipated crop prices decrease. This result indicates that increases in advance deficiency payments are not a substitute for the planting incentive generated by high anticipated crop prices.

The model predicts that, in 1993, farmers will irrigate 26,221 acres on the Lakeside District, and 25,371 acres on the Gulf Coast District. These figures overestimate actual 1993 rice acreage on both districts. Several factors contribute to this discrepancy. An unusually wet spring delayed planting for several weeks and at the time of planting, most farmers anticipated a low market price for rice. Also of interest are the rather low values for crop years 1984 through 1987. These are the result of lower than average ASCS acreage allowances.

Table 3.5
District Acreage Model Regression Results

Variable	Coefficients	Lakeside District	Gulf Coast District
Intercept	β_0	7.849	10.842
Trend (Y)	β_1	0.313	0.197
		(4.624)*	(1.497)
Maximum Base (M)	β_2	15.840	26.814
		(3.612)*	(3.132)*
Advance Payment (D)	β_3	-1.534	-6.3813
		(-1.801)	(-3.837)*
R-squared		0.665	0.865
Adj. R-squared		0.617	0.846
Model F		13.876	45.099

Source: Coefficients calculated by the author based on program provisions and payments rates data provided by the Agricultural Stabilization and Conservation Service, Columbus, Texas.

Note: T-statistics given in parenthesis. (*) Asterisks indicate significance at the 95% confidence level.

Figure 3.1
Actual and Estimated First Crop Acreage on Lakeside District

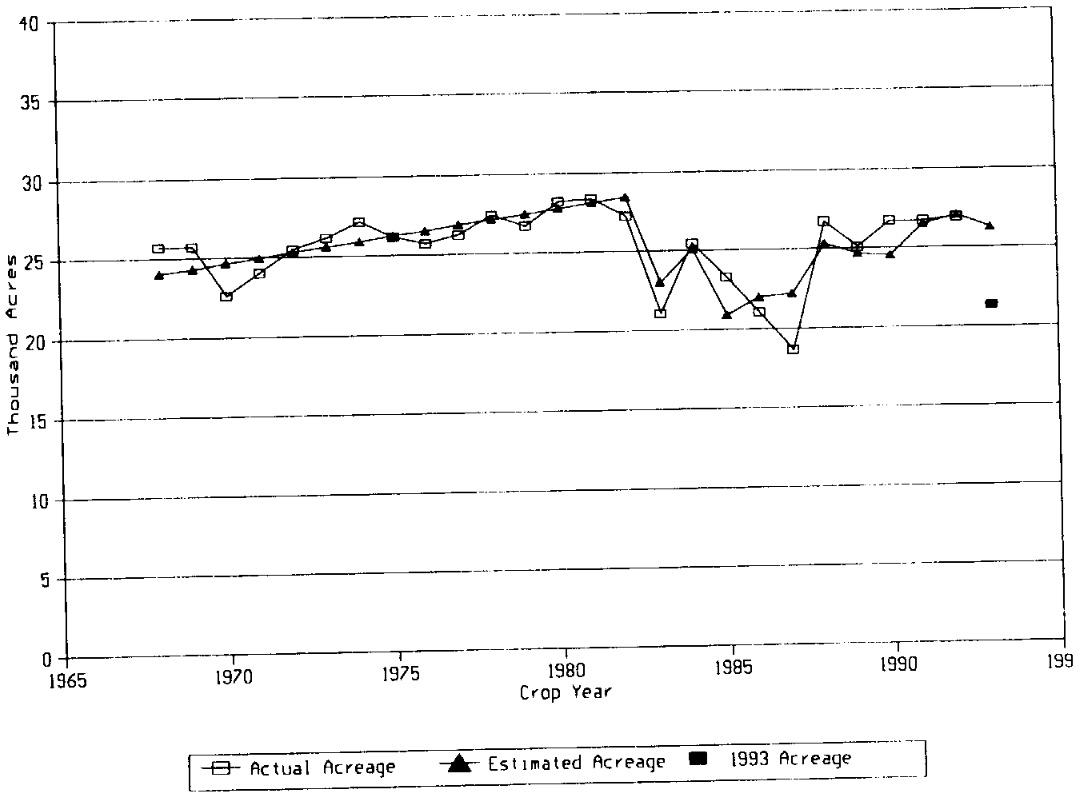
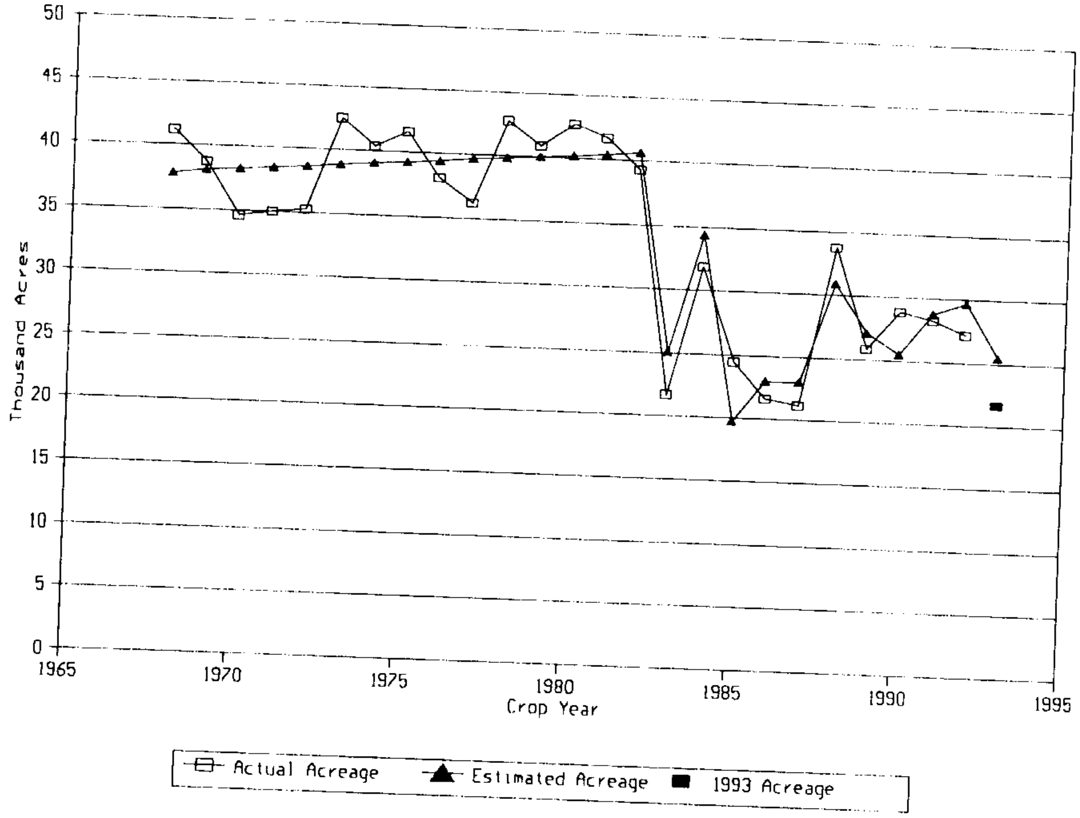


Figure 3.2

Actual and Estimated First Crop Acreage on Gulf Coast District



Since 1968, farmers on both districts have practiced double cropping of their rice fields. Farmers usually plant the first crop about mid-March and harvest the crop at the end of July. In August, they re-irrigate their rice fields to grow a second crop. Second crop yields are much lower than the first crop, but require little capital investment and few inputs. In addition, the second crop requires less water than the first crop because the rice plants are well established. The second cropping rate tends to be much lower and much more erratic on Gulf Coast District than on Lakeside District. The difference between the two districts is probably related to weather patterns and the date of first planting. Spring rains tend to last longer near the coast, and farmers on Gulf Coast District plant their fields slightly later than on Lakeside District. In addition, fall rains come earlier near the coast, and can make a second crop impossible to harvest. For this reason, these farmers are reluctant to invest in a second crop.

The amount of land that farmers irrigate each year and the second cropping rate are significant factors that affect irrigation water demand on the district, but many other factors can affect the demand for water both on the district as a whole, and between individual fields. Differences in rainfall between crop years can influence the total water diversions and crop water requirements (Martin, 1988). Relative differences in farming practices and water management styles between farmers can lead to differences in the demand for water. The field soil type, the variety of rice a farmer plants, and structural differences between fields may also lead to differences in irrigation water use. Some less obvious factors that influence the demand for surface water in the river basin are the crop price, the set of feasible crop alternatives, and the availability and relative cost of groundwater.

Water Management Practices

Water management practices can be evaluated using at least three measures that reflect water efficiency. A technical measure is the amount of water a farmer uses per acre of irrigated land (acre-feet per acre). Although often preferred because it is easily calculated, it provides only a weak basis for comparing efficiency between farmers because it ignores differences in production and net returns to farming. Water efficiency, a unit-less measure of the amount of water actually used in production (evapotranspiration) as a percentage of field inflows, may be a better measure of on-farm water management. However, differences in physical characteristics of fields cause non-crop water use to differ between fields. This measure more appropriately describes field efficiency rather than farmer efficiency. In the economic sense, irrigation efficiency might be measured by net returns per acre-foot of water (Small, 1992). The farmer who receives higher returns per acre-foot of water is more efficient. Although a technical measure of water management (acre-feet of water used per-acre of rice irrigated) may not be the best means of evaluating farmer's water management practices, information on which to base an alternative measure of on-farm water management is not available.

Water management practice refers to both farming methods and water management styles. Farming methods are fairly consistent on the irrigation districts. Among other things, farmers use continuous flood irrigation, and plant their crop by drill seeding. Alternative methods are available which might use more or less water, but farmers have adopted these practices on the basis of what works best in the area. In contrast, water management style, the active decision of when to use water and how much water to use, varies considerably between farmers that use the same farming practices. Farmers who use a high level of water management place a high emphasis on controlling the timing of water deliveries and the flow of water into the field.

Water coordinators, those responsible for operating the canal and making water deliveries, provided a subjective assessment of each farmer's relative water management style based on their knowledge of each individual's farming practices. They rated each farmer as one who uses high, medium, or low management. Water coordinators *did not* rate farmers on the basis of the volume of water used. All else equal, farmers that use high management should use water at a lower rate than farmers who use low management. Given the above definition of water management, water coordinators on both districts were given the opportunity to establish their own indicators of water management style.

On Lakeside District, water coordinators used three criteria to rate farmers. These included the frequency with which the farmer contacts the water coordinator, the quality of the farmer's field hands, and the emphasis the farmer places on field preparation before planting. On Gulf Coast District, water coordinators used two criteria. These included the frequency with which the farmer checks his levees for leaks and spills, and the frequency with which the farmer turns his water on and off.

Tables 3.6 and 3.7 show the proportion of farmers on each district that water coordinators placed in each management category, and the average water use among those farmers in 1993. For example, water coordinators on Lakeside District rated 26 percent of their farmers as using a high level of water management, and the average water use in the fields in which those farmers cultivated rice. First crop water use was 28.47 acre inches per-acre during the first crop, and 23.76 acre inches during the second crop. Regression of water use on dummy variables representing management styles showed little difference in irrigation efficiency between the management categories. The model used to test whether there were statistically significant differences in irrigation efficiency between farmers is given in equation 3.2. The model states that per-acre water use is a function of the amount of rainfall, the length of the growing season, farmers water management styles, and the crop type:

$$W = \beta_0 + \beta_1 R + \beta_2 D + \beta_3 H + \beta_4 L + \beta_5 S + S (\beta_6 H + \beta_7 L) \qquad \textbf{(Eq. 3.2)}$$

W	field-specific water use (acre-feet per-acre)
R	rainfall between first irrigation and last irrigation in that field (inches)
D	number of days between first irrigation and last irrigation
S	a dummy variable equal to one for observations from second crop fields
H, L	dummy variables equal to one for high and low management respectively
β	coefficients estimated by ordinary least squares regression

Data on rainfall were collected by the National Weather Service at Columbus and Bay City Waterworks for Lakeside District and Gulf Coast District respectively. For Gulf Coast District, the variables R and D were excluded from the model because, for many observations, the database did not include those dates on which the farmer either began taking water or stopped taking water.

Table 3.8 gives the parameter estimates. The intercept term is interpreted as mean per-acre water use during the first crop period among farmers using a medium water management style. This interpretation assumes no differences in these farmers' rainfall and irrigation period. On Lakeside District, every inch of rainfall during the crop period reduces inflows 0.067 acre-feet, or 0.804 inches. This is the trade-off between rainfall and irrigation inflows. Per-acre water use increases 0.021 acre-feet for each one-day increase in the irrigation period.

Parameter estimates for the second crop dummy variable (S) are negative. Negative values indicate farmers use less water per acre during the second crop relative to the first crop. All other variables equal, medium water managers on Lakeside District use 1.239 acre-feet per acre less water than 2.065 acre-feet during the second crop period. This comparison assumes constant values of rainfall and irrigation period variables between crop periods.

Most parameter estimates for water management variables are insignificant. Results show that farmers classified as "low" water managers on Gulf Coast District's East Side consistently use an additional 0.5 acre-feet per acre than medium water managers on Gulf Coast District during the first crop period. The insignificance of management variables are most likely related to the subjective method used to classify farmers by water management style.

Lakeside management variables are insignificant and contrary in sign to what would be expected. This might indicate that water coordinators assessments of each farmer's water management style was not accurate. It may also indicate that differences in water management style have little affect on water use on that district. Gulf Coast management variables are insignificant, but the ordinal arrangement of management groups based on predicted first crop per-acre water use is generally consistent with prior expectations. Results for the second crop are less consistent with priors than those for the first crop.

Table 3.6
Management Practices and Water Use on Lakeside District in 1993
(Acre-Inches per Acre)

		Water Use	
Management Style	**Percent of Farmers**	**First Crop**	**Second Crop**
High	26%	28.47	23.76
Medium	56	30.00	22.64
Low	18	27.86	23.37
Average		**29.27**	**23.06**

Source: Calculated by the author based on: Lower Colorado River Authority. 1993. Irrigation District Water Accounting Database. Lakeside Irrigation District, Eagle Lake, Texas. (Computer File.)

Note: Water use is the amount of water farmers use to irrigate one acre. Average water use is the average for all fields.

Table 3.7
Management Practices and Water Use on Gulf Coast District in 1993
(Acre-Inches per Acre)

	East Side			**West Side**		
		Water Use			**Water Use**	
Management Style	**Percent of Farmers**	**First Crop**	**Second Crop**	**Percent of Farmers**	**First Crop**	**Second Crop**
High	10%	43.38	22.83	43%	40.35	26.07
Medium	59	45.56	29.44	19	44.77	23.99
Low	31	51.70	31.38	38	46.27	24.89
Average		**47.14**	**28.63**		**43.58**	**25.33**

Source: Calculated by the author based on: Lower Colorado River Authority. 1993. Irrigation District Water Accounting Database. Gulf Coast Irrigation District, Bay City, Texas. (Computer File.)

Note: Water use is the amount of water farmers use to irrigate one acre. Average water use is the average for all fields.

Table 3.8
Parameter Estimates and T-Statistics for the Water Management Model (Eq. 3.2)

Variable	Coefficient	Lakeside District	Gulf Coast District East Side	Gulf Coast District West Side
Intercept	β_0	2.065	3.7963	3.7306
Rainfall (R)	β_1	-0.067	-	-
		(-4.048)*	-	-
Days Watered (D)	β_2	0.0211	-	-
		(3.971)*	-	-
High Management (H)	β_3	-0.112	-0.1813	-0.3699
		(-0.728)	(-0.5432)	(-1.0220)
Low Management (L)	β_4	-0.215	0.5117	0.1254
		(-0.929)	(2.1755)*	(0.3423)
Second Crop (S)	β_5	-1.239	-1.3428	-1.7314
		(-4.729)*	(-3.2275)*	(-2.3331)*
Interaction Term (S*H)	β_6	0.036	-0.3699	0.5410
		(0.145)	(-0.5427)	(0.6005)
Interaction Term (S*L)	β_7	0.085	-0.3506	-0.0504
		(0.241)	(-0.5939)	(-0.0454)
R-squared		0.118	0.2280	0.1551
Adjusted R-squared		0.114	0.2015	0.1149
Model F		5.735	8.6245	3.8577

Source: Calculated by the author based on: Lower Colorado River Authority. 1993. Irrigation District Water Accounting Database. Lakeside Irrigation District, Eagle Lake, Texas. (Computer File.); Lower Colorado River Authority. 1993. Irrigation District Water Accounting Database. Gulf Coast Irrigation District, Bay City, Texas. (Computer File.)

Note: T-statistics given in parenthesis. Asterisks indicate significance at the 95 percent confidence level.

Other Factors Influencing Field-Specific Water Use

Differences in the water-holding capacity between soil types can influence irrigation water use between fields. However, the consensus among soil scientists in the Gulf Coast region is that differences in soil type do not cause differences in irrigation water use on these districts. After the soil becomes saturated during planting, there is little difference in the ability of different soils to maintain a flood on the surface. In addition, there is no deep percolation of water on the districts, so the soil remains saturated in the absence of evaporation. For this reason, differences in irrigation water use between soil types are the result of differences in the amount of water a soil needs to become saturated.

Differences in soil type do not cause more than a 3 to 5 acre-inch per-acre difference in field inflow between fields (Crenwelge, Interview, December 1, 1993; McCauley, Interview, October 29, 1993). A 1993 study that related irrigation water use in individual fields to soil types also showed no difference between soil types when fields were grouped according to high, medium, or low permeability of their respective soils types (Lyndon B. Johnson School of Public Affairs, 1995).

For the most part, farmers raise three varieties of rice on the irrigation districts. These are Gulfmont, Lemont, and Maybelle. Differences in the variety of rice a farmer plants may be the cause of some of the differences in irrigation water use between fields because the length of the growing season differs among the rice varieties. However, because most water use occurs during the first part of the growing season, differences in the water requirements among the varieties of rice do not cause more than a 2 to 3 acre-inch per acre difference in water use between fields (McCauley, Interview, October 29, 1993).

Adequate land preparation before planting can reduce irrigation water use. Each year, farmers level their fields to create an even grade. Farmers also build levees at regular intervals within the field to help control the flow of water. These practices help reduce on-farm water use by reducing water depth. For a relatively small additional cost, farmers can use two other practices to reduce water use. These practices are not common on the districts. In-field laterals can result in a 26 percent reduction in field inflow by concentrating the flow of water through the field and reducing evaporation losses. Spacing levees at closer vertical intervals, from regional standard of 0.20 vertical feet to 0.15 vertical feet, can reduce water depth within a field and result in a 14 percent reduction in field inflow (Stansel and Lindemann, 1987).

The cost associated with implementation of these water-saving technologies is small. In the case of infield laterals, cost is related to construction rather than maintenance. A farmer that uses infield laterals estimates that installing a half mile lateral in a 150 acre field requires a maximum of four hours to form the lateral with a levee plow and install checks and turnouts to deliver water to the cuts. If the cost of labor is $6.10 per hour, the labor cost is $24.40. He also estimates that $15.00 of material would be required to construct checks and turnouts in the lateral, and $3.00 of fuel would be required to pull the plow. For this field, the total cost of construction is $42.40, or $0.28 per-acre (Krenek, Interview, February 16, 1994). Actual cost will vary with the shape and size of the field. This practice may also improve the farmer's control over the depth of water in cuts at the upper end of the field and increase crop yield.

A second water-saving technology is to reduce the vertical distance between in-field levees. The regional standard for spacing levees is 0.2-0.3 vertical feet. Farmers that maintain a three-year field rotation survey and reconstruct levees at six to nine year intervals. Although there appears to be no specific reason for the regional spacing standard, reducing the vertical distance between levees can make the operation of machinery more difficult, especially when the slope of the field is high. Labor and machinery cost increases because farmers must repair damage caused by machinery.

The extent to which closer levees increase cost depends upon the slope of the field. For example, if the vertical distance between the top and the bottom of the field is 1.2 vertical feet, and the levees are spaced at 0.2 vertical feet, a farmer must add 0.67 additional levees to an existing six levees. This results in an 11 percent increase (0.67/6) in labor and machinery costs. However, if the vertical distance from one end of the field is 3 feet, the farmer must add five levees to his existing 15 levees. This results in a 30 percent increase in field labor and machinery costs. According to the Colorado County model farm budget, an 11 percent increase in variable field labor and machinery costs increases the cost of production $15.45 per-acre, and a 30 percent increase in these costs raises the cost of production $41.71 per-acre.

Although empirical evidence shows that these practices reduce field inflow and may even increase a farmer's yield (Stansel and Lindemann, 1987), farmers on Lakeside District and Gulf Coast District have not adopted the practice. The reason for this is probably a matter of cultural farming practice (Krenek, Interview, February 16, 1994; Crenwelge, Interview, December 1, 1993; McCauley, Interview, October 29, 1993). This suggests that the practice might be introduced in the area through some form of technology transfer, but that unless the price of water becomes very high, farmers will not adopt the practice on the basis of economic factors alone.

Laser levelling is another structural modification which has been shown to reduce field inflow. Although it is an expensive investment, its effect on water use is permanent (Krenek, Interview, February 16 1994). For the purposes of this project, laser levelling is not considered a viable technology input. For the most part, farmers on these irrigation districts do not own the land they farm. Most farmers sharecrop or cash-rent their lands. Table 3.9 shows the ratio of land under different landlord-tenant arrangements. Farmers who sharecrop or cash rent have little incentive to make long-run capital investments in the land. Landowners might have an incentive to make this investment if the price of water were so high that the water savings associated with that investment contributed to an increase in the rental rate, or an increase in their portion of net farm returns. Several landowners who farm their own land on Lakeside District, have begun laser levelling on a limited scale (Harbers, Interview, December 8, 1993).

Table 3.9
1982 Land Tenure Arrangements in Colorado, Wharton, and Matagorda Counties

	Percent of Acreage		
	Owned	**Sharecrop**	**Cash Rent**
County			
Colorado	7.7%	89.6%	2.8%
Wharton	14.9	76.6	8.4
Matagorda	17.9	79.5	2.7

Source: Griffin, Ronald C., Gregory M. Perry, and Garry N. McCauley. 1984. *Water Use and Management in the Texas Rice Belt Region*. Texas A&M University, College Station, Texas. (June.) p.60.

Although farming practices are similar between the districts, farmers on Lakeside District use less water per acre of rice than farmers on Gulf Coast District. These differences may be due at least in part to differences in water management practices. On Gulf Coast District, many farmers maintain a continuous flow of water, or a holding stream, through the field and over the levee which surrounds the field. These holding streams reduce the time and effort required to tend fields. Another difference between the districts is that farmers on Gulf Coast District reconstruct the levees which surround their fields before each crop season. If the levee is not completely settled before the farmer irrigates his field, water has a tendency to seep under the base of the levee.

Crop Alternatives and Feasible Crop Areas

Crop prices and crop alternatives influence the quantity of water demanded and the elasticity of demand. When agriculture represents the best land use, crop prices and crop alternatives define the opportunity cost of producing rice. If rice is the most remunerative alternative, or there are no crop alternatives, there is no opportunity cost and water demand will be less elastic. One means of determining the elasticity of surface water demand is to estimate what the crop mix would be on rice acreage that farmers irrigate with surface water if those farmers did not plant rice. The estimate of a potential crop mix must include constraints on the physical characteristics of the land, crop rotation practices, crop prices, and ASCS base acreage allotments for program crops. These variables limit the ability of a farmer to select a crop mix that maximizes profits.

The existing crop mix on Lakeside District consists of cattle, corn, cotton, sorghum, and soybeans. The map of the Lakeside District in Figure 3.3 shows the feasible crop areas. Information on the location and distribution of base acreage has not been collected as part of this project. However, there is no reason to assume the base acreage allotments which farmers irrigate with surface water is not distributed randomly throughout the district (Jahn, Interview, December 8, 1993). The estimated base acreage allotment in each area is equal to the projected rice base acreage in 1993 times the proportion of total land area within the feasible crop area:

$$A_{it} = \hat{A}_t * \left(\frac{L_i}{\sum_i L_i} \right) \qquad \textbf{(Eq. 3.3)}$$

A	number of acres irrigated (acres)
$\hat{A}$	acreage projection calculated in equation 3.1 (acres)
L	total land area (acres)
i	an index of feasible crop area $i = (1, 2, 3)$
t	an index of crop year $t = (1, 2, 3, \ldots, n)$

The acreage projection in feasible crop area 1 for 1993 is 13,010 acres. The only crop alternative in area 1 is cattle. In Area 2, the estimated rice acreage is 4,359 acres, and in Area 3, the estimated rice acreage is 8,852 acres. Farmers have several crop alternatives in these areas including cattle, sorghum, cotton, corn, and soybeans (Cosper, Interview, January 26, 1994).

Good farming practices dictate that farmers maintain a temporal and a spatial crop mix. Each year, farmers rotate their crops between fields and leave some fields fallow. Therefore, crop mix within each area will vary from year to year. Local experts defined the boundaries of feasible crop areas on the basis of their knowledge of the area, farming practices, and soil type (Jahn and Fair, Interview, December 8, 1993). Local conditions within these areas may lead to differences in the set of feasible crops on any one piece of land. However, the feasible crop set is representative for the areas as a whole.

Soils in Area 1 are dominated by soils of the Katy and Edna associations. Their heavy clay content makes them unsuitable for dryland farming; therefore cattle is the only crop alternative. In Areas 2 and 3, soils are dominated by soils of the Crowley and Edna associations and crop alternatives are also limited. Although these soils are slightly more versatile, and farmers currently use this land for a variety of crops other than rice including cattle, corn, cotton, sorghum, and soybeans, the area is not well suited for dryland farming (Cosper, Interview, January 26, 1994). What the exact crop mix would be is not known; however, the estimates in Table 3.10 represent informed estimates of the possible crop mix given the physical and economic constraints facing farmers in these areas.

Feasible crop areas on the Gulf Coast District are East Side and West Side (Figure 3.4). Local environmental conditions within these areas vary considerably. As on Lakeside District, the assumption is that base acreage is distributed randomly throughout each feasible crop area. Estimates of rice base acreage in each area are based on exponential smoothing forecasts of the proportion of total rice acreage irrigated in the feasible crop area between 1980 and 1992. Equation 3.4 states that proportion of land area on the East Side of the river in the coming season is a function of the proportion of total rice acreage on the East Side in previous years.

$$A_{i(t+1)} = \alpha \frac{Y_{it}}{\sum_i Y_{it}} + (1 - \alpha) \frac{A_{it}}{\sum_i A_{it}} \qquad \textbf{(Eq. 3.4)}$$

Y	actual number of acres planted on the East Side
A	forecast acreage for East Side
α	a smoothing constant

i an index of feasible crop area $i = (1, 2)$
t an index of crop year $t = (1, 2, 3 \ldots, n)$

Alpha ($\alpha = .99$) is the smoothing constant which minimizes the mean squared error of the estimates. The high value of the smoothing constant indicates that the fraction of Gulf Coast acreage on the East Side last year is the best predictor of the fraction next year. On the East Side, the mean squared error of the estimate equals 0.01514. For the West Side, the proportion of rice acreage equals one minus the estimated fraction on the East Side. Rice acreage in each area equals the projected proportion for 1993 times the estimated rice acreage on the district. The estimated rice acreage on the East Side is 13,776 acres. On the West Side, the estimated rice acreage is 11,594 acres.

Given a scenario in which farmers were deprived of their use of surface water, the county extensionist in Matagorda County estimated the proportion of rice acreage farmers would convert to different feasible crops on each side of the river. He made this estimate on the basis of his knowledge of the physical characteristics of the land, farming practices, current crop prices, and existing ASCS farm programs. Farmers will select their crop mix to maximize profits. Even if farm programs and crop prices remain constant, farmers will select a different crop mix in successive years.

Participation in ASCS farm programs requires base acreage allotments, and farmers need to establish a history of production before they can participate. It can take several years for a farmer to build his base acreage, and the amount of land on which he receives deficiency payments will increase as he continues to raise program crops. Therefore, the crop mix which maximizes profits will change as the farmer gains partial participation in the program. For this reason, the estimates presented in Table 3.11 represent the potential crop mix in the first year that farmers convert rice acreage to alternative crops (Engbrock, Interview, December 14, 1993).

Table 3.10
Estimated Maximum Crop Acreage in Feasible Crop Areas on Lakeside District

	Area 1		Area 2		Area 3	
	Percent of Area*	Acreage	Percent of Area*	Acreage	Percent of Area*	Acreage
Crop Type						
Cattle	100.0	13,043.14	80.0	3,496.10	90.0	7,987.25
Corn	0.0	0.00	1.7	72.84	1.7	147.91
Cotton	0.0	0.00	1.7	72.84	1.7	72.84
Sorghum	0.0	0.00	15.0	655.52	5.0	443.74
Soybeans	0.0	0.00	1.7	72.84	1.7	72.84

Sources: Calculated by the author based on interviews with county extensionists: Cosper, John, 1994. County Extensionist, Texas Agricultural Extension Service, Wharton, Texas. Telephone Interview, January 26.; Fair, Connie M., 1993. District Conservationist, US Soil Conservation Service, Columbus, Texas. Interview, December 8.; Jahn, Rick. 1993. County Extensionist, Texas Agricultural Extension Service, Columbus, Texas. Interview, December 8.

Note: (*) Percent of rice acreage potentially converted to a particular crop type in the feasible crop area.

Figure 3.3
Feasible Crop Areas on Lakeside District

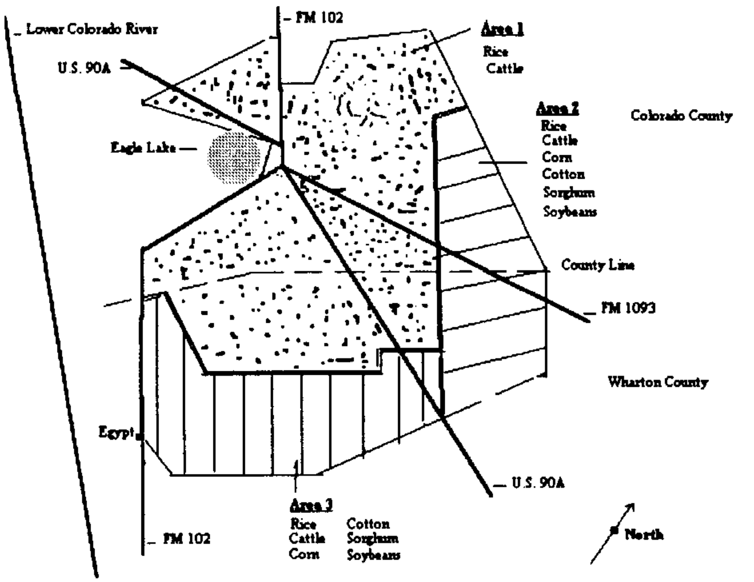


Figure 3.4
Feasible Crop Areas on Gulf Coast District

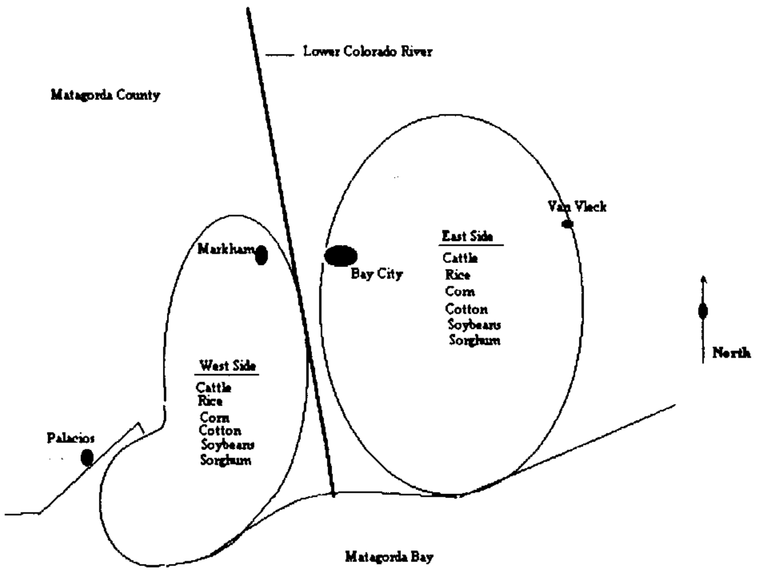


Table 3.11
Estimated Maximum Crop Acreage in Feasible Crop Areas on Gulf Coast District

	East Side		West Side	
Crop Type	Percent of Area*	Acreage	Percent of Area*	Acreage
Cattle	75 %	10,405.26	45 %	5,254.79
Corn	1	138.74	5	583.87
Cotton	5	693.68	10	1,167.73
Sorghum	4	554.94	15	1,751.58
Soybeans	15	2,081.05	25	2,919.33
Turf Grass	0	0.00	0	0.00

Source: Engbrock, James. 1993. County Extensionist, Texas Agricultural Extension Service, Bay City, Texas. Interview, December 14.

Note: (*) Percent of rice acreage converted to a particular crop type in the feasible crop area.

Farmers on Gulf Coast District also cultivate turf-grass. At this time, turf-grass is not considered a feasible crop alternative. The decision to plant turf-grass is a long-run decision and requires a significant capital investment over and above the variable costs of production. Several years ago, when turf-grass prices were higher, many farmers decided to make this investment. Since then, prices have fallen, and many farmers have converted from turf-grass to other crops. Those farmers that continue to raise turf-grass are sustained by their initial investment, but it is not considered feasible to establish new turf farms (Engbrock, Interview, December 14, 1993).

Farm Budget Residuals

Crop prices and production costs affect the demand for irrigation water. For example, the higher the crop price, the greater the farmer's willingness to pay. The farm budget residual (residual) measures farmers' willingness to pay (Gibbons, 1986). Equation 3.5 states that the residual is equal to farm revenue minus production costs, plus the variable cost of irrigation water:

$$\text{Residual} = \text{Revenue} - (\text{Variable Cost} + \text{Water Cost}) \qquad \textbf{(Eq. 3.5)}$$

If there are no crop alternatives and no opportunity costs associated with crop production, then the residual equals the value of water in rice production. If there are crop alternatives, the relationship between the residual and the value of water becomes less clear because the productive value of water does not change, but the farmer's willingness to pay for that water does. Therefore, the value of water and the farmer's willingness to pay equal the residual minus the profit associated with the most remunerative crop alternative.

Production costs will differ between those farmers that use surface water and those that use groundwater. The availability of groundwater as an alternative source of irrigation water influences the elasticity of demand. Farmers in Colorado and Wharton Counties use both surface water and groundwater. However, there is currently no reliable information on the extent, condition, and pumping capacity of privately owned groundwater wells on the Lakeside District. Model farm budgets do not discriminate between farms that use ground water and farms that use surface water. The district owns five groundwater wells, but the volume of water pumped amounts to only about two percent of total surface water diversions. Farmers on Gulf Coast District do not have access to groundwater wells for rice irrigation.

County extensionists in Colorado, Wharton, and Matagorda Counties provided model farm budgets for rice and alternative crops. Model budgets are based on actual farm data, and represent the average production costs for farms in each county. Because many farmers on Lakeside District use groundwater, Colorado and Wharton County budgets included some costs specific to groundwater pumping. These budgets were modified by removing these costs before calculating the residual.

Tables 3.12, 3.13, and 3.14 present the model rice budgets for each county. For example, in Table 3.12, total projected returns from a first crop in Colorado County are \$724.01, and the total short-run variable costs of production are \$409.74. Therefore, the residual value of water is \$314.07. In Wharton County, the total projected returns during the first crop are \$616.55, and the total short-run variable costs of production are \$361.98. Therefore, the residual value of water is \$254.57. Total short-run variable costs are the sum of planting and harvest costs, and irrigation water costs have been removed from these budgets. Budgets for alternative farm products have not been modified and are not reproduced here.

Table 3.15 and 3.16 present long-run and short-run farm budget residuals for all crops in each feasible crop area. Because there are model rice budgets for both Colorado and Wharton counties, residuals for each feasible crop area on Lakeside District are the sum of the weighted residuals for each county. The residuals and farm profits are weighted by the proportion of land in the feasible crop area falling in each of the counties. For example, 75.77 percent of feasible crop area 1 is in Colorado County, and 24.23 percent of feasible crop area 1 is in Wharton County. The short-run residual for the first crop is:

$$(0.7577 * 314.07) + (0.2423 * 254.57) = 299.65 \qquad \textbf{(Eq. 3.6)}$$

No farm budgets were available for non-rice crops in Colorado County. Therefore, Wharton County budgets represent farm profits for all areas on Lakeside District. On the Gulf Coast District, the residuals and farm profits for all crops are the same on both sides of the river and come directly from the Matagorda County rice budget. The short-run residual is calculated by subtracting total variable costs from the projected returns. The long-run residual is calculated by subtracting both total variable and total fixed costs from the projected returns. Because farm budget residuals for the rice crops do not incorporate any irrigation costs, they should not be interpreted as farm profit.

Table 3.12
Colorado County Rice Budget, 1993
(Cost per Acre)

	Value per Unit		Input Use	First Crop	Second Crop	Full Crop
PROJECTED RETURNS						
Yield per-acre (cwt)				58.00 cwt	14.00 cwt	72.00 cwt
Crop sales	$ 6.5	cwt		377.00 $	91.00 $	468.00 $
Deficiency Payment	4.21	cwt		242.20	0.00	242.20
Loan Gain	1.16	cwt		67.11	16.20	83.30
Premium	0.65	cwt		37.70	9.10	46.80
TOTAL PROJECTED RETURNS:				**724.01**	**116.30**	**840.31**
VARIABLE COSTS						
PLANTING COST ITEM						
Seed	$ 21.50	cwt	1	21.50	-	21.50
Nitrogen	0.21	lb	153	31.67	-	31.67
Phosphate	0.18	lb	54	9.72	-	9.72
Potash	0.12	lb	27	3.11	-	3.11
Furadan	0.73	lb	17	12.41	-	12.41
Fungicide	29.48	acre	0.5	14.74	-	14.74
Insecticide	3.12	acre	2	6.24	-	6.24
Prop-ord	28.89	acre	1	28.89	-	28.89
Propanil	17.61	acre	1	17.61	-	17.61
Cust Air Fert	2.85	cwt	2.25	6.41	-	6.41
Cust Air Fert	3.75	appl.	2	7.50	3.75	11.25
Cust Air Insect	2.50	appl.	2	5.00	-	5.00
Cust Air Fung	9.00	appl.	0.5	4.50	-	4.50
Cust Air Herb	4.50	appl.	2	9.00	-	9.00
Irrigation Water	0.0	acre	1	0.00	0.00	0.00
Nitrogen 2nd crop	0.26	lb	45	11.74	-	11.74
Machinery - fuel	26.76	acre	1	21.56	5.20	26.76
lube	26.77	acre	1	21.56	5.21	26.77
Repair	6.10	hour	4.51	22.19	5.36	27.54
Irrigation - labor	5.25	hour	6.1	25.80	6.23	32.03
Flagging	0.50	appl.	8	4.00	-	4.00
Operating Capital	0.09	dollar	183.43	14.04	3.39	17.43
PLANTING SUBTOTAL				**287.44**	**40.87**	**328.32**
HARVEST COST ITEM						
Drying	0.85	cwt	79.2	54.23	13.09	67.32
Hauling	0.28	cwt	79.2	17.864	4.31	22.17
Sales Commission	0.05	cwt	72	2.90	0.70	3.60
Machinery - fuel	11.89	acre	1	9.58	2.31	11.89
lube	41.85	acre	1	33.71	8.14	41.85
labor	6.10	hour	0.857	4.21	1.02	5.23
HARVEST SUBTOTAL				**122.50**	**29.57**	**152.07**
TOTAL VARIABLE COSTS				**409.94**	**70.44**	**480.38**
FIXED COST ITEM						
Depreciation, Interest, Taxes & Insurance on Machinery	102.89	acre	1	102.89	-	102.89
Land, Net Share-Rent	89.08	acre	1	78.39	10.69	89.08
TOTAL FIXED COSTS				**181.28**	**10.69**	**191.97**
TOTAL COSTS				**591.22**	**81.13**	**672.35**

Source: Texas Agricultural Extension Service. 1993. "Model Farm Budget, Rice." Columbus, Texas.

Note: Numbers may not add due to rounding.

Table 3.13
Wharton County Rice Budget, 1993
(Cost per Acre)

	Value per Unit		Input Use	First Crop	Second Crop	Full Crop
PROJECTED RETURNS						
Yield (cwt)				55.00 cwt	12.00 cwt	67.00 cwt
Crop Sales (first crop)	$ 7.00	cwt		385.00 $	-	385.00 $
Crop Sales (second crop)	6.40	cwt		-	76.80 $	76.80
Deficiency Payment	4.21	cwt		231.55	-	231.55
Loan Gain (*)	-	cwt		-	-	-
Premium (*)	-	cwt		-	-	-
TOTAL PROJECTED RETURNS				**616.55**	**76.80**	**693.35**
VARIABLE COSTS						
PLANTING COST ITEM						
Seed	$ 20.00	cwt	1	20.00	-	20.00
Nitrogen	0.20	lb	220	44.00	-	44.00
Phosphate	0.28	lb	40	11.20	-	11.20
Potash	0.12	lb	40	4.80	-	4.80
Fungicide and flying	54.00	acre	0.33	17.82	-	17.82
Insecticide	3.00	acre	4.12	12.36	-	12.36
Herbicide	24.64	acre	2	49.28	-	49.28
Cust Air Fert	3.00	cwt	5	15.00	-	15.00
Cust Air Insect	3.00	acre	3	9.00	-	9.00
Cust Air Herb	4.40	acre	2.5	11.00	-	11.00
Irrigation Water	0.0	acre	1	0.00	0.00	0.00
Machinery - fuel and lube	17.25	acre	1	14.16	3.09	17.25
labor	6.10	hour	2	10.01	2.18	12.20
Irrigation labor	6.10	hour	6	30.04	6.55	36.60
Operating Capital	0.09	dollars	156.87	11.59	2.53	14.12
PLANTING SUBTOTAL				**260.27**	**14.36**	**274.63**
HARVEST COST ITEM						
Drying	0.85	cwt	75.04	52.36	11.42	63.78
Hauling	0.30	cwt	75.04	18.48	4.03	22.51
Sales Commission	0.07	cwt	67	3.85	0.84	4.69
Machinery - fuel	6.32	acre	1	5.19	1.13	6.32
lube	18.67	acre	1	15.33	3.34	18.67
labor	6.10	hour	1.3	6.51	1.42	7.93
HARVEST SUBTOTAL				**101.71**	**22.19**	**123.91**
TOTAL VARIABLE COSTS				**361.98**	**36.55**	**398.53**
FIXED COST ITEM						
Depreciation, Interest, Taxes & Insurance on Machinery	141.75	acre	1	141.75	-	141.75
Land Net Share-Rent	75.00	acre	1	66.00	9.00	75.00
TOTAL FIXED COSTS				**207.75**	**9.00**	**216.75**
TOTAL COSTS				**569.73**	**45.55**	**615.28**

Source: Texas Agricultural Extension Service. 1993. "Model Farm Budget, Rice." Wharton, Texas. (Photocopy.)

Note: (*) Loan Gain and Premium included in other Projected Returns. Numbers may not add due to rounding

Table 3.14
Matagorda County Rice Budget, 1993
(Cost per Acre)

	Value per Unit		Input Use	First Crop	Second Crop	Full Crop
PROJECTED RETURNS						
Yield (cwt)				55.00 cwt	10.00 cwt	65.00 cwt
Crop Sales	$ 6.50	cwt		357.50 $	65.00 $	422.50 $
Deficiency Payment	4.30	cwt		223.30	-	223.30
Loan Gain	1.16	cwt		63.65	11.75	75.21
Premium	0.75	cwt		41.25	7.50	48.75
TOTAL PROJECTED RETURNS				**685.68**	**84.07**	**769.75**
SHORT RUN VARIABLE COSTS						
PLANTING COST ITEM						
Seed	19.50	cwt	1.2	23.40	-	23.40
Nitrogen	0.20	lb	310	60.76	-	60.76
Phosphate	0.15	lb	40	6.04	-	6.04
Potash	0.11	lb	20	2.30	-	2.30
Methyl Para	2.76	appl.	2	5.52	-	5.52
Furadan	0.65	lb	17	11.05	-	11.05
Fungicide - tilt	23.00	acre	1	23.00	-	23.00
Fungicide - roveral	18.08	acre	1	18.08	-	18.08
Prop-ord	26.14	acre	0.33	8.62	-	8.62
Propanil	15.60	acre	2	31.2	-	31.20
Cust Air Fert	4.80	cwt	4.06	19.49	-	19.49
Cust Air Insect	3.10	acre	2	6.20	-	6.20
Cust Air Fung	3.10	appl.	2	6.20	-	6.20
Cust Air Herb	3.10	acre	2.33	7.22	-	7.22
Cust Air Seed	3.35	acre	1.2	4.02	-	4.02
Irrigation Water	0.00	acre	1	0.00	0.00	0.00
Machinery - fuel and lube	14.24	acre	1	12.05	2.19	14.24
repair and labor	6.10	hour	6.46	22.65	4.12	26.77
Irrigation - labor	6.12	hour	5.25	27.16	4.94	32.10
Operating Capital	168.88	dollar	0.09	13.57	2.47	16.04
PLANTING SUBTOTAL				**308.55**	**13.72**	**322.27**
HARVEST COST ITEM						
Drying	0.85	cwt	58.34	41.96	7.63	49.59
Hauling	0.28	cwt	58.34	13.83	2.51	16.33
Sales Commission	0.05	cwt	53.04	2.24	0.41	2.65
Machinery - fuel and lube	9.04	acre	1	7.65	1.39	9.04
labor	6.10	acre	0.95	4.91	0.89	5.81
repairs	35.09	acre	1	29.69	5.40	35.09
HARVEST SUBTOTAL				**100.28**	**18.23**	**118.52**
TOTAL VARIABLE COSTS				**408.83**	**31.95**	**440.78**
FIXED COST ITEM						
Depreciation, Interest, Taxes & Insurance on Machinery	58.75	acre	1	58.75	-	58.75
Land Net Share-Rent	57.30	acre	1	50.42	6.88	57.30
TOTAL FIXED COSTS				**109.17**	**6.88**	**116.05**
TOTAL COSTS				**518.01**	**38.83**	**556.83**

Source: Texas Agricultural Extension Service. 1993. "Model Farm Budget, Rice." Bay City, Texas. (Photocopy.)

Note: Numbers may not add due to rounding.

Table 3.15
Long-Run Farm Budget Residuals and Farm Profits in Feasible Crop Areas
(Dollars per Acre)

	Lakeside District			Gulf Coast District	
	Area 1	Area 2	Area 3	East Side	West Side
Crop Type					
Rice, first crop	$ 111.95	$ 70.62	$ 47.47	$ 167.67	$ 167.67
Rice, full crop	146.17	102.96	78.75	212.92	212.92
Cattle	-140.68	-140.68	-140.68	-188.11	-188.11
Corn	-58.98	-58.98	-58.98	-52.50	-52.50
Cotton	82.77	82.77	82.77	46.88	46.88
Sorghum	-1.40	-1.40	-1.40	-43.80	-43.80
Soybeans	33.45	33.45	33.45	-42.50	-42.50
Turf Grass	-	-	-	-780.56	-780.56

Source: Calculated by the author based on information in: Texas Agricultural Extension Service. 1993. "Model Farm Budgets for Matagorda County." Bay City, Texas. (Photocopy.); Texas Agricultural Extension Service. 1993. "Model Farm Budgets for Wharton County." Wharton, Texas. (Photocopy.); Texas Agricultural Extension Service. 1993. "Model Farm Budgets for Colorado County." Columbus, Texas. (Photocopy.)

Note: For rice, the only irrigated crop, the numbers represent the farm budget residual. For all other crops, numbers represent expected farm profits.

Table 3.16
Short-Run Farm Budget Residuals and Farm Profits in Feasible Crop Areas
(Dollars per Acre)

	Lakeside District			Gulf Coast District	
	Area 1	Area 2	Area 3	East Side	West Side
Crop Type					
Rice, first crop	299.65	271.04	255.01	276.85	276.85
Rice, full crop	344.15	312.85	295.31	328.97	328.97
Cattle	67.32	67.32	67.32	59.49	59.49
Corn	48.79	48.79	48.79	37.69	37.69
Cotton	196.67	196.67	196.67	182.56	182.56
Sorghum	91.19	91.19	91.19	47.69	47.69
Soybeans	82.05	82.05	82.05	34.54	34.54
Turf Grass	-	-	-	-180.56	-180.56

Source: Calculated by the author based on information in: Texas Agricultural Extension Service. 1993. "Model Farm Budgets for Matagorda County." Bay City, Texas. (Photocopy.); Texas Agricultural Extension Service. 1993. "Model Farm Budgets for Wharton County." Wharton, Texas. (Photocopy.); Texas Agricultural Extension Service. 1993. "Model Farm Budgets for Colorado County." Columbus, Texas. (Photocopy.)

Note: For rice, the only irrigated crop, the numbers represent the farm budget residual. For all other crops, numbers represent expected farm profits.

Farmers Reactions to Changes in the Marginal Cost of Water

Under the old fixed irrigation charge, farmers had no control over water costs. Economic theory suggests that, given an opportunity to reduce water costs and increase farm profits, farmers will use less water. LCRA's 1993 transition from a completely fixed irrigation water charge to one with a volumetric price component presents an opportunity to evaluate farmers responses to changes in the marginal cost of water.

In 1992, the LCRA measured water deliveries at each field delivery structure, but continued to charge farmers on a per-acre basis. The objective was to give farmers an opportunity to learn how their management practices affect irrigation efficiency. In 1993, LCRA implemented its new rate structure with a ten percent cap on the difference between each farmer's 1992 and 1993 per-acre cost of water. LCRA's objective was to give the farmers another opportunity to see how management practices influenced irrigation efficiency.

Changes in irrigation water use between years provide a means of estimating the absolute change in irrigation water use which results from proportional changes in the marginal cost of water. This is in one sense a demand function for irrigation water. However, estimates are based on irrigation efficiency and do not include information on other relevant factors such as crop alternatives. Estimates are based on data collected over a small range of prices and the ten percent cap on differences in water cost between years may have influenced farmers' irrigation decisions.

Another method of estimating farmers responses to changes in the marginal cost of water might be to gather information on irrigation efficiency from rice irrigation districts in other parts of the country. Environmental and economic conditions can vary substantially from one farming region to another, and volumetric pricing of water is a rare characteristic of rice irrigation districts. The empirical observations from within the river basin provide a better measure of farmers reactions than an extrapolation from other parts of the country.

Equation 3.7 presents the regression equation used to estimate farmers reactions to changes in the marginal cost of water. Parameter estimates are based on a data set that includes 1992 and 1993 water accounting database records of the volume of water delivered to fields. For Lakeside District, the analysis includes only those farmers farming in both 1992 and 1993. For Gulf Coast District, the analysis includes all farmers because many records were incomplete, and restricting the data set only to those farmers farming in both years would have resulted in an unacceptably small data set. This equation states that the volume of water used in irrigation is a function of the effective price of water, the size of the field, the number of days over which a farmer takes water, and the crop type:

$$V = \beta_0 + \beta_1 \ln(PE) + \beta_2 A + \beta_3 D + \beta_4 C \qquad \textbf{(Eq. 3.7)}$$

V	field-specific total water use (acre-feet)
PE	effective price of water (dollars per acre-foot)
A	field acreage (acres)
D	number of days between first irrigation and last irrigation (days)
C	a dummy variable equal to one for observations from second crop fields
β	coefficients are estimated by ordinary least squares regression

To test whether or not there is a significant difference between farmer's reactions on Gulf Coast District and on Lakeside District, the districts were combined in a single model using dummy variables and interactions terms:

$$V = \beta_0 + \beta_1 \ln(PE) + \beta_2 A + \beta_3 D + \beta_4 C + \beta_5 G + \beta_6 INTG \qquad \textbf{(Eq. 3.8)}$$

G	a dummy variable equal to one for observations from Gulf Coast District
INTG	an interaction term equal to G times the natural log of the effective price of water on Gulf Coast District.

All other variables are identical to those in equation 3.7. The coefficient for the INTG variable measures difference in how Gulf Coast farmers react to price changes relative to Lakeside farmers.

The effective price of water in equations 3.7 and 3.8 is the price farmers anticipate paying. Because the districts charge an additional volumetric fee for stored water and farmers do not know what fraction of a delivery is stored water, farmers do not know the exact price of water at the time irrigation occurs. The anticipated price is calculated on the basis of the probability that the farmer draws stored water. Equation 3.9 states that the effective price of water during each crop period is equal to the volumetric price of water diverted under irrigation district water rights plus the expected cost of drawing stored water during that crop period:

$$PE_i = PD + \left(\frac{\sum_j VS_j}{\sum_j VT_j} * PS \right) \qquad \textbf{(Eq. 3.9)}$$

PE	effective price of water (dollars per acre-foot)
PD	variable price of water on the irrigation district (dollars per acre-foot)
PS	price of stored water from the Highland Lakes (dollars per acre-foot)
VS	total volume of stored water diversions on the district (acre-feet)
VT	total volume of water diversions on the district (acre-feet)
i	an index of first or second crop period $i = (1, 2)$
j	an index of month $j = (1, 2, 3, \ldots, 12)$

All water diversions prior to August 1 may be attributed to the first crop, and all water diversions on or after August 1 may be attributed to the second crop (Martin, 1988). On Lakeside District, the effective price of water during the first crop period is \$10.22 and during the second crop period is \$12.59. On Gulf Coast District, the effective price of water during the first crop period is \$6.11 and during the second crop period is \$7.27.

Equation 3.8 can be modified by removing the acreage variable to relate changes in the effective marginal cost of water to on-farm irrigation efficiency. The dependent variable then represents field-specific acre-feet per acre rather than field-specific total water use. The equation states that irrigation efficiency is a function of the number of days during the growing season, the effective price of water, the crop type, and the location of the field (by district):

$$W = \beta_0 + \beta_1 \ln(PE) + \beta_3 D + \beta_4 C + \beta_5 G + \beta_6 INTG \qquad \textbf{(Eq. 3.10)}$$

W	field inflow (acre-feet per-acre)

All other variables are identical to those in equation 3.7.

Table 3.17 presents the regression results for equations 3.8 and 3.10. The parameter estimate for PE provides a measure of the absolute change in water use per acre resulting from a proportional change in the effective price of water. The R-squared value for equation 3.8 is relatively high because acreage has a strong influence on field water use. When the dependent variable is irrigation efficiency, as in equation 3.10, the regression model loses its explanatory power. This does not invalidate the parameter estimates. The fact that the t-statistics for PE, the effective marginal cost of water, and the model F-statistic are consistently significant across the two specifications supports the use of equation 3.10 as a tool for anticipating changes in water use.

The data on which these estimates are based include only two price points. Clearly, an estimate of how farmers react to changes in the price of water will improve with an increase in the number of observations at different prices. For this reason, this report does not rely on these data to estimate demand or to predict how water use will change. These equations are incorporated into the linear programming model as one factor of demand.

The functional form was selected to capture farmer's diminishing marginal propensity to conserve water. In contrast, a linear model would indicate that there is a constant change in the volume of water saved. The effect would be to overestimate the elasticity of demand for water at higher prices. Despite advantages, equation 3.10 is asymptotic at an effective water price of 0. This implies that farmers will use an infinite amount of water if it has no marginal cost (as is the case when districts charge farmers only on a per-acre basis). Because too much water can ruin a rice crop, farmers will not behave this way. This inconsistency will not affect any estimates or conclusions about the demand for water later in this paper.

An interpretation of regression results with respect to the effective price variable suggests increasing water price will produce marginally decreasing water savings on each districts. Mean on-farm water use on Lakeside District (acre-feet per acre) decreases 0.073 acre-feet per acre with a one unit increase in the natural log of the effective price. Mean on-farm water use on Gulf Coast District decreases 0.059 acre-feet per acre $(-0.073 + 0.014 = -0.059)$ with a one unit increase in the natural log of the effective price. The difference in the rate of decrease in water use between districts (β_6) is not statistically significant. This suggests essentially no difference between the districts in farmers' propensity to conserve water in response to increases in marginal cost.

Figure 3.5 projects total water savings under assumptions. Projected water savings are for on-farm water use during the first crop only assuming 25,000 planted acres on each district and 100 days between first and last irrigation in all fields. Projected water savings do not reflect decreases in water use associated with acreage reductions or any change in canal losses associated with reduced pumpage requirements. Changes in the effective water price represent increases in the marginal cost of water above current first crop effective prices ($10.22 on Lakeside District and $6.55 on Gulf Coast District). Increases in the marginal cost of water will not increase district revenues, or necessarily increase a farmers' total cost of irrigation service if increases in volumetric prices are balanced by decreases in the fixed per-acre irrigation charge. The short-run nature of these estimates is discussed in Chapter 6.

In a competitive market, equation 3.8 might itself be interpreted as a demand curve for water. However, the price of water on the irrigation districts is established on a cost of service basis, and is not based on competitive demand. Therefore, it is inappropriate to interpret the curve as if it were a demand curve.

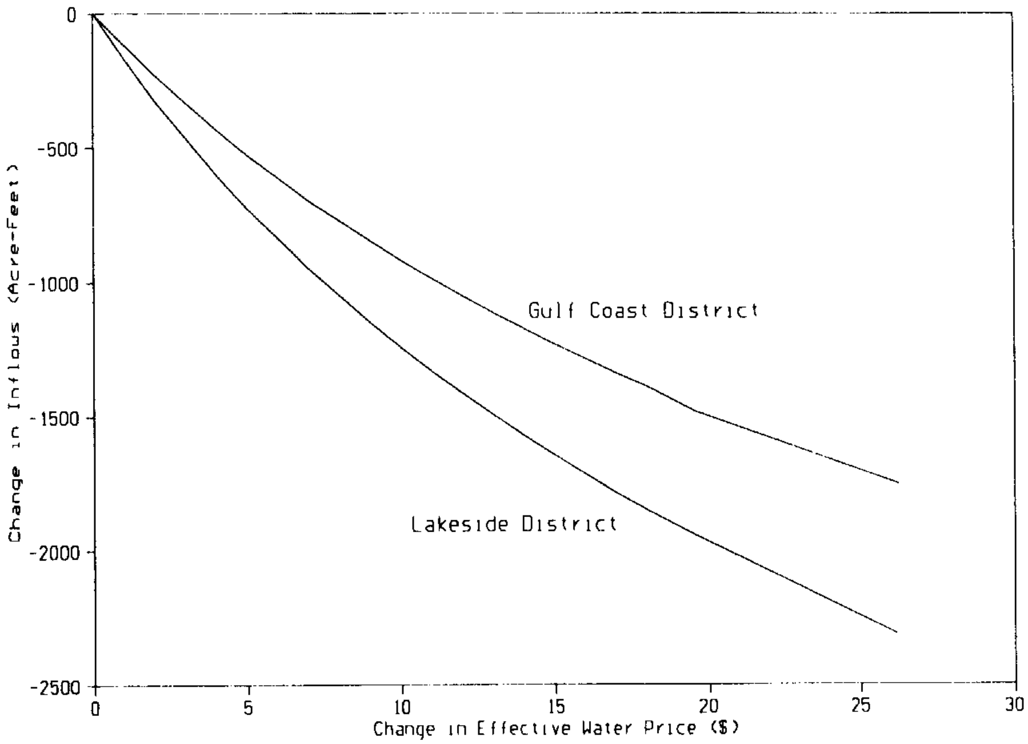
Table 3.17
Parameter Estimates and T-Statistics for the Model of Farmers Reactions

Variable	Coefficients	Eq. 3.8	Eq. 3.10
Intercept	β_0	-166.318	1.074
Effective Price (PE)	β_1	-6.349	-0.073
		(-3.597)*	(-4.400)*
Field Acreage (A)	β_2	2.629	-
		(47.181)*	-
Days Watered (D)	β_3	2.163	0.022
		(8.007)*	(8.097)*
Crop Type† (C)	β_4	-31.366	-0.446
		(-2.929)*	(-4.119)*
District‡ (G)	β_5	59.808	0.739
		(4.879)*	(6.046)*
Interaction Term (INTG)	β_6	2.077	0.014
		(0.694)	(0.448)*
R-squared		0.742	0.243
Adjusted R-squared		0.740	0.239
Model F		422.400	56.807

Source: Calculations by the author based on data in: Lower Colorado River Authority. 1993. Irrigation District Water Accounting Database. Lakeside Irrigation District, Eagle Lake, Texas. (Computer File.); Lower Colorado River Authority. Irrigation District Water Accounting Database. Gulf Coast Irrigation District, Bay City, Texas. (Computer File.)

Note: T-statistics given in parenthesis. (*) Asterisks indicate significance at the 95 percent confidence level. (†) Crop type is a dummy variable indicating first or second crop. (‡) District is a dummy variable indicating observations from Gulf Coast District.

Figure 3.5
Projected Water Savings Associated with Increases in the Effective Water Price



Note: Projected water savings are for on-farm water use during the first crop only assuming 25,000 planted acres on each district and 100 days between first and last irrigation in all fields. Water savings do not reflect decreases in water use associated with acreage reductions or any change in canal losses associated with reduced pumpage requirements. Changes in the effective water price represent increases in the marginal cost of water above current first crop effective prices ($10.22 on Lakeside District and $6.55 on Gulf Coast District). The short-run nature of these estimates is discussed in the text.

Summary

The information in this chapter forms the basis for constructing a linear programming model of on-farm irrigation water demand. Table 3.18 summarizes the information presented in this chapter, and identifies the source of that information. This data represents the best information available about the irrigation districts and the factors that influence demand.

Many factors that influence the demand for water are not known. In the final section, the elasticity estimates appear extremely low. This is perhaps an artifact of the statistical methods or a reflection of the ten percent cap on the difference in the cost of irrigation between 1992 and 1993. The following chapter applies data envelopment analysis to determine whether or not farmers actually can save water and whether or not the price elasticity of demand has been underestimated.

Table 3.18
Summary of Information about the LCRA Irrigation Districts

	Information	Source
1	Total water diversions and percent of consumptive use in the river basin.	Texas Water Commission and Lower Colorado River Authority.
2	Stored water diversions, 1989-1992.	Lower Colorado River Authority.
3	First and second crop rice acreage, 1968-1993.	Lakeside and Gulf Coast Irrigation Districts.
4	Farmer's individual water management styles.	Irrigation district water coordinators.
5	Field acreages, field water deliveries, length of field irrigation period.	Irrigation district water accounting databases.
6	District rainfall	National Weather Service field stations at Bay City Waterworks and Columbus.
7	Feasibility of alternative crops.	Texas Agricultural Extension Service, county agricultural extension agents.
8	Rice and alternative crop budgets.	Texas Agricultural Extension Service, model farm budgets by county.
9	Farmer's reactions to a change in the marginal cost of water.	Irrigation district water accounting databases.
10	Potential water savings associated with irrigation technologies.	Texas A&M University, Less Water-More Rice research project.
11	Irrigation technology costs.	Rice farmer interviews.
12	Effect of soil type and rice varieties on field water use.	Texas Agricultural Experiment Station and US Soil Conservation Service.
13	Operational costs on each LCRA irrigation district.	Lower Colorado River Authority.

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Chapter 4
The Irrigation Efficiency Frontier in First Crop Rice Fields

For a water conservation program to work, there must be water to save through conservation. Therefore, it is necessary to determine whether or not farmers can actually improve irrigation efficiency. Can farmers maintain or improve yields while simultaneously using less water for irrigation? If so, there is a win-win solution to the problems of resource scarcity. This chapter presents empirical evidence to suggest that improved water management practices in rice farming can save a substantial amount of water. Results prescribe technically efficient field inflow for sample fields; however, more work is need to develop general standards for irrigation water use. Results can be used to establish on-farm irrigation water conservation targets for Lower Colorado River Authority (LCRA) rice irrigation districts. Conclusions rest on demonstrated performance at farms in Texas' gulf coast region.

Between 1982 and 1988, researchers at Texas A&M University's Texas Agricultural Experiment Station in Beaumont collected information on water budgets and rice yields at sample fields throughout the gulf coast region during the "Less Water-More Rice" research project. In all cases, fields contained a semidwarf variety of rice (TAES, 1982 - 86). These data provide a means of assessing on-farm water efficiency and the crop-water inflow production frontier for rice fields in South Texas. Knowledge of the production frontier is useful because it provides farmers and water management agencies with information about what might be an appropriate standard for irrigation efficiency.

There is a definite relationship between the amount of irrigation water applied to a field and crop yield. As discussed in Chapter 2, these relationships are usually expressed in the quadratic or the Cobb-Douglas forms. However, when the data on crop yield and water use collected by Texas A&M scientists is analyzed using these functional forms, there appears to be no statistically significant relationship between crop yields and field water use. One possible reason is that water in continuous flood irrigation serves more than just a means of satisfying the minimum water requirements of the rice plant. Water also serves as a substitute for labor, pesticides, and infrastructural improvements such as land levelling.

Figure 4.1 shows a scatterplot of crop yields on field water use. If one follows the highest yielding fields across the various levels of field use, there appears to be a slightly quadratic production frontier. However, economic theory suggests that farmers will not use more water than they need if this will reduce their yields. Therefore, it is not realistic to equate these estimates with a true quadratic production function. In Figure 4.1, boxes around the sample field indicate that these fields are laser-levelled. Specific information about fields is listed in Table 4.1.

Data Envelopment Analysis

Data envelopment analysis (DEA) is a linear programming technique that locates a firm's production efficiency frontier based on the performance of other firms. The DEA methodology was originally introduced by Farrell (1957), and further developed by Charnes *et al.* (1978). The following analysis presents an application of DEA methods, but the logical development and proof of these methods are beyond the scope of this paper. Rhoades (1978) provides a mathematical statement of DEA. Ganley and Cubbin (1992) provide a good reference for the reader that is interested in the logical development and application of DEA methods. Most of the analysis presented in this paper was conducted using Ideas Software, available from 1-Consulting, in Amherst, Massachusetts.

DEA estimates the technically efficient level of input use. Technical efficiency with respect to a particular input is defined in terms of two minimum conditions. The firm must produce at a level such that it may not increase its outputs without first either increasing one or more of its inputs, or reducing one or more of its other outputs. In addition, none of the firm's inputs may be reduced without also decreasing some of its outputs, or increasing some of its other inputs (Norman and Stoker, 1991, p. 15). The method may be used to establish management objectives and evaluate performance based on demonstrated achievement in private or public organizations.

DEA has been the subject of strong criticism because of limitations and ambiguities in the interpretation of results and because of operational constraints. Recent software developments have reduced some of the operational constraints. Specifically, it is no longer necessary to assume constant returns to scale. Therefore it is possible to evaluate a firm on the basis of its technical efficiency as well as its scale efficiency (Ganley and Cubbin, 1992). It is also possible to write programs that account for uncontrollable inputs (Banker and Morey, 1986) and multiple noncompeting outputs (Banker and Maindiratta, 1986).

DEA postulates that, for a given set of decision making units (DMUs), there is a convex production surface which can be located in a multidimensional world of n inputs (X_k, $(k = 1, 2, ..., n)$) and m outputs (Y_i, $i = (1, 2, ..., m)$). This surface is referred to as the hyperplane. Depending upon the management objectives and the way the program is written, the hyperplane can define how few inputs are required to produce a given output (input minimization), or how much output can be produced for a given number of inputs (output maximization).

The problem may be formulated in two ways. Although it is nonlinear, a fractional program provides a conceptually simple and logical description of the DEA methodology. It is a total factor productivity ratio (Ganley and Cubbin, 1992). The objective function for each DMU in the fractional program is maximize the ratio of the sum of weighted outputs divided by the sum of weighted inputs by adjusting the weights (prices) μ_i and ν_k where the indices i and k identify specific inputs and outputs:

$$\text{MAX} \quad Z = \frac{\sum_i \mu_i Y_i}{\sum_k \nu_k X_k} \qquad \textbf{(Eq. 4.1)}$$

Y	a vector of m outputs	
X	a vector of n inputs	
μ	weights on outputs	
ν	weights on inputs	
i	an index of outputs	$i = (1, 2, ..., m)$
k	an index of inputs	$k = (1, 2, ..., n)$

The weights μ_i and ν_k are weights on outputs and inputs. DEA programs calculate weights to maximize the ratio. The ratio of the weighted sum of outputs and the weighted sum of inputs must fall between 0 and 1. This ensures that the weighted sum of outputs cannot exceed the weighted sum of inputs and that the program restricts efficiency scores to a number less than or equal to 1:

$$0 \leq \frac{\sum_i \mu_i Y_i}{\sum_k \nu_k X_k} \leq 1 \qquad \textbf{(Eq. 4.2)}$$

To differentiate between the input minimization and output maximization objectives, either the numerator or the denominator is constrained to one. In the input minimization model, the numerator is constrained to one:

$$\sum_i \mu_i Y_i = 1 \qquad \text{(Eq. 4.3)}$$

In both the input minimization and the output maximization models, all weights are constrained to non-zero values (Ganley and Cubbin, 1992). The constraint also ensures that the program first calculates the maximum proportional reduction in inputs before identifying any additional slack in the input variables (Banker and Morey, 1986):

$$\mu_i , \nu_k > \varepsilon \qquad \text{for all } i , k \qquad \text{(Eq. 4.4)}$$

The variable ε is a constant greater than zero, usually 10E-6.

The linear form of the program flows logically from its fractional form. Since the numerator for each DMU in the input minimization model is constrained to one, the linear objective function is the reciprocal of the fractional objective function. The objective is to minimize the weighted sum of given inputs at each DMU to achieve the stated output by adjusting the weights on inputs:

$$\text{MIN} \sum_k \nu_k X_k \qquad \text{(Eq. 4.5)}$$

The variable X_k is the input level, and ν_k is the weight on input k. The first constraint limits the sum of weighted inputs to less than the sum of weighted outputs, and is tantamount to stating that outputs cannot exceed any possible combination of inputs:

$$\sum_k \nu_k X_k \geq \sum_i \mu_i Y_i \qquad \text{(Eq. 4.6)}$$

The variables X_k and Y_i are as before. As in the fractional program, the sum of weighted outputs is constrained to one, and weights on both input and output variables are constrained to positive values:

$$\sum_i \mu_i Y_i = 1 \qquad \text{(Eq. 4.7)}$$

$$\mu_i , \nu_k > \varepsilon \qquad \text{for all } i, k \qquad \text{(Eq. 4.8)}$$

The primal formulation given above imposes constant returns to scale. Once all weights are established, DEA programs then determine efficiency at an individual DMU according its relative distance from the hyperplane. Banker, Charnes, and Cooper (1984) develop the dual program and add additional constraints to incorporate returns to scale by restricting the set of DMU's used in this comparison. The effect is to create a piecewise efficiency frontier composed of facets along the outer edge of the production possibility set.

Figure 4.1
The Relationship Between Field Water Use and Crop Yields, First Crop Fields

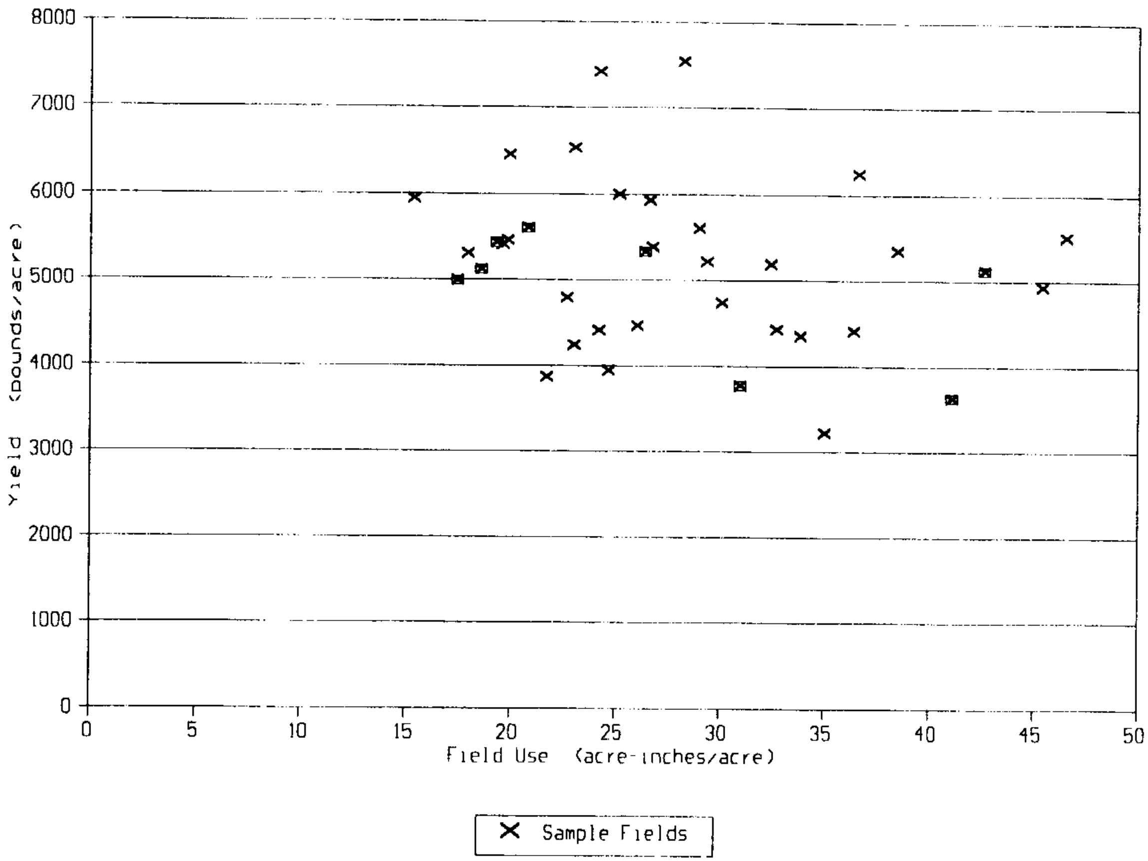

Table 4.1
Sample Field Data, First Crop Rice Fields, Texas Gulf Coast

Year	Field	Note	Rice Variety	County	Acreage	Yield lbs/ac	Inflow in/ac	Rainfall in/ac	Runoff in/ac	Field Use in/ac	N* lbs/ac	P** lbs/ac	K*** lbs/ac	Efficient in Model:
1982	821	L	Bellemont	Wharton	73.4	5,426	25.9	11.7	18.4	19.3	154.2	72.0	36.0	
1982	822		Bellemont	Jackson	27.0	4,933	55.3	10.1	19.9	45.4	121.1	45.5	45.5	
1982	823		Labelle	Colorado	28.0	5,184	30.1	9.9	7.6	32.4	109.1	28.6	28.6	5
1982	824		Labelle	Colorado	32.0	6,444	21.4	9.5	11.0	19.9	147.2	46.0	128.0	
1982	825	L	Labelle	Fort Bend	18.9	5,118	14.4	10.3	6.1	18.6	105.5	41.2	82.5	
1982	826		Labelle	Waller	83.4	5,941	16.3	11.1	12.1	15.3	92.0	50.0	80.0	2, 3, 4, 5
1983	831	L	Labelle	Fort Bend	18.9	5,113	36.8	18.0	12.3	42.6	91.4	49.4	49.4	1, 2, 3
1983	832		Labelle	Jefferson	36.0	4,399	40.3	34.7	38.6	36.4	178.0	40.0	12.5	3
1983	833		Labelle	Matagorda	43.2	5,449	16.9	18.9	16.1	19.8	121.5	40.0	20.0	
1983	834		Lemont	Chambers	23.4	4,343	40.5	35.5	42.2	33.8	173.5	40.0	10.0	
1983	835		Labelle	Colorado	25.5	3,865	46.0	13.5	37.9	21.7	129.0	30.0	30.0	
1983	836		Labelle	Liberty	67.6	4,725	28.1	26.0	24.1	30.0	128.8	0.0	0.0	3, 5
1983	837		Labelle	Jackson	41.3	5,391	12.8	15.6	8.9	19.5	120.7	40.0	20.0	3, 4, 5
1983	838	L	Labelle	Wharton	52.0	5,345	42.7	20.5	24.8	38.4	144.8	40.0	20.0	
1984	841		Lemont	Jefferson	94.0	5,330	32.4	17.5	23.5	26.4	190.4	19.3	0.0	3, 5
1984	842A		Lemont	Liberty	22.1	4,423	23.6	21.4	12.3	32.7	200.2	0.0	0.0	3
1984	842B		Labelle	Liberty	29.3	3,942	14.8	18.8	9.0	24.6	125.0	0.0	0.0	3, 5
1984	843		Labelle	Chambers	49.4	4,241	30.9	9.6	17.6	22.9	162.0	54.0	27.0	
1984	844		CB801	Brazoria	46.4	4,463	32.1	12.7	18.8	26.0	181.5	40.0	20.0	
1984	845	L	Labelle	Fort Bend	18.9	3,628	65.4	8.0	32.3	41.1	104.5	52.0	52.0	
1984	846		Lemont	Wharton	50.1	5,989	37.4	13.0	25.2	25.1	171.0	36.0	18.0	5
1984	847		Lemont	Matagorda	69.3	3,213	33.6	14.4	13.0	35.0	162.0	40.0	20.0	
1984	848		Labelle	Colorado	66.0	5,209	23.9	14.1	8.7	29.3	105.0	57.5	40.0	
1984	849	L	Lemont	Jackson	79.9	3,769	32.4	10.4	11.8	31.0	181.5	22.5	22.5	

(Continued on the following page.)

Table 4.1 (Continued)
Sample Field Data, First Crop Rice Fields, Texas Gulf Coast

Year	Field	Note	Rice Variety	County	Acreage	Yield lbs/ac	Inflow in/ac	Rainfall in/ac	Runoff in/ac	Field Use in/ac	N* lbs/ac	P** lbs/ac	K*** lbs/ac	Efficient in Model:
1985	851		Lemont	Jefferson	71.3	5,918	26.8	14.6	14.9	26.6	228.0	34.5	19.4	
1985	852	L	Lemont	Liberty	71.3	5,589	18.7	13.0	10.9	20.8	155.0	45.0	60.0	
1985	853		Skybonnet	Chambers	69.5	5,383	24.5	13.8	11.6	26.7	141.2	43.9	11.8	5
1985	854		Lemont	Brazoria	101.0	6,529	29.0	12.2	18.3	23.0	155.5	40.8	40.8	
1985	855		Lemont	Fort Bend	42.5	7,415	23.4	10.5	9.8	24.1	166.0	45.5	55.5	1, 2, 3, 4, 5
1985	856		Labelle	Wharton	30.3	4,410	19.8	14.1	9.7	24.2	153.8	59.5	16.5	
1985	857		Skybonnet	Matagorda	57.7	5,516	44.3	17.2	14.9	46.5	115.0	0.0	0.0	5
1985	858		Labelle	Colorado	18.8	4,783	21.8	15.1	14.3	22.6	127.4	52.8	26.4	
1985	859		Lemont	Jackson	37.9	5,300	22.0	9.2	13.2	17.9	198.0	45.6	24.0	5
1986	861	L	Gulfmont	Jefferson	42.6	4,982	11.6	19.1	13.2	17.4	116.7	38.9	40.0	3, 4 ,5
1986	863		Lemont	Chambers	50.0	5,597	30.1	17.4	18.6	28.9	198.0	40.9	51.8	
1986	864		Lemont	Brazoria	65.0	7,545	36.8	17.5	26.0	28.2	219.6	29.4	29.4	1, 2, 3
1986	866		Skybonnet	Wharton	43.1	6,232	31.9	14.1	9.4	36.6	163.3	44.8	56.0	

Source: Texas Agricultural Experiment Station (TAES). 1982-86. *Progress Report on Cooperative Rice Irrigation Study.* Texas A&M University: Beaumont, Texas. (Annual Report.)

Note: L denotes laser levelled fields. (*) Nitrogen. (**) Phosphorous. (***) Potassium.

In a multidimensional variable returns to scale model, the location of the target point (Y-hat, X-hat) on the hyperplane for a DMU j is:

$$\sum_{i} \mu_{ij} \phi_j Y_{ij} - \sum_{k} \nu_{kj} \theta_j X_{kj} + \omega_j = 0 \qquad \textbf{(Eq. 4.9)}$$

ϕ	proportional augmentation in outputs *possible* with no concurrent reduction in inputs	
θ	proportional input reduction *possible* with no concurrent reduction in output	
ω	constant term of the hyperplane associated variable returns to scale models	
j	an index of DMUs	j = (1, 2, 3, ..., l)
i	an index of inputs	i = (1, 2, 3, ..., m)
k	an index of outputs	k = (1, 2, 3, ..., n)

The variable ω_j has a unique value for each facet of the hyperplane, and indicates increasing returns to scale at the DMU for ω_j greater than 0, and decreasing returns to scale at the DMU for ω_j less than 0. Efficiency scores (θ) indicate the DMU's distance from the hyperplane relative to its distance from the origin:

$$\gamma_j = 1 - \theta_j \qquad \textbf{(Eq. 4.10)}$$

γ proportional reduction in inputs *necessary* to achieve maximum efficiency at DMU j

For an individual input at DMU j, there may be residual excess (e) after proportional reductions in inputs. If, after a proportionate reduction in inputs, there remains some residual excess input, a DMU may only become technically efficient by altering the ratio of its inputs. DEA programs calculate the residual reduction in a particular input that is necessary to achieve technical efficiency:

$$X_{kj} - \theta_j X_{kj} - \gamma_j X_{kj} = e_{kj} \qquad \textbf{(Eq. 4.11)}$$

e excess quantity of input X used in the production process that could be eliminated after the proportional reduction of all inputs ("the residual excess").

The term $\theta_j X_{kj}$ is the prescribed quantity of input k necessary for DMU j to achieve its target point on the hyperplane, and the variable X is the actual quantity of input k used at DMU j. The variable In a model with multiple inputs, the value of e for at least one input will equal zero.

Including variable returns to scale constraints in the DEA program enables the analyst to discriminate between scale inefficiency and technical inefficiency because firms operating at a less than optimum scale may be classified as efficient. Byrnes *et al.* (1984) note that firms may appear scale inefficient because of differences in the production technology at individual firms in the set of DMUs under analysis. It is possible to avoid this confusion by strictly limiting the analysis set to DMUs using similar technology.

For the purposes of this paper, it is sufficient to recognize two characteristics of the variable returns to scale model. First, the model provides a purer measure of technical efficiency than the constant returns to scale model because there is no confusion between technical and scale efficiency. Second, the efficiency scores tend to be higher than in the constant returns to scale model (Ganley and Cubbin, 1992).

It is worth discussing the difference between efficiency in the DEA sense, and ordinary production efficiency described in chapter 2. First, the efficiency scores (θ) in this chapter refer only to technical efficiency. To be classified as Pareto efficient in conventional economic theory, a DMU must meet three conditions. It must be simultaneously allocative, scale, and technically efficient. Such a definition is useful in terms of allocating resources among a group of users, but practical applications of the theory are rare. Secondly, the efficiency score (θ) is revealed technical efficiency and reflects the level of efficiency achieved through best practices. Given a hypothetical set of ideal (better) practices, DEA-efficient DMUs could potentially become more efficient.

Because the efficiency score (θ) is based on revealed efficiency, the location of the efficiency frontier is sensitive to the set of DMU's under analysis. In addition, the performance of individual DMUs may vary across time periods. Therefore, Ganley and Cubbin (1992) recommend using panel data sets to minimize the bias related to stochastic variation in individual DMU performance over time. These authors also recommend using parametric statistical methods to evaluate the accuracy of efficiency scores over different time periods. Banker *et al.* (1986) use the χ^2 test for non-parametric data to evaluate the differences in results between DEA and other methods. These techniques might also be applied to evaluate discrepancies between DEA models. In the analysis of irrigation efficiency that follows this discussion, four years of data collected in different fields are combined into a single DMU analysis set. Although this aggregation of data helps minimize the risk of underestimating the true frontier, there are other problems specific to the reliability of these DEA results which are discussed later in this chapter.

DEA-Defined Technical Efficiency in Rice Irrigation

Perhaps one of the most difficult problems the analyst must deal with in applying DEA is the selection of appropriate variables. Because DEA is a non-parametric approach to frontier estimation, it assumes no normality or independence between the variables, and does not require the analyst to define a functional relationship between inputs and outputs (Banker, 1978; Ganley and Cubbin, 1992). Perhaps as a result, the technique is more useful in determining what is possible than how to achieve that possible outcome. Therefore, the following discussion will focus as much on developing the problem and choosing the variables as on the presenting, interpreting, and discussing the results.

Consistent with previous chapters, the DEA model assumes that each farmer makes water management decisions in a field to maximize profits. As discussed in Chapter 2, that is distinctly different than maximizing output. Therefore, it is not reasonable to impose an output maximization objective on individual farmers. Suppose a hypothetical water management agency would like farmers to minimize their water use. DEA defines the agency's objective in terms of minimizing the distance between the amount of water a farmer uses and the amount of water his peers on the frontier (hyperplane) do use in the production of rice.

Further suppose this water management agency would like farmers to reduce their field water use according to the yields they achieve. Such an objective would be consistent with the allocation of marginal water resources to their most productive use. Model 1 consists of one output (yield) and one input (field water use). Water that enters the field via irrigation inflows or rainfall may either be used in the production process (field water use) or runoff the field. Field use is calculated by an equation that states water consumed in a field is equal to rainfall and irrigation water inflows minus water runoff:

$$F = R + I - N \qquad \textbf{(Eq. 4.12)}$$

F	water used in the production process [field water use] (inches per acre)
R	rainfall (inches per acre)
I	irrigation inflows (inches per acre)
N	water runoff (inches per acre)

Implicit in the water management agency's request is the assumption that water is a factor in the production process, and that lower yields should require less water.

Results of Model 1 are presented in Table 4.2 and indicate that fields 826, 855, and 864 are the efficient fields. These three fields are the dominant DMUs and therefore define the efficiency frontier. These results indicate the potential reduction in field water use that is possible at individual fields. For example, the farmer in field 821 could reduce field water use by 24 percent ($\gamma = 0.24$) without reducing yield.

From the water management agency's perspective, asking farmers to minimize field water use is not practical. Farmers do not measure their field use, and probably have little intuitive sense of how the relative combination of rainfall, inflow, and runoff affects their field water use. In addition, water is an intermediate factor in the production process, not a component of the final product. Therefore, water that leaves a field through runoff may or may not serve a productive purpose other than as an input to satisfy the evapotranspiration needs of the rice plant. Perhaps that purpose is as a substitute for infrastructural improvements or farm labor.

A different measure of the water input allows for the possibility that all water serves some productive purpose. From the equation 4.13, total water use can be calculated as the sum of field use and runoff, or as the sum of rainfall and irrigation inflows:

$$F + N = R + I = T \qquad \textbf{(Eq. 4.13)}$$

T field-specific total water use (inches per acre)

Other variables are as in equation 4.12. The water management agency's verbal statement of the problem might go something like this: "For the stated yield in this field, minimize the total amount of irrigation water inflows entering the field by finding as many reasonable substitutes for water as possible." In the DEA context, "reasonable substitutes" are implied by the farmer's peer group on the hyperplane. However, substitutes are not explicitly identified.

DEA Model 2 has one output (yield) and one input (total water use). Model 2 efficiency scores (θ) for individual fields are given in column 2 of Table 4.2. The average efficiency score for Model 2 is approximately 3 percent higher than for Model 1. Why might the scores for Model 2 be slightly higher than for the Model 1? One possible reason is that farmers adjust inflows according to the amount of rainfall entering the field. The input variable in Model 1 was only related to some abstract field water use variable and gave no consideration to the amount of rainfall or the volume of inflows. It is possible to test this hypothesis by looking at the correlation coefficient between the efficiency score and rainfall in Table 4.3. The coefficient is more negative for Model 2 than for Model 1. However, note that the differences are small, and that only one additional DMU is identified as efficient ($\theta = 1$). In addition, some of the other coefficients are also more negative and it is not certain that this increase in negativity is not related to random disturbances.

Also note that the runoff variable is more highly correlated with the efficiency score in Model 2 than in Model 1. A logical explanation for this is that the higher the volume of runoff, the higher the water use in relation to crop yield. There is also a high correlation between fertilizer and the efficiency score. The logical explanation is that crop yields increase in response to the amount of fertilizer applied. This idea is reinforced by the high correlation with yield. However, this is undesirable. The DEA program normalizes yields before identifying efficient DMUs and should not assign high efficiency scores to fields simply because they have high yields. Model 3 attempts to overcome this apparent bias by including the fertilizer variables along with the total water input.

Model 3 consists of one output (yield) and four inputs (total water use, nitrogen, phosphorous, and potassium). Results for Model 3 in Table 4.2 now show many more firms on the efficiency frontier and there has been no change in the original designation of efficient firms. Note, however, that efficiency scores are in general much higher than in Models 1 and 2. One possible reason is that farmers now have several different ways to be efficient. Because there are a greater number of facets on the hyperplane, the random probability that a point is close to a facet (has a high efficiency score) is greater.

The discrepancy in efficiency scores may be related to the larger number of input variables relative to the sample size. Because a larger number of inputs increases the number of facets on the hyperplane, a farmer with a unique ratio of inputs can be efficient by virtue of the fact that no other fields have a similar input ratio.

There are additional problems with Model 3. One is the persistent correlation between the efficiency measure and yields. This may indicate a bias towards fields with high yields, and result in artificially low estimates of the efficient volume of total water use. Third, in estimating the inflow requirement, there is no allowance for the periodicity or intensity of rainfall. Periodicity and intensity can affect farmers ability to make use of rainfall.

Temporarily ignoring these problems, suppose the water management agency would like to develop specific irrigation targets for inflows using this model. If each field were to somehow become efficient by reducing its inputs according to the DEA results, each field would reduce its total water use to T':

$$\theta T - e = T' \qquad \textbf{(Eq. 4.14)}$$

T	field-specific total water use (acre-inches per acre)
θ	field-specific efficiency score
e	the residual excess (acre-inches per acre)
T'	technically efficient total water use (acre-inches per acre)

Table 4.4 lists the target volume for total water use at each DMU prescribed by Models 2 and 3. The underlying objective in Models 2 and 3 was to have farmers maximize their use of rainfall. Farmers have no control over the amount of rainfall. Estimates represent the "efficient" volume of irrigation water inflows in a particular field if the farmer made maximum use of his rainfall. This is the column headed "I'." It is the difference between total water use at the target point for the field and rainfall:

$$T' - R = I' \qquad \textbf{(Eq. 4.15)}$$

I'	field-specific inflows with maximum use of rainfall (acre-inches per acre)

Table 4.2
Model Parameters and Efficiency Scores (θ) for DEA Models 1, 2, and 3

		Model 1	Model 2	Model 3
Model Parameters				
Outputs				
	Yield (Y)	x	x	x
Inputs				
	Field Water Use (F)	x	-	-
	Total Water Use (T)	-	x	x
	Nitrogen	-	-	x
	Potassium	-	-	x
	Phosphorous	-	-	x
			Efficiency Scores (θ)	
Fields				
	821	0.79596	0.68276	0.75540
	822	0.33803	0.37796	0.81347
	823	0.47394	0.62260	0.98924
	824	0.92280	0.95947	0.96856
	825	0.82590	1.00000*	1.00000*
	826	1.00000*	1.00000*	1.00000*
	831	0.36038	0.44996	1.00000*
	832	0.42225	0.32943	0.62910
	833	0.77314	0.71851	0.95672
	834	0.45393	0.32484	0.64859
	835	0.70829	0.41493	0.82468
	836	0.51080	0.45627	1.00000*
	837	0.78458	0.89893	1.00000*
	838	0.39964	0.40258	0.75807
	841	0.58176	0.50979	1.00000*
	842A	0.46974	0.54882	1.00000*
	842B	0.62328	0.73361	1.00000*
	843	0.66855	0.60896	0.71823
	844	0.59002	0.55090	0.67379
	845	0.37378	0.33665	0.88912
	846	0.62253	0.54977	0.82289
	847	0.43864	0.51414	0.70541
	848	0.52368	0.65375	0.96926
	849	0.49565	0.57699	0.72606
	851	0.57739	0.66046	0.89446
	852	0.73788	0.82814	0.88342
	853	0.57415	0.66688	0.86080
	854	0.82089	0.72821	0.89990
	855	1.00000*	1.00000*	1.00000*
	856	0.63512	0.72928	0.86021
	857	0.33004	0.42364	1.00000*
	858	0.67919	0.66946	0.85594
	859	0.85627	0.81136	0.90999
	861	0.87929	0.80449	1.00000*
	863	0.53018	0.55365	0.67439
	864	1.00000*	1.00000*	1.00000*
	866	0.46690	0.62503	0.78565

Note: (*) Asterisks indicate efficient fields.

Table 4.4 includes Model 2 results to illustrate the sensitivity of the analysis to changes in the definition of variables. The results for Model 2 show that efficient total water use (T') is fairly consistent across fields. This contrasts with highly variable values for efficient water use prescribed by Model 3. Note, however, that for efficient fields, the value of efficient total water use is identical in both models. Extrapolation of the results to estimate a value for efficient irrigation water inflows (I') in particular fields also produces divergent results. The negative I' values for Model 2 make these results highly suspect. The I' values for Model 3 are much more reasonable, however, variation between fields makes it doubtful that there would be enough information to apply an irrigation efficiency standard to individual fields on the LCRA rice irrigation districts.

Table 4.3
Correlation of Factors of Production with Efficiency Measures

	Correlation with Efficiency Measure		
	Model 1	**Model 2**	**Model 3**
Output Variable			
Yield	0.5601	0.5992	0.3947
Input Variable			
Field Acreage	0.1961	0.1595	-0.0082
Field Water Use	-0.8818	-0.7518	-0.2219
Irrigation Water Inflow	-0.6328	-0.7709	-0.4041
Rainfall	-0.3262	-0.4415	-0.2252
Runoff	-0.2525	-0.6302	-0.4820
Nitrogen	0.0719	-0.0095	-0.3905
Phosphorous	0.2609	0.2114	-0.3299
Potassium	0.3672	0.4547	0.0945

Table 4.4
DEA-Efficient Values for Total Water Use (T') and Inflows (I') in Sample Fields
DEA Models 2 and 3 (Acre-Inches per Acre)

	Model 2		Model 3	
Field Number	Total Water Use θT - e	Technically Efficient Inflow (θT - e) - R	Total Water Use θT - e	Technically Efficient Inflow (θT - e) - R
821	25.77	14.00	28.52	16.75
822	24.73	14.61	53.23	43.11
823	24.95	14.97	39.65	29.67
824	29.72	20.22	30.01	20.51
825	24.73	14.43	24.73	14.43
826	27.52	16.38	27.52	16.38
831	24.73	6.65	54.96	36.88
832	24.73	-10.03	47.23	12.47
833	25.85	6.86	34.42	15.43
834	24.73	-10.85	49.38	13.80
835	24.73	11.15	49.15	35.57
836	24.73	-1.28	54.20	28.19
837	25.66	9.99	28.54	12.87
838	25.50	4.93	48.02	27.45
842A	24.73	3.29	45.06	23.62
842B	24.73	5.91	33.71	14.89
841	25.45	7.94	49.92	32.41
843	24.73	15.09	29.17	19.53
844	24.73	11.99	30.25	17.51
845	24.73	16.72	55.38	47.37
846	27.73	14.72	41.51	28.50
847	24.73	10.25	33.93	19.45
848	24.90	10.72	36.92	22.74
849	24.73	14.30	31.12	20.69
851	27.44	12.75	37.16	22.47
852	26.33	13.25	28.08	15.00
853	25.63	11.79	33.08	19.24
854	30.08	17.81	37.17	24.90
855	33.98	23.43	33.98	23.43
856	24.73	10.63	29.17	15.07
857	26.08	8.87	61.56	44.35
858	24.73	9.63	31.62	16.52
859	25.35	16.13	28.43	19.21
861	24.73	5.62	30.74	11.63
863	26.35	8.89	32.10	14.64
864	54.35	36.83	54.35	36.83
866	28.80	14.68	36.19	22.07
Average	26.70	11.17	38.65	23.12
Standard Deviation	5.00	8.11	10.06	9.37

Uncontrollable Input Analysis for First Crop Rice Fields

Models 2 and 3 consider only total water use. Because farmers cannot control rainfall, and the Ideas software (version 5.02) cannot model uncontrollable inputs, these analyses do not treat inflows and rainfall as unique inputs. Banker, Charnes, and Cooper (1984) have addressed this problem by developing a linear program that accounts for the uncontrollable nature of inputs, thus allowing a distinction between inflows and rainfall. These programs treat an uncontrollable input such as rainfall as a potential substitute for controllable inputs. Each DMU receives an efficiency score based only on the demonstrated achievement of DMUs with smaller amounts of uncontrollable inputs. Residual excess (e) in the uncontrollable input represents that portion that cannot be substituted (Banker and Morey, 1986). This section presents DEA models 4 and 5. These variable returns to scale models were run in a DEA program developed by Bardhan (1994).

Suppose the hypothetical water management agency discussed in the previous section is interested in determining the minimum volume of irrigation inflows (I) rather than total water use. This agency could not compare water use across fields directly because rainfall varies between fields. Model 4 characterizes the problem with one output (yield) and two inputs (irrigation inflows, rainfall). The rainfall variable is considered to be an uncontrollable input. Efficiency scores are presented in Table 4.5. As in the previous models, the efficient level of input use is calculated by multiplying the efficiency score (θ) by irrigation inflows, and subtracting residual excess (e):

$$\theta I - e = I' \qquad \textbf{(Eq. 4.16)}$$

θ the efficiency score
I field-specific irrigation inflow (acre-inches per acre)
e the residual excess irrigation inflow (acre-inches per acre)
I' field-specific efficient irrigation inflow (acre-inches per acre)

As in Model 2, the efficiency scores and inflow prescriptions appear low. Efficient DMUs are 826, 837, 855, and 861. Model 4 results show an average efficiency score of 0.523 and an average efficient inflow of 13.14 acre-inches per-acre (the standard deviation is 3.33). Correlations with input and output variables are provided in Table 4.7. The efficiency score is much less correlated with rainfall than in previous models. However, correlations with the runoff variable appear similar to those in previous models. There is also a slight increase in the correlation with inflow. Finally, the estimates appear correlated with yield, suggesting a bias towards fields with high yields. Increasing the number of inputs in the DEA model could resolve correlations with yield.

As in the transition from Model 2 to Model 3, Model 5 addresses the correlation with yield by including fertilizers as input variables. Model 5 has one output (yield) and five inputs (irrigation inflows, rainfall, nitrogen, phosphorous, and potassium). The rainfall variable is considered an uncontrollable input. Efficiency scores and efficient levels of irrigation inflows are presented in Table 4.5. Correlations with efficiency measures are presented in Table 4.6.

Efficiency scores for Model 5 are higher than for Model 4. This is probably the result of an increase in the number of facets surrounding the production possibility set. The average efficiency score for DMUs in Model 5 is 0.831. The average efficient irrigation inflows is 22.11 acre-inches per acre (standard deviation is 7.27). The average efficient irrigation inflow in Model 5 is 1.01 acre-inches per acre lower than the average efficient irrigation inflows estimated in Model 3.

Table 4.5
Model Parameters and Efficiency Scores (θ) for Uncontrollable Input Models 4 and 5

	Model 4	Model 5
Model Parameters		
Outputs: Yield (Y)	x	x
Uncontrollable Inputs: Rainfall (R)	x	x
Controllable Inputs:		
Irrigation Inflows (I)	x	x
Nitrogen	-	x
Potassium	-	x
Phosphorous	-	x

	Model 4		Model 5	
Field Number	Efficiency Score θ	Technically Efficient Inflow (acre-inches per acre) θ I - e	Efficiency Score θ	Technically Efficient Inflow (acre-inches per acre) θ I - e
821	0.554	14.388	0.758	19.692
822	0.240	13.289	0.788	25.403
823	0.472	14.200	1.000*	30.100
824	0.934	20.067	0.945	20.058
825	0.960	13.859	0.974	14.054
826	1.000*	16.380	1.000*	16.380
831	0.326	12.023	0.960	22.511
832	0.255	10.269	0.529	21.324
833	0.755	12.829	0.959	16.293
834	0.250	10.138	0.538	21.815
835	0.198	9.093	0.572	24.359
836	0.361	11.030	1.000*	28.190
837	1.000*	12.870	1.000*	12.870
838	0.292	12.488	0.745	31.863
841	0.389	12.607	1.000*	32.410
842A	0.437	10.321	0.997	23.549
842B	0.618	9.202	1.000*	14.890
843	0.358	11.087	0.578	17.900
844	0.334	10.738	0.558	17.939
845	0.146	9.555	0.614	16.594
846	0.424	15.870	1.000*	37.430
847	0.223	7.497	0.418	14.053
848	0.535	12.791	0.919	21.973
849	0.283	9.177	0.513	16.636
851	0.560	15.041	0.905	24.308
852	0.774	14.481	0.824	15.417
853	0.549	13.499	1.000*	24.590
854	0.620	18.004	0.897	26.048
855	1.000*	23.430	1.000*	23.430
856	0.528	10.459	0.638	12.638
857	0.295	13.083	1.000*	44.350
858	0.520	11.356	0.768	16.773
859	0.693	15.259	1.000*	22.020
861	1.000*	11.630	1.000*	11.630
863	0.441	13.291	0.644	19.410
864	0.532	19.593	0.939	34.583
866	0.510	16.294	0.769	24.569

Table 4.6
Correlation of Factors of Production with Efficiency Measures

	Correlation with Efficiency Measure	
	Model 4	Model 5
Output Variable		
Yield	0.5592	0.5994
Input Variable		
Field Acreage	0.0722	0.0900
Field Water Use	-0.7465	-0.2620
Irrigation Water Inflow	-0.8325	-0.4686
Rainfall	-0.2759	-0.1404
Runoff	-0.6015	-0.4717
Nitrogen	-0.1789	-0.2368
Phosphorous	0.1980	-0.2974
Potassium	0.4078	0.0364

The addition of input variables in Model 5 has not resolved the high correlation with yield in Model 4. The correlation between the efficiency measure and yield in Model 5 is 0.599, slightly higher than in Model 4. As discussed earlier, this might suggest that the efficiency scores are biased towards those fields with higher yields. However, correlation between the efficiency score and rainfall is, as in Model 4, lower than in Models 2 and 3. This would suggest that Model 5 is closest of all the models to eliminating bias towards assigning high scores to fields with high rainfall. Overall, the correlations between Model 5 efficiency scores and each of the input variables appear lower than in previous models.

Estimates of efficient irrigation inflows in Model 5 appear to be slightly more consistent than those in Model 3. This is evidenced by the lower standard deviation for the estimates in Model 5. However, these estimates still do not seem consistent enough to develop targets for irrigation water use in individual fields.

The most practical use of the information presented here appears to be an estimate of the total water savings potential associated with on-farm water conservation programs. In other words, "how much water could farmers potentially save on the irrigation districts by collectively adopting best practices?" Given a value for water, it would also be possible to estimate how much LCRA should invest in an on-farm water conservation program that encourages farmers to adopt best practices. The potential water savings is the difference in average technically efficient irrigation inflows in sample fields and average irrigation inflows. Tables 3.6 and 3.7 give the average irrigation inflows in 1993 for fields on LCRA irrigation districts.

On Lakeside District for example, average irrigation inflows during the first crop period in 1993 were 29.27 acre inches. The difference between 29.27 acre-inches per-acre and average technically efficient inflows prescribed by Model 5, 22.11 acre-inches per-acre, is 7.16 acre-inches per-acre. The potential water savings associated with on-farm water conservation on Lakeside District during the first crop period in 1993 is therefore 24.46 percent of irrigation inflows. Based on 1993 acreage estimates from equation 3.1, and average first crop irrigation inflows during the 1993 crop year, an on-farm water conservation program could produce a maximum of 10,916 acre-feet of water during the first crop period on Lakeside District.

On Gulf Coast District, average irrigation inflows during the first crop period in 1993 were 45.51 acre inches per-acre. The difference between 45.51 acre-inches per-acre and 22.11 acre-inches per-acre is 23.4 acre-inches per-acre. The potential water savings associated with on-farm water conservation on Gulf Coast District during the first crop in 1993 was 51.42 percent of irrigation inflows. Based on 1993 acreage estimates from equation 3.1 and average first crop irrigation inflows during the 1993 crop year, an on-farm water conservation program could produce a maximum of 47,338 acre-feet of water during the first crop period on Gulf Coast District.

These results are useful for planning. However, estimates of potential water savings may be overstated. The variable I' represents a frontier efficiency, not necessarily an "acceptable efficiency." It would be unreasonable to expect all farmers to operate at 100 percent efficiency all of the time. Errors in judgement, stochastic environmental influences, and unique properties of individual fields may all influence an individual farmer's ability to achieve DEA-efficient water use. For these reasons, some sources consider that efficiency scores of 0.80 or larger represent a satisfactory level of efficiency in private enterprise (Ganley and Cubbin, 1992). Estimates of the potential water savings should probably be adjusted downward to reflect these considerations.

Summary

This chapter has presented a methodology for analysis of on-farm water efficiency. The method could be applied to any area of the state and to any crop type. More analysis is needed to develop an enforceable standard for irrigation inflows in rice fields on the LCRA Districts. However, results are useful for developing on-farm irrigation water conservation targets. This summary presents a discussion of two interesting results and makes several points that would be useful in future DEA analyses.

Two interesting results of this analysis deserve discussion. First is the apparent non-performance of laser-levelled fields. Second is that rice farmers in Texas' gulf coast region appear to operating in the region of increasing returns to scale. Laser levelling is an expensive investment designed to improve yields by creating a more constant depth of water throughout the field. Because there is less variation in the elevation of the field, farmers can maintain a more consistently shallow water depth. This should reduce the amount of water inflows required to maintain a flood and reduce runoff and seepage (Stansel and Lindemann, 1987). The results presented here suggest that laser-levelling is not necessarily a key to achieving high levels of irrigation efficiency.

Farmers appear to operate in the region of increasing returns to scale. This conclusion is based on the value of the constant term of the hyperplane, ω, described in equation 4.9. It implies that farmers could achieve proportionally higher yields relative to increases in the input variables. However, more analysis is needed to firmly establish this result. Banker *et al.* (1986), and Byrnes *et al.* (1984) show that estimates of scale efficiency are often sensitive to the specific input variables used in DEA models.

The most efficient fields according to this model are distributed in time and space throughout Texas' gulf coast region. This supports the conclusion that high levels of irrigation efficiency are achievable in different fields throughout the region and in different years despite environmental factors. However, the exclusion of factors that influence yield or irrigation efficiency could bias results and lead to unreliable estimates of the maximum achievable efficiency level in certain fields. For example, evaporation rates from fields will vary across locations according to differences in temperature, relative humidity, and wind. Similarly, the frequency and timing of rainfall is an important factor that influences a farmer's ability to use that water input. Although soils do not appear to influence water use between fields on these irrigation districts, there may be significant differences in water holding capacity across soils in the region.

Results of this analysis are applicable to semidwarf varieties of rice only. Other varieties of rice may exhibit significantly different irrigation efficiency frontiers. A future DEA study should compare results across rice varieties. Similarly, a future study should consider a greater number of variables. This will require a larger set of DMUs in the analysis set. As a general rule, there should be at least seven DMU's for each analysis variable. Alternatively, a future study might substitute more appropriate variables in the analysis. In particular, this study has been constrained by the range of data collected during the Texas A&M study and the small number of sample fields.

DEA results show large differences in field-specific inflow prescriptions. Differences between fields may be the result of differences in the ratio of those inputs specified in the model as well as field characteristics and unspecified input variables. These variables could be identified through further analysis.

Additional analysis could also draw conclusions about best irrigation practices. This might be accomplished by examining all of the relevant data regarding sample fields to identify those practices that are correlated with the lowest frontier estimates (lowest potential water use). This differs from the traditional method that focuses on correlations between specific practices and those fields with the lowest actual water use. Aligning all farmers practices with best practices identified in this manner will mean that all farmers have a similar target efficiency level on the production frontier.

Implementing best irrigation practices among farmers could increase the potential water savings associated with on-farm water conservation programs relative to estimates of water savings presented in this report. Implementation of best irrigation practices might be accomplished through monetary incentives such as subsidies or water prices that encourage farmers to voluntarily adopt different technologies or alter their input ratios.

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Chapter 5
A Linear Programming Model for Estimating Derived Demand

The purpose of this chapter is to present the linear programming model and the assumptions used to analyze the demand for water on LCRA's rice irrigation districts. The approach and assumptions employed in this study are a product of several factors. These factors include the nature of the method itself, the availability of data, and the objectives of the study. Many of the assumptions presented in Table 5.1 are common assumptions of farm budget and linear programming techniques.

Assumptions of the Linear Programming Model

One assumption common to all models of this type is that demand for farm products is perfectly elastic. As farm output decreases in response to a changing water cost, crop prices do not increase. For these irrigation districts, this is probably not an unreasonable assumption. Farmers serve a world market that is so large in relation to the district rice output that reduced output would not affect supply. Two other factors also support this assumption. First, US rice stores provide a buffer between the farmer and the market so that there is a lag time between market response to a reduction in farm output and farmers' decisions to stop producing. Secondly, farmers typically operate within Agricultural Stabilization and Conservation Service (ASCS) programs that usually provide the farmer with a higher-than-market price for his rice.

The second set of assumptions deals with farmer behavior. A standard assumption throughout economic theory is that the individual acts to maximize profits. Therefore, each farmer will plant the crop that provides the highest return. However, because of a lack of information about individual farms, this model treats the irrigation district as one farm unit. Different farms face different constraints, and the crop mix that maximizes profits on the irrigation districts may not be the same as the one that maximizes profits on individual farms. A detailed survey of individual farm firms was beyond the scope of this report.

Because farming costs and water demand are determined on a per-acre basis, this linear programming model is valid as long as farms exhibit constant returns to scale and farmers use a fixed proportion of inputs. A recent study by the US Department of Agriculture supports the assumption that rice farms exhibit constant returns to scale (USDA-ERS, 1992). However, a study by Texas A&M University contradicts this conclusion (AFPC, 1989). That study found that variable cash expenses on a 1300 acre rice farm were 5.17 percent higher than on a 500 acre farm. The methods used here assume that model farm budgets average out any differences in variable cash expenses among different size farms.

Another assumption this model makes about farmer behavior is that farmers make their planting decisions in the short run. The study by the Agriculture and Food Policy Center (AFPC) at Texas A&M University (1989, p.43) supports this assumption and concludes that farmers may continue to farm rice despite negative economic returns in the hope that conditions will improve in the long run. If a farmer can meet variable and cash costs in the short-run, and expects conditions to improve in the future, the decision to farm rice is still a rational one. However, a farmer with an optimistic outlook may actually withstand negative returns on variable costs in one year in order to preserve an ability to take advantage of rice markets in the future. The reason for this is that a farmer must maintain ASCS base acreage allotments by farming rice in every year in order to participate in ASCS programs in the future. In the context of this model, farmers have no perception of the future, and therefore only maximize profits in the current year. Therefore, the model may not accurately describe how farmers make their planting decisions.

Table 5.1
Assumptions of the Linear Programming Model

	Subject	Assumption	Implications
1	Output price	Farmers are price takers.	Crop price does not vary with farm output, and the marginal cost of the last unit produced is equal to the output price.
2	Farmer behavior	Farmers make their planting decisions individually and collectively to maximize profits. Farmers make their planting decisions in the short run.	Farmers will select the most remunerative crop alternative. The budgets include only short-run costs, and exclude fixed costs.
3	Farm budgets	Model farm budgets are valid for all areas of the irrigation district. There are no opportunity costs associated with land use or farm management. Soils, farm management, and technology inputs have no effect on crop yield. There are constant returns to scale with respect to field acreage.	Farm production and farm inputs do not vary across farms. Budgets do not include opportunity costs for land or farm management. Crop yields do not differ across farms, or in response to management and technology inputs. There is no minimum field size, and farm budgets are applicable on one acre of land.
4	Farm inputs	The cost of farm inputs other than water is equal to the marginal value product.	The farm budget residual equals the value of water in crop production.
5	Farm water requirements	Water requirements do not differ across soil types or rice varieties.	The water requirement is fixed in the model farm budget.
6	ASCS base acreage	Farmers participate in ASCS programs on all rice land. ASCS base acreage is randomly distributed throughout the districts.	Farmers plant rice in an area equal to the what the acreage model (equation 3.1) projects given ASCS program parameters. The area of base acreage in each feasible crop area is equal to the proportion of district base acreage within the feasible crop area.
7	Farm management	There are no costs associated with higher levels of water management style. Farmers do not alter their water management style in response to higher water prices.	Farm budget residuals are equal across all management categories. The acreage managed under a particular water management style is fixed in proportion to the number of farmers using that style.
8	Irrigation technology	Farmers do not currently use closer levees or infield laterals as a means of reducing farm water requirements. The reason farmers do not use closer levees or infield laterals is a matter of cultural farming practice, and not economic.	Farmers can reduce irrigation water costs by adopting irrigation technology. The number of farmers using a particular technology is limited through acreage constraints in the linear program rather than additional costs in the farm budget.
9	Canal water losses	Canal losses are 17 percent of on-farm water demand.	May underestimate actual canal losses at low levels of on-farm water use.

Model farm budgets fix crop yields and farm inputs. A fixed input assumption imposes constant returns to scale. However, the use of model farm budgets based on county averages accounts for differences in the proportion of farm inputs across different size farms. Of greater concern is the fact that farmers may alter the proportion of farm inputs as the price of water increases. Therefore, the model may not accurately portray production costs under varying levels of irrigation intensity.

Farm budgets do not include opportunity costs. The assumption is that no opportunity costs associated with land use and farm management. This assumption implies no better alternatives to current land use, and no non-farm employment opportunities available to the farmer. This is an appropriate assumption in the short-run context of a linear programming demand model (Gisser, 1970).

Crop yield does not vary across management and technology categories. While soils and management may obviously affect crop production there is little reliable information on the effect of technology and management on production. Therefore, this latter assumption is a necessary over-simplification of a complex relationship.

Similarly, there is little information on differences in the water requirement of soils and rice varieties. Although these differences appear to be small, they could result in as much as a 7-8 acre-inch per acre difference in water requirements between farms. However, because the model uses an average on-farm water requirement for farms on the irrigation districts, differences in individual farm water requirements that are a direct result of differences in the variety of rice and field soil types should not vary more than about 4 acre-inches from those specified in this model.

Under the assumption that all farmers participate in ASCS programs, the extent of ASCS base acreage on the districts defines the area which may be used in rice production. The extent of base acreage will not affect estimates of farmers willingness to pay for water or water price prescriptions. Estimates of benefits and costs associated with water rights will be sensitive to acreage variables. Acreage projections may be less appropriate for retrospective studies when acreage is known, but are necessary when the model is used as a planning tool.

Another assumption is that ASCS base acreage is distributed randomly throughout the districts, and is therefore proportionally distributed among feasible crop areas. Interviews with county extensionists and others indicate that this is an appropriate assumption. If the location of ASCS base acreage is not random, the model will not accurately reflect the elasticity of demand for irrigation water because the feasible crop set differs between feasible crop areas.

There are no costs associated with higher levels of water management style. Water coordinators rated farmers on characteristics that indicate more intensive management strategies require more labor inputs. However, there is little information on the cost of these inputs or their effect on crop yield. Therefore, the proportion of land managed under various management strategies is fixed and farmers will not improve their management styles in response to an increase in water price. In reality, a profit maximizing farmer would increase his management intensity as long as the cost of additional labor was less than the cost of additional water. As a result, the linear programming model will tend to underestimate the elasticity of demand for irrigation water.

Many of the assumptions used in this model are valid. While the analysis also highlights potential flaws in assumptions, these flaws do not invalidate model results. The analysis of model assumptions is a weigh station on the road to perfection. Knowledge of the potential flaws in a model assists in the interpretation of results. Understanding how possible flaws affect the results permits the analyst to develop methods of overcoming those flaws. It opens up new avenues for research into what factors affect the value of water on the irrigation districts. It also gives insights into how the model may be manipulated to provide additional information about the allocation of water and the potential benefits associated with water conservation.

The Linear Programming Formulation

The objective function for this linear program is to maximize profit subject to constraints on the availability of land, water, and crop alternatives:

$$\text{MAX} \quad \sum_i \sum_j \sum_k \sum_l PR_{ijkl} * A_{ijkl} \qquad \textbf{(Eq. 5.1)}$$

PR	profit on one acre of land (dollars per acre)
A	the number of acres planted (acres)
i	an index of crop type
j	an index of the farmer's water management style
k	an index of irrigation technology
l	an index of feasible crop area

Profit per acre is calculated by subtracting the cost of water from the farm budget residual. The calculation of other parameters is discussed in Chapter 3 and is not repeated here. Differences between the irrigation districts resulted in a slightly different assignment of indices. Table 5.2 shows how each index was assigned on each district.

The index i represents crop type. With the exception of turf grass, alternative crops are identical on both districts. Turf grass is not a crop alternative on Lakeside District because there are no farmers that raise this crop. Although turf grass is a crop alternative on Gulf Coast District, it is not considered a feasible alternative. The reason is that the economics of turf grass farming do not seem to fit the theoretical basis on which the model rests. The model assumes that farmers will switch from irrigated crops to dryland crops when they can no longer meet their variable production costs. In 1993, the variable production cost on turf grass farms was approximately $0.67 per square yard, and the sale price was approximately $0.475 per square yard (Engbrock, Interview, 1993). Although theory suggests that these farmers should switch crops, this has not been the case. This is apparently related to farmer's large capital investments in turf farms and an optimistic perception of the market for turf in the future.

Although turf grass is not a feasible alternative to rice on either district, irrigation of turf grass contributes to the total on-farm demand for water. Therefore, excluding turf grass farms from the model will bias the estimate of total irrigation water demand downward, but will not affect the estimate of water demand on rice farms. In 1993, 1,113.5 acres of turf grass farms accounted for only 1,424.54 acre-feet of water demand on Gulf Coast District (LCRA, 1993b). In 1993, this represented less than 2 percent of the total demand for water among a marginal user group. For the district as a whole, the specification bias that results from excluding these users will be small and restricted to estimates at low water prices.

The index j represents water management style. Statistical analysis of water coordinator's assessment of farmer's water management style showed that, with the exception of farmers who use a "low" water management style on Gulf Coast District, there were no significant differences in water consumption between groups. On Lakeside District, the actual difference in average water use between categories showed no logical pattern; therefore, management categories are excluded from the model on Lakeside District. On Gulf Coast District, these differences appeared to follow a logical pattern and are included in the model despite the weak statistical evidence. However, this is consistent with casual reports from the water coordinators who suggest that there is an identifiable block of farmers who are inefficient water managers.

The index k represents farming technologies. Farmers can implement two simple irrigation technologies that conserve water. The index k = 1 is a base case for which the operative assumption is that farmers do not currently implement the two alternative water-saving technologies. Because these farming practices are apparently cultural, and the actual cost of implementing improved technologies is low, the barrier to adoption of these practices is greater than the cost of implementation alone. This barrier must be imposed on the model in the form of acreage constraints. For the index k = 2 or 3, the assumption is that if the marginal cost of water increases, farmers will have an incentive to implement these technologies, but will not necessarily do so.

The index l represents the set of feasible crop alternatives. In contrast to the technology index, each farmer has a unique set of alternative crops to which he may switch his land use. The index l represents feasible crop areas in which farmers have a common set of crop alternatives. As the marginal cost of water increases, farmers in each of these areas will alter their land use according to these alternatives.

Table 5.2
Assignment of Model Indices

Index		**Value**	**Lakeside District**	**Gulf Coast District**
i	Crop Type	1	Rice, first crop only	Rice, first crop only
		2	Rice, full crop	Rice, full crop
		3	-	Turf grass
		4	Cattle	Cattle
		5	Sorghum	Sorghum
		6	Corn	Corn
		7	Cotton	Cotton
		8	Soybeans	Soybeans
j	Management Style	1	Average management	Low management
		2	-	Medium management
		3	-	High management
k	Irrigation Technology	1	No specific technology	No specific technology
		2	Closer levees	Closer levees
		3	Infield laterals	Infield laterals
l	Feasible Crop Area	1	Area 1	East side
		2	Area 2	West side
		3	Area 3	-

Constraints on the availability of land, water, and crop alternatives describe the agricultural and economic conditions that farmers face. Equation 5.2 is a constraint on the availability of land. It states that acreage for rice and all crop alternatives, regardless of the farmer's water management style and technology inputs, may not exceed the maximum amount of acreage available for each crop in each feasible crop area:

$$\sum_{j} \sum_{k} A_{ijkl} \leq L_{il} \qquad \text{for all } i, l \qquad \textbf{(Eq. 5.2)}$$

A number of acres planted (acres)
L maximum land area that could be planted in an alternative crop (acres)

Two constraints limit the acreage for all crops combined. The constraint in equation 5.3 states that the total acreage for all crops combined in each feasible crop area may not exceed the total acreage on which farmers could choose to plant rice in that feasible crop area:

$$\sum_{i} \sum_{j} \sum_{k} A_{ijk} \leq L_{l} \qquad \text{for all } l \tag{Eq. 5.3}$$

The constraint in equation 5.4 states that the acreage for all crops in all feasible crop areas may not exceed the total acreage on which farmers could choose to plant rice on the irrigation district:

$$\sum_{i} \sum_{j} \sum_{k} \sum_{l} A_{ijkl} \leq LA \tag{Eq. 5.4}$$

LA	maximum land area on which farmers could choose to plant rice on all feasible crop areas on the irrigation district (acres)

The fourth constraint is a limit on the availability of water. The constraint states that total diversions may not exceed the water right:

$$\sum_{i} \sum_{j} \sum_{k} \sum_{l} A_{ijkl} * W_{ijkl} \leq WQ \tag{Eq. 5.5}$$

W	water requirement on each acre of land (acre-feet)
WQ	district water quota (acre-feet)

The water quota is the maximum volume of water each district can deliver to farmers under its water right. Because the volume of water rights must satisfy the demands associated with canal losses as well as farm water requirements, the water quota must be less than the maximum allowable diversion to accurately reflect the volume of water available to farmers. LCRA estimates that canal efficiency on both districts is approximately 17 percent (Taylor, Interview, January 25, 1993). Therefore, the variable WQ is equal to maximum allowable diversions multiplied by a factor of 0.83.

There is probably a non-linear relationship between canal efficiency and farm water requirements. If farm water requirements are low, the actual volume of water lost as a result of inefficiencies in the canal system will be relatively large. However, because the linear programming model estimates on-farm water use only it will not be sensitive to an increasing proportion of canal losses as rice acreage decreases.

For the purposes of estimating total diversions, this report assumes canal losses vary in direct proportion to the district-wide farm water requirement. Once farm water requirements are established through the linear program, the quantity of water can be adjusted outward by the appropriate volume to account for canal losses. This is an important consideration because part of on-farm demand includes water losses in the canal system as water is transported from the river to the farm gate.

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Chapter 6
Linear Programming Model Results

This chapter presents linear programming results to estimate derived demand for water, the value of water, and farmer;s willngness to pay for water. Analysis of irrigation district costs and willingness to pay suggests an appropriate price for irrigation water in the absence of a competitive market. Another direct application is evaluation of the costs and benefits of irrigation water rights. The model can be manipulated through sensitivity analysis to provide more information about different management alternatives on the districts. For example, the Lower Colorado River Authority (LCRA) might evaluate the benefits of investing in irrigation technologies. The LCRA might also evaluate the impacts associated with implementation of its drought management plan. That plan restricts the sale of interruptible stored water to farmers during drought periods.

The first section of this chapter presents the model results in terms of rice acreage and water use at increasing water prices. This model does not incorporate the farmer reaction curve and therefore assumes a fixed irrigation rate. This is the standard method in the absence of information on how water use and crop production vary with water price. A second set of linear programming solutions follow the first set of results. These models include the farmer reaction curve so that the model adjusts on-farm water use as water price increases. This is a unique addition and a more adequate assumption than a fixed irrigation rate. The fact that the kind of empirical data on which this reaction curve is based is almost never available probably explains why such an estimate has not previously been used as a surrogate for the crop-water production relationship. Estimates of the value of water, the subsidy to irrigators, and the appropriate price for water under an average cost pricing system follow linear programming results.

The Linear Programming Solution

Tables 6.1 through 6.5 summarize model results. Figures 6.1 and 6.2 display the linear programming solutions to changes in the marginal cost of water under a fixed irrigation rate. Tables 6.2 and 6.3 list acreage solutions and water demand at different price points. For example, Table 6.2 shows how the acreage would be allocated at select water prices. If the price of water were $54.25 per acre-foot, farmers would cultivate 26,000 acres of rice during the first crop, but would not cultivate a second crop. On Lakeside District, 220 acres of rice would be diverted to the production of cotton. The total volume of water demanded at a price of $54.25 would be 63,235 acre-feet. This figure does not include canal losses.

Figures 6.1 and 6.2 graph the stepped demand curves for water. For example, in Figure 6.1, farmers would demand approximately 86,000 acre-feet of water at a price of $40.00 per acre-foot. The steep rise in the curves at $24.25 per acre-foot on Lakeside District and $34.25 per acre-foot on Gulf Coast District indicate a region of inelastic demand. As the price increases, farmers continue growing rice, but achieve lower profits as the price rises. Corners in Figures 6.1 and 6.2 represent "no-profit" points. These are points at which rice acreage on the irrigation districts is converted to alternative crops because the farmers have more remunerative crop alternatives available. The term "no-profit" point is a misnomer. At these points, farmer's can still earn a profit growing rice, but in order to maximize profits in the short run, farmers switch to non-irrigated crops for which the profit is higher.

The stepped demand curve is generated by raising the price of water at intervals of $5.00 per acre-foot. In theory, demand curves are smooth to reflect the gradual change in the quantity demanded as the price changes. These stepped curves are not smooth for two reasons. The steps are first a product of raising the price at relatively large intervals and secondly, a reflection of the detail of the data on which the model rests.

Tables 6.4 and 6.5 list acreage solutions and water demand for different price points. These estimates are based on the linear programming model that incorporates the farmer reaction curve. Figures 6.3 and 6.4 display the derived demand curves on Lakeside District and Gulf Coast District with the farmer reaction curves (Eq. 3.9) included in the linear program. The solutions are similar to the more basic solution, but are less steeply sloped in regions of inelastic demand. The interpretation of these figures is the same as in Figures 6.1 and 6.2. The demand curve reflects on-farm demand for water and does not include canal losses. Therefore, it may not be equated with the total diversion of water on the LCRA districts. All subsequent analysis is based on estimates of derived demand that incorporate the faremr reaction curve.

The derived demand equations in Table 6.1 are based on a line between critical values on the X-axis. Critical values are those points on the X-axis at which the slope of the demand curve changes dramatically. Table 6.1 shows the piecewise equations for the derived demand functions in Figures 6.3 and 6.4. For example, if the maximum quantity of water available on Lakeside District is 70 thousand acre-feet, farmer's maximum willingness to pay can be calculated from the equation in the third row. Therefore, farmers maximum willingness to pay is:

$$P = 43.746 - (0.00032 * 70000) = 21.35 \qquad \textbf{(Eq. 6.1)}$$

P water price at which farmers use exactly 70,000 acre-feet (dollars per acre-foot)

The quantity of water available on the irrigation district, 70,000 acre-feet, has been substituted for Q.

Table 6.1
Piecewise Estimates for Derived Demand with Farmer Reaction Curves

	Q-Range			Equation
Lakeside District				
	0	≤ Q ≤	56,217.3	P = 104.250 -0.00036Q
	56,217.3	≤ Q ≤	61,568.9	P = 657.109 -0.01028Q
	61,568.9	≤ Q ≤	108,937.0	P = 43.746 -0.00032Q
Gulf Coast District				
	0	≤ Q ≤	86,216.9	P = 75.400 - 0.00029Q
	86,216.9	≤ Q ≤	88,797.8	P = 885.559 - 0.00969Q
	88,797.8	≤ Q ≤	126,109.7	P = 49.203 - 0.00027Q
	126,109.7	≤ Q ≤	127,985.0	P = 685.498 - 0.00531Q

Note: Q-Range is the range of volumes over which the linear equation describes the demand curve. P is farmers maximum willingness to pay in dollars per acre-foot. Q equals the volume of water delivered to farmers on the irrigation district.

Figure 6.1
Derived On-Farm Demand for Surface Water on the Lakeside Irrigation District without the Farmer Reaction Curve

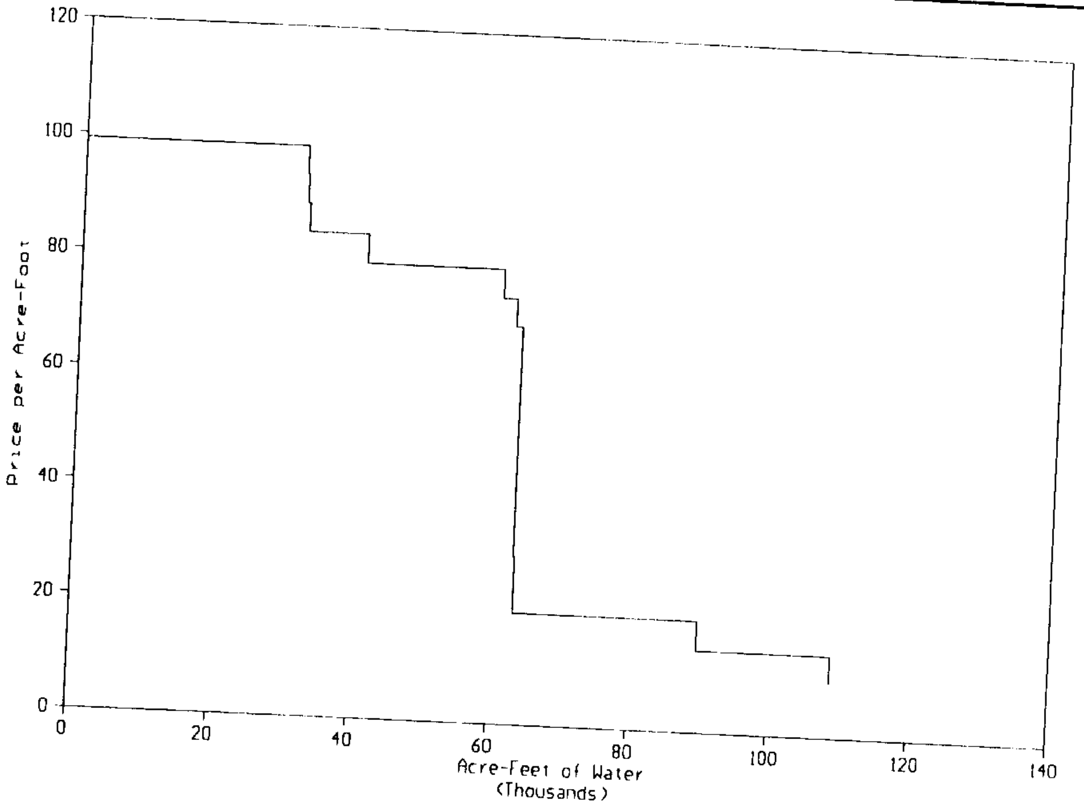


Figure 6.2
Derived On-Farm Demand for Water on Gulf Coast District without the Farmer Reaction Curve

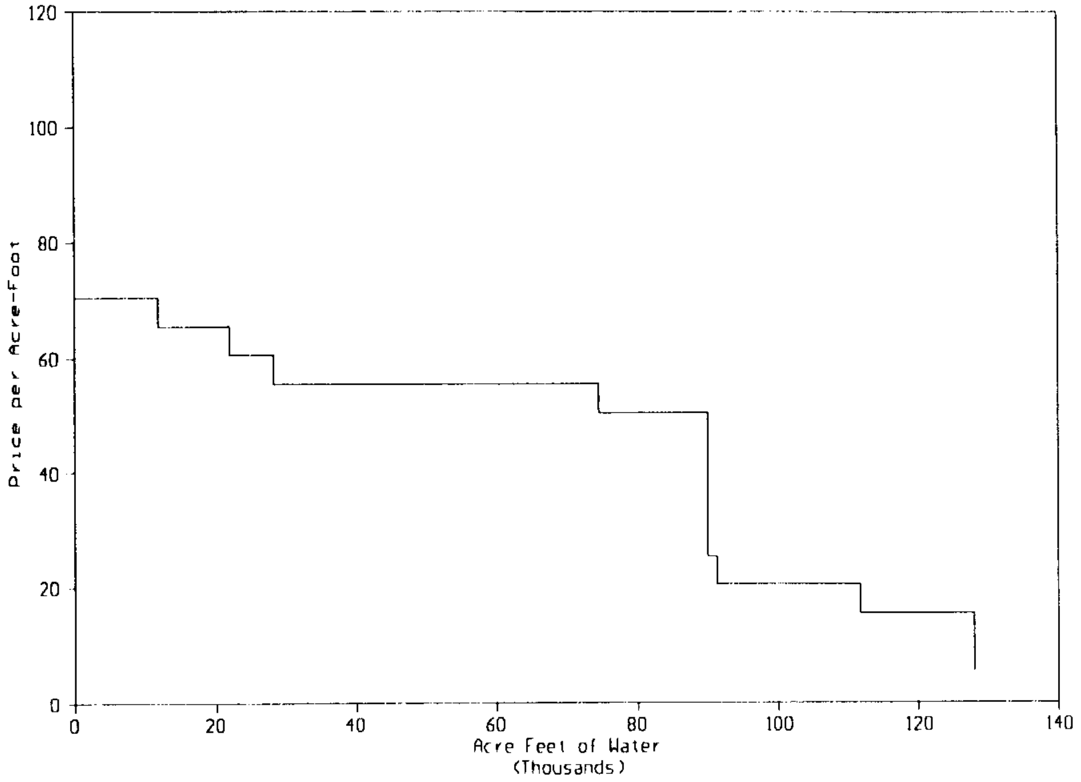


Table 6.2
Acreage Solutions and Volume of On-Farm Water Demand without the Farmer Reaction Curve, Lakeside District

	Acreage for Crop Type							
Rice - First Price ($/Acre-Foot)	Rice Crop Only (Acres)	Full Crop (Acres)	Cattle (Acres)	Corn (Acres)	Cotton (Acres)	Sorghum (Acres)	Soybeans (Acres)	Volume of Water (Acre-Feet)
9.25	3,566	22,655	0	0	0	0	0	108,937
14.25	3,566	22,655	0	0	0	0	0	108,937
19.25	13,211	13,010	0	0	0	0	0	89,708
24.25	26,073	0	0	0	147	0	0	63,412
29.25	26,073	0	0	0	147	0	0	63,412
34.25	26,000	0	0	0	220	0	0	63,235
39.25	26,000	0	0	0	220	0	0	63,235
44.25	26,000	0	0	0	220	0	0	63,235
49.25	26,000	0	0	0	220	0	0	63,235
54.25	26,000	0	0	0	220	0	0	63,235
59.25	26,000	0	0	0	220	0	0	63,235
64.25	26,000	0	0	0	220	0	0	63,235
69.25	26,000	0	0	0	220	0	0	63,235
74.25	25,558	0	0	0	220	442	0	62,158
79.25	24,756	0	0	0	220	1,096	147	60,209
84.25	16,717	0	7,966	0	220	1,096	220	40,657
89.25	13,230	0	11,454	0	220	1,096	220	32,176
94.25	13,082	0	11,454	147	220	1,096	220	31,817
99.25	13,009	0	11,454	220	220	1,096	220	31,640
104.25	0	0	24,463	220	220	1,096	220	0

Note: Prices reflect the stated variable price for one acre-foot of water, not the effective price that results from the probability of drawing stored water. The volume of water demanded reflects on-farm demand only and does not represent total diversions of water on the irrigation district. Numbers rounded down for tabulation.

Table 6.3
Acreage Solutions and Volume of On-Farm Water Demand without the Farmer Reaction Curve, Gulf Coast District

	Acreage for Crop Type							
Price ($/Acre-Foot)	Rice - First First Only (Acres)	Rice Full Crop (Acres)	Cattle (Acres)	Corn (Acres)	Cotton (Acres)	Sorghum (Acres)	Soybeans (Acres)	Volume of Water (Acre-Feet)
5.4	12,104	13,266	0	0	0	0	0	127,985
10.4	12,104	13,266	0	0	0	0	0	127,985
15.4	12,104	13,266	0	0	0	0	0	127,985
20.4	18,587	6,783	0	0	0	0	0	111,740
25.4	22,802	720	0	0	1,848	0	0	91,469
30.4	23,522	0	0	0	1,848	0	0	90,128
35.4	23,522	0	0	0	1,848	0	0	90,128
40.4	23,522	0	0	0	1,848	0	0	90,128
45.4	23,522	0	0	0	1,848	0	0	90,128
50.4	23,522	0	0	0	1,848	0	0	90,128
55.4	19,940	0	3,581	0	1,848	0	0	74,488
60.4	7,972	0	15,549	0	1,848	0	0	28,297
65.4	6,363	0	15,549	137	1,848	782	688	22,108
70.4	3,478	0	15,549	137	1,848	2,290	2,066	11,895
75.4	0	0	15,549	717	1,848	2,290	4,965	0

Note: Second cropping rate restricted to a maximum of 60 percent of first crop acreage. Prices reflect the stated variable price for one acre-foot of water on the district, not the effective price that results from the probability of drawing stored water. The volume of water demanded reflects on-farm demand only and does not represent total diversions of water on the irrigation district. Numbers rounded down for tabulation.

Figure 6.3
Derived On-Farm Demand for Surface Water on the Lakeside District with the Farmer Reaction Curve

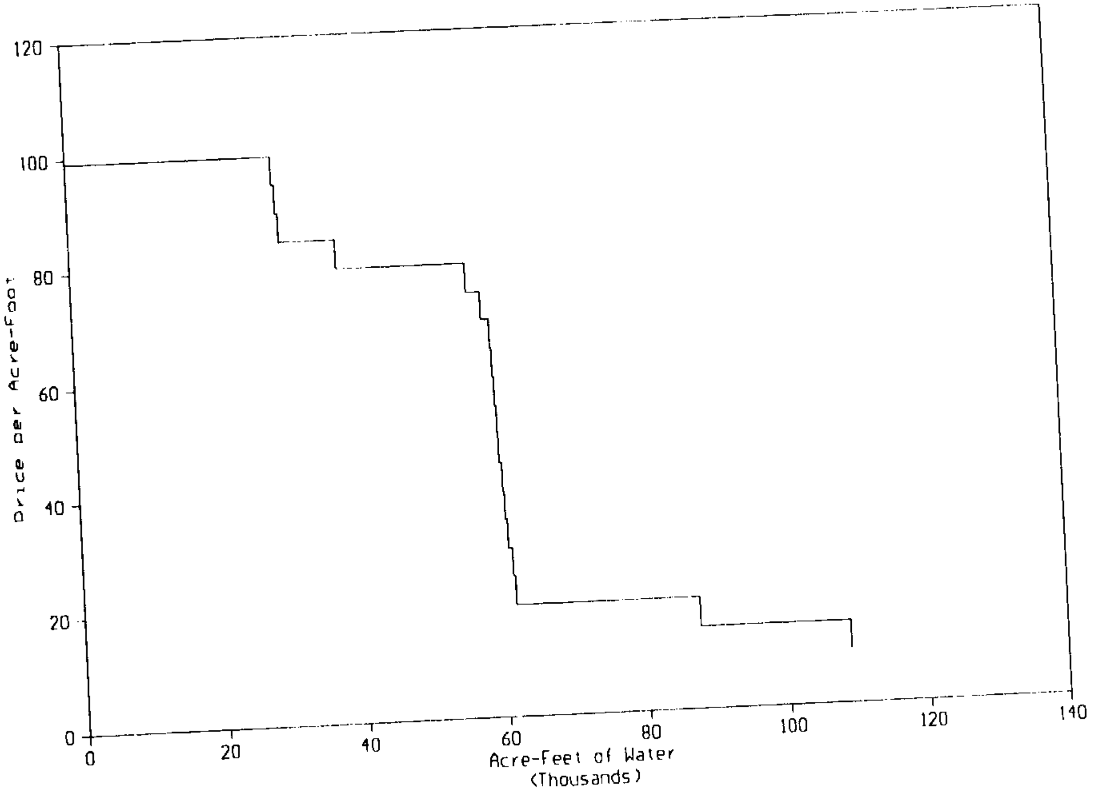


Figure 6.4
Derived On-Farm Demand for Surface Water on the Gulf Coast District with the Farmer Reaction Curve

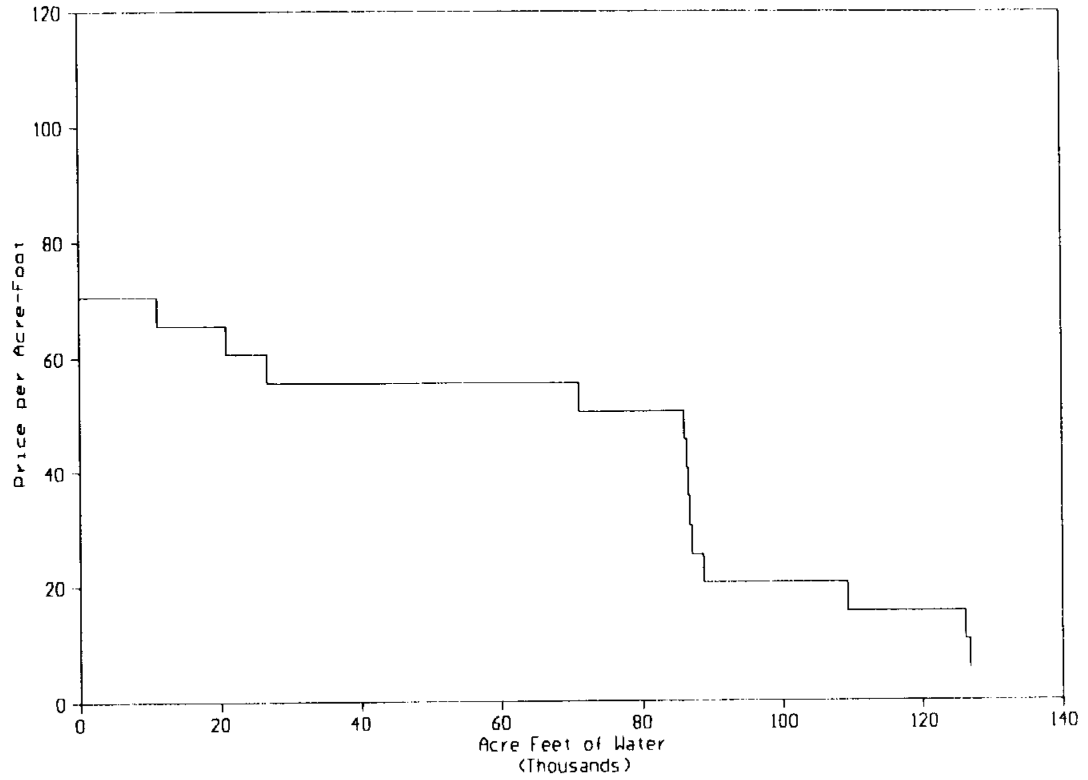


Table 6.4
Acreage Solutions and Volume of On-Farm Water Demand with the Farmer Reaction Curve, Lakeside District

	Acreage for Crop Type							
Price ($/Acre-Foot)	Rice - First Crop Only (Acres)	Rice Full Crop (Acres)	Cattle (Acres)	Corn (Acres)	Cotton (Acres)	Sorghum (Acres)	Soybeans (Acres)	Volume of Water (Acre-Feet)
9.25	3,566	22,655	0	0	0	0	0	108,937
14.25	2,815	23,406	0	0	0	0	0	108,937
19.25	13,211	13,010	0	0	0	0	0	87,654
24.25	26,073	0	0	0	147	0	0	61,568
29.25	26,073	0	0	0	147	0	0	61,119
34.25	26,000	0	0	0	220	0	0	60,717
39.25	26,000	0	0	0	220	0	0	60,447
44.25	26,000	0	0	0	220	0	0	60,208
49.25	26,000	0	0	0	220	0	0	59,995
54.25	26,000	0	0	0	220	0	0	59,802
59.25	26,000	0	0	0	220	0	0	59,625
64.25	26,000	0	0	0	220	0	0	59,463
69.25	26,000	0	0	0	220	0	0	59,313
74.25	25,558	0	0	0	220	442	0	58,165
79.25	24,756	0	0	0	220	1,096	147	56,217
84.25	16,717	0	7,966	0	220	1,096	220	37,882
89.25	13,230	0	11,454	0	220	1,096	220	29,920
94.25	13,082	0	11,454	147	220	1,096	220	29,532
99.25	13,009	0	11,454	220	220	1,096	220	29,315
104.25	0	0	24,463	220	220	1,096	220	0

Note: Prices reflect the stated variable price for one acre-foot of water, not the effective price that results from the probability of drawing stored water. The volume of water demanded reflects on-farm demand only and does not represent total diversions of water on the irrigation district. Numbers rounded down for tabulation.

Table 6.5
Acreage Solutions and Volume of On-Farm Water Demand with the Farmer Reaction Curve, Gulf Coast District

Rice - First Price ($/Acre-Foot)	Acreage for Crop Type							Volume of Water (Acre-Feet)
	Rice Crop Only (Acres)	Full Crop (Acres)	Cattle (Acres)	Corn (Acres)	Cotton (Acres)	Sorghum (Acres)	Soybeans (Acres)	
5.4	12,104	13,266	0	0	0	0	0	127,985
10.4	12,104	13,266	0	0	0	0	0	126,829
15.4	12,104	13,266	0	0	0	0	0	126,103
20.4	18,587	6,783	0	0	0	0	0	109,304
25.4	22,802	720	0	0	1,848	0	0	88,797
30.4	23,522	0	0	0	1,848	0	0	87,131
35.4	23,522	0	0	0	1,848	0	0	86,856
40.4	23,522	0	0	0	1,848	0	0	86,617
45.4	23,522	0	0	0	1,848	0	0	86,406
50.4	23,522	0	0	0	1,848	0	0	86,216
55.4	19,940	0	3,581	0	1,848	0	0	71,026
60.4	7,972	0	15,549	0	1,848	0	0	26,859
65.4	6,363	0	15,549	137	1,848	782	6,88	20,922
70.4	3,478	0	15,549	137	1,848	2,290	20,66	11,226
75.4	0	0	15,549	717	1,848	2,290	49,65	0

Note: Second cropping rate restricted to a maximum of 60 percent of first crop acreage. Prices reflect the stated variable price for one acre-foot of water on the district, not the effective price that results from the probability of drawing stored water. The volume of water demanded reflects on-farm demand only and does not represent total diversions of water on the irrigation district. Numbers rounded down for tabulation.

The Value of Water on LCRA Irrigation Districts

The total value of water on the irrigation districts at a particular price is equal to the area beneath the derived demand curve and above the price line. Because this model is defined in the short run, values reflect the value of water in a single crop year. This value is equal to the consumer surplus that farmers making a positive profit receive by having access to water during the crop year. The value of water is not equal to farm profit on the irrigaiton districts, but is specifically the increase in farm profit that results from having access to water. The value of water is net of all delivery and purchase costs. Figure 2.2 displays the value of water graphically. It is calculated by the area of the shaded triangle in Figure 2.2 minus fixed irrigation charges. In this case, per-acre charges are subtracted from the estimate because fixed irrigation charges were removed from the budgets.

If effective water prices are averaged over the full crop period, the effective price is $11.11 per acre-foot on Lakeside District and $6.55 per acre-foot on Gulf Coast District. More exact estimates would distinguish between the cost of water used during the first and second crop periods. But the difference is small, and that level of detail is beyond the useful scope of the data presented here. The value of 108,937 acre-feet of water delivered to fields on Lakeside District is $4,133,852 and the value of 127,985.6 acre-feet of water delivered to fields on Gulf Coast District is about $4,198,270. The short-run average value of one acre-foot on Lakeside District is about $37.94, and on Gulf Coast District is about $32.80. By themselves, these values indicate that farmers on Lakeside District make more profitable use of water than farmers on Gulf Coast District. They also show that the net returns from water during both crop periods combined are less than the minimum average value of stored water purchased from the Highland Lakes.

Table 6.6 presents average values of water during each crop period. For example, the average value of one acre-foot of water delivered to fields during the first crop period on Lakeside District is $61.44, and the average value of one acre-foot of water delivered to fields during the second crop is $7.41. The difference in the average values can be attributed to the difference in yields relative to the volume of water used in the production process.

Table 6.6 also presents average values for land during each crop period. For example, the average value of one acre of land on Lakeside District during the first crop period is $144.27, and the average value of one acre of land during the second crop period is $13.38. The average value of land may be interpreted as the difference between the value of one acre with access to irrigation water and the value of one acre without access to irrigation water. The values of land and water are not additive. Implicit in the value of water is the assumption that land is available to use that water. Similarly, the value of land implies that there is water on that land with which to irrigate a rice crop.

There are large differences in the average value of water between the two districts. This is the result of the difference in the cost of water, production, and water use. Farmers on Lakeside District use less water per-acre, pay a higher price for water diverted under the district's water right, and use a higher proportion of stored water.

Table 6.6
Short-Run Average Value of Water on LCRA Irrigation Districts in 1993

Description		Lakeside District	Gulf Coast District
Average Value of Water:			
(Value per acre-foot)	Full Crop*	$37.95	$32.80
	First Crop	61.44	41.47
	Second Crop	7.41	13.15
Average Value of Irrigated Land:			
(Value per-acre)	First Crop	$144.26	$145.16
	Second Crop	13.38	33.85

Source: Calculated by the author based on data generated by the linear program using XA Software.

Note: Values based on 1993 agricultural markets, farming costs, and farm water use. (*) The average value during the full crop period is the average value of water in the first and second crop period combined.

Allocational decisions within a region must be made on the basis of marginal values of water, not average values. In most cases, it is possible to derive the marginal value directly from the slope of the demand curve. However, in this case, the limiting factor on the irrigation districts is rice acreage, not irrigation water. Therefore, the marginal values must be derived from the change in total profits on the districts as the supply of water is restricted. This is accomplished by holding the price of water constant at the effective price ($11.11 on Lakeside District and $6.55 on Gulf Coast District) and reducing the quantity of water available to farmers in 10 percent increments. Because the objective function maximizes profits on the irrigation district, water supplies are allocated to acreage where farmers make the most profitable use of that water. This is consistent with economic theory that suggests scarce resources will be allocated to those willing to pay the highest price.

The marginal value is the increased profit associated with access to additional water supplies minus the cost of supplying that water divided by the increased volume:

$$V_t = \frac{(\Pi_t - (A_t * F)) - (\Pi_{t-1} - (A_{t-1} * F))}{W_t - W_{t-1}} \qquad \textbf{(Eq. 6.2)}$$

V	marginal value of water (dollars per acre-foot)
Π	farm profits on rice and non-rice acreage as calculated in the linear program (dollars)
A	first crop acreage (acres)
F	fixed per-acre charge for all first crop rice acreage (dollars per acre)
W	the volume of the water increment (acre-feet)
t	an index of an increasing water increment

Table 6.7 lists the marginal values and the corresponding water volume. For example, if the quantity available to farmers on Lakeside District were restricted to 64,231 acre-feet, the potential increase in aggregate farm profits associated with access to one additional acre-foot of water on this district would be $42.52. Notice that on Gulf Coast District, there is a rise and a drop in the marginal value of water. This is the result of acreage dropping out of production in the feasible crop area on the East Side, therefore a reduction in the total cost of the fixed per- acre charge.

It is not possible to go from these estimates to a determination of exactly how much water has been inefficiently allocated. The reason for this is that no information on the marginal value of water in other economic sectors of the river basin is available. The price for stored water from the Highland Lakes does not provide this value because, like the prices for irrigation service on LCRA's Districts, that price is determined on a cost of service basis rather than by market forces. A simple illustration demonstrates how an allocation by marginal values might occur.

Suppose these two districts were forced to bid for the right to divert each acre-foot of water. It can be seen from Table 6.7 that the first 42,205 acre-feet of water have a higher value on Lakeside District than Gulf Coast District. This would suggest that, under conditions of water scarcity, Lakeside District would win the first 42,205 bids against Gulf Coast District to divert the first 42,205 acre-feet. Once Farmers on Lakeside District have diverted that water, farmers on Gulf Coast District would win subsequent bids to divert the next 23,715 acre-feet. At this point, farmers on Lakeside would be able to divert water again because the marginal value is again higher on that district.

However, these results may be misleading. Farmers cannot make use of the water if that water is diverted in large chunks. Water must be drawn over the length of a crop season. Therefore, it is necessary to determine what the marginal value of water is during that point in the crop season when the run-of-river flows are available for diversion. That is a complex stochastic problem that can only be addressed by linear programming methods through the use a multiperiod model. This problem is very similar to the rationale for substituting a Jensen growth stage equation for quadratic or Cobb-Douglas production functions.

The Value of the Indirect Subsidy to Farmers

The value of the indirect subsidy to farmers is shown graphically in Figure 2.3. With reference to Figure 2.3, the value of the subsidy is estimated by the sum of areas A and B. Area A is bounded on the X-axis by the quantity of water farmers would use at its current price on the irrigation district, and the quantity of water farmers would use at a competitive price P*. The area is equal to the value of that water to farmers. The difference between the competitive price and the value of water is equivalent to the subsidy farmers receive.

There is little information on the demand for water among those that own water rights, or among those who would use water if they owned water rights. Therefore, it is not possible to make an exact estimate of what the competitive price, P*, might be. However, it seems likely that a competitive price would be less than the price of stored water. The price of stored water from the Highland Lakes is $50.50 per acre-foot. The rationale for selecting this value rather than the total cost of maintaining stored water contracts is the assumption that less-senior owners of water rights would continue to maintain their firm water contracts for security in the event of a drought despite any increase in run-of-river water supplies.

Assuming that the competitive price for run-of-river water is less than the price of stored water, the maximum value of the subsidy to Lakeside District can be estimated as shown graphically in Figure 6.5. The benefit to farmers that results from the allocation of water rights is equal to the value of water farmers would not have access to in a competitive market. Farmers would use 59,009 acre-feet of water if the variable cost of water were $50.50 per acre-foot. The volume of water diverted at the current price is 108,937 acre-feet. Therefore, the additional volume of water farmers have access to is 49,929 acre-feet. The value of that water to farmers on Lakeside District is $395,249. Following a similar analysis on Gulf Coast District, farmers have access to 42,122 acre-feet for which they would be unwilling to pay a price of $50.50 per acre-foot. The value of this water to farmers on Gulf Coast District is $561,895.

Table 6.7
Marginal Value of the Water Delivered to Farmers on LCRA Irrigation Districts

Lakeside District		Gulf Coast District	
Total Water (Acre-Feet)	Marginal* Value (Dollars per Acre-Foot)	Total Water (Acre-Feet)	Marginal* Value (Dollars per Acre-Foot)
-	-	127,985	13.42
-	-	115,187	12.67
108,987	8.04	103,668	12.33
98,043	8.97	93,301	27.98
88,239	10.12	83,971	32.33
79,415	10.12	75,574	36.14
71,474	10.12	68,016	36.84
64,327	39.05	61,215	37.44
57,894	49.47	55,093	37.44
52,104	49.47	49,584	37.44
46,894	49.47	44,625	37.44
42,205	53.67	40,163	37.44
37,984	56.06	36,146	38.12
34,186	59.57	32,532	38.20
30,767	67.82	29,279	48.26
27,690	67.82	26,351	48.62
24,921	67.82	23,715	57.76
22,429	67.82	21,344	59.87
20,186	67.82	19,209	59.87
18,168	67.82	17,288	48.29
16,351	67.82	15,560	46.43
14,716	67.82	14,004	46.43
13,244	67.82	12,603	47.71
11,920	67.82	11,343	49.35
10,728	67.82	10,208	50.01

Source: Calculated by the author based on data generated by the linear program using XA Software.

Note: (*) Marginal value is the increase in total farm profits that results from the delivery of one additional acre-foot of water to a rice field on the irrigation district.

If water were allocated efficiently among those who own water rights, farmers would not have access to water for which their maximum willingness to pay is below the competitive price. In the absence of senior water rights, farmers would have to replace the lost water with stored water (firm yield) from the Highland Lakes. Farmers could not afford to do this, but if they did, the cost on Lakeside District would be $50.50 times the 49,929 acre-feet, or $2,521,380. Similarly, on Gulf Coast District, the cost would be $50.50 times 42,122 acre-feet, or $2,127,208. Because there is no cost for run-of-river water to those that own water rights, farmer's replacement cost may be equated with the current cost to those less-senior owners of water rights who would have had access to that water.

The sum of areas A and B in Figure 2.3 equals the total subsidy that farmers receive as a result of owning senior water rights and diverting water at a cost less than a competitive market price. The area B is not included in calculations of the indirect subsidy because that subsidy is potentially no different than the subsidy any owner of water rights receives. The values presented here are not exact estimates. However, they are useful because they represent the magnitude of the market inefficiency related to each district's ownership of water rights.

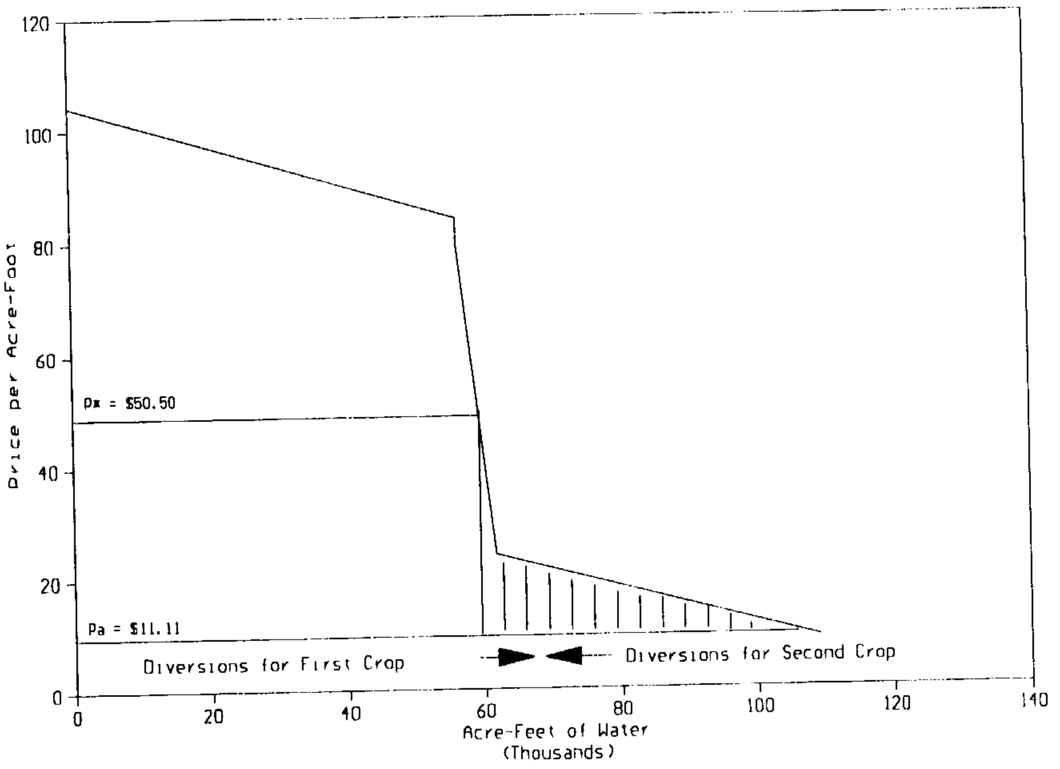
Linear programming results show that demand decreases significantly at higher prices but there is little reduction in first crop rice acreage at price of water was $50.50 per acre-foot (Tables 6.3 and 6.4). As marginal cost increases, farmers eliminate the second crop because higher water prices result in negative profits. There are no alternative crops at that point in the growing season; therefore, the change in acreage for which farmers pay a fixed rate is very small. On Lakeside District, 220 first crop acres go out of production and on Gulf Coast District, 1,848 acres go out of production.

Estimates of the value of water and the value of the indirect subsidy are sensitive to changes in the price of rice, the price of alternative crops, and the demand for irrigated acreage. When banks impose restrictions on farmer's rice acreage as a condition of lending, or when the Agricultural Stabilization and Conservation Service increases the minimum setaside requirement, the total value of the subsidy to farmers will decrease in proportion to the reduced water requirement. Therefore, precise estimates must be made for a given year with known acreage and crop price. In general, reductions in the second crop acreage will have a larger effect on the market inefficiency than reductions in first crop acreage. The reasoning behind this is that the water farmers would be unwilling to purchase at a price of $50.50 is the water they use during the second crop period. Similarly, increases in acreage during the first crop period will have a smaller effect on the value of this indirect subsidy than increases in the second cropping rate. Therefore, it seems that an effective water conservation program should focus first on reducing the demand for second crop acreage. This interpretation is important in determining the volume of water savings that LCRA should seek to achieve through its water conservation program, and the objectives that LCRA should establish for that program.

The estimates presented here reflect the maximum subsidy to farmers. The estimates imply that all water that is not diverted on the irrigation districts would be diverted elsewhere in the river basin. The estimates are valid as long as this is true. However, it is not clear how the hydrology of the river or the availability of water would change if the irrigation districts stopped diverting water. In addition, some of the run-of-river water diverted by the irrigation districts originates from run-off below other major diversion points. Reductions in the diversion of this water might not increase run-of-river flows at other diversion points. Unless there are owners of water rights that could make use of the increase in run-of-river flows, and offset their purchase of water from the Highland Lakes, there is no alternative use for that portion of district water diversions. In this case, there is no opportunity cost associated with its use in rice irrigation. One next logical step in refining this model is to determine what portion of stored water diversions would be offset by reductions in water diversions on the irrigation districts.

Figure 6.5

Value of the Indirect Subsidy to Farmers on Lakeside District



The Potential for Average Cost Pricing

The LCRA irrigation districts, like most public utilities, operate on a cost of service basis. When the cost structure of a public utility organization exhibits a high fixed cost and a small variable cost, public utilities frequently use average cost pricing to establish rates. The price is equal to the average cost of providing service divided by the total amount of goods or services provided. Historically, this has been the method of establishing irrigation water rates on the districts. However, those rates have been based on the number of acres a farmer irrigates, not the volume of water he uses. Because farmers have paid for the irrigation service, not the water itself, farmers have had very little incentive to control their use of water. By assigning a marginal cost to the water itself, and calculating the average cost of service on the basis of the total volume of water delivered, rather than the total number of acres irrigated, LCRA can maximize the farmers incentives to conserve water.

Knowledge of the demand for water should help LCRA evaluate its options for establishing a volumetric water rate under an average cost pricing strategy. LCRA has been reluctant to use this approach because it fears the cost of water will be too high, and the acreage and total volume of water delivered on the districts will decline as a result of some farmers unwillingness to pay the higher price. A high volumetric water rate would make it difficult for inefficient farmers to continue their farming operations. If the acreage on the districts declines, the average cost of providing service could increase. If the average cost of providing water to remaining farmers is too high, these farmers could not afford to operate and the districts would close.

LCRA completed a rate study in 1992 in preparation for the water measurement and volumetric pricing program. That study evaluated fixed and variable costs on the irrigation districts to plan the distribution of each district's fixed costs to a per-acre irrigation charge and its variable cost of pumping and delivering water to a volumetric water charge. Each district's 1993 rates are based on this study and are presented in Table 3.3.

Figure 3.3 gives the general form of the average cost function. The equation states that total average cost is a function of fixed and variable costs:

$$C = \frac{(F + (V * Q))}{Q} \qquad \textbf{(Eq. 6.3)}$$

C	average cost of pumping and delivering water (dollars per acre-foot)
Q	volume of water delivered to farmers on the district (acre-feet)
V	variable cost of operating and maintaining the districts (dollars)
F	fixed cost of operating and maintaining the districts including administrative overhead and debt service (acre-feet)

An exponential function can substitute for variable cost to account for increasing returns to scale as the district pumpage requirements increase:

$$C = \frac{F + (Q(\beta_1 Q^{\beta_2}))}{Q} \qquad \textbf{(Eq. 6.4)}$$

β	parameters estimated by ordinary least squares regression from data on the cost of meeting three specific pumpage requirements

Table 6.8 lists LCRA's estimates of the average cost of delivering enough water to meet specific pumpage requirements. For example, if the pumpage requirement on Lakeside District is 124,960 acre-feet, the average variable cost of delivering that water would be $7.13.

Equations 6.5 and 6.6 give the specific total cost functions with parameter estimates for the Lakeside and Gulf Coast Districts respectively:

$$C = \frac{1678522 + Q \exp(5.027 - 0.26098 \ln Q)}{Q} \qquad \textbf{(Eq. 6.5)}$$

$$C = \frac{1887194 + Q \exp(4.867 - 0.29001 \ln Q)}{Q} \qquad \textbf{(Eq. 6.6)}$$

For example, if the Lakeside District delivered 124,960 acre-feet of water to the farmgate, the average total cost would $20.56. These equations are estimated on a narrow range of water volume and they may not adequately represent the true average cost of pumping water below the lowest pumpage estimates provided in Table 6.8.

Setting each equation equal to the derived demand curve solves for the quantity of water farmers would demand and indicates the appropriate price that farmers should pay for one acre-foot of water under an average cost pricing strategy. Therefore, LCRA can allocate all of its costs to the volumetric rate, eliminate the per-acre charge, and maximize farmer's incentive to conserve water while providing irrigation water on a cost of service basis. According to the model of derived demand, the appropriate variable cost per acre-foot on Lakeside District is approximately $36.42, and the appropriate price per acre-foot on Gulf Coast District is approximately $26.05. At these prices, all second crop acreage goes out of production on both districts. Average cost pricing estimates assume that the price elasticities reflected in the derived demand curves do not change in the long-run. If the price elasticities have been underestimated, the average cost of delivering water will stabilize at a higher rate.

Table 6.8
Variable Cost Estimates at Different Pumpage Requirements

	On-Farm Demand (Acre-Feet)	Pumpage Requirement (Acre-Feet)	Average Variable Cost* (Dollars)
Lakeside District			
Low	106,803	124,960	$7.13
Medium	121,367	142,000	6.89
High	131,077	153,360	6.17
Gulf Coast District			
Low	142,135	166,298	$3.97
Medium	162,903	190,596	3.84
High	203,680	238,306	3.58

Source: Lower Colorado River Authority. 1992. "Lakeside and Gulf Coast Rate Options." Austin. Texas.

Note: Estimated pumpage requirements represent on-farm demand adjusted 17 percent to account for canal losses. (*) Average variable cost per acre-foot of water delivered to the farmgate.

The Price Elasticity of Demand for Irrigation Water

Price elasticities reflect the percentage decrease in on-farm water demand that may be expected in response to a one percent increase in the price of water. Elasticities may be used to estimate the potential reduction in water use associated with increases in the variable price of water. The elasticity of demand for water will vary depending upon the price of water at which the elasticity is calculated, and whether it represents an arc price elasticity or a point price elasticity. Point price elasticities are specific to a single price value. To calculate the point elasticity, the derived demand equations given in Table 6.5 may first be rearranged to express quantity as a function of price. The equation for derived demand is:

(Eq. 6.7)

$$P = \beta_0 + \beta_1 Q$$

P	water price at which farmers use exactly Q acre-feet (dollars per acre-foot)
Q	quantity of water (acre-feet)
β_0	the intercept term of the derived demand equation
β_1	the slope term of the derived demand equation

The values of these variables are described in equation 6.1 and listed in Table 6.5. The equation may be rewritten to express quantity as a function of price:

(Eq. 6.8)

$$Q = -\frac{\beta_0}{\beta_1} + \frac{1}{\beta_1} P$$

Since β_0 and β_1 are known, the price elasticity is easily calculated by equation 6.9. The equation states that the percent change in water consumption that results from a one percent change in the price is a function of the ratio of the price and quantity at the price point of interest:

(Eq. 6.9)

$$\varepsilon = \frac{1}{\beta_1} * \frac{P}{Q}$$

If the concern over price elasticity centers around a range of prices, for example a particular leg of the derived demand equations, the price elasticity can be calculated at a price and quantity associated with the midpoint of the price range.

The price elasticity may be calculated at various price points along the derived demand curve. The decision about which estimate of the elasticity to use will be a matter of the analysts particular interest. From the LCRA's perspective, the elasticity is appropriately calculated within the narrow range of prices that LCRA might set its volumetric water rate. In the lower leg of the demand curve, the price elasticity at $16.46 per acre-foot on Lakeside District is -0.6035, and the price elasticity at $10.87 per acre-foot on Gulf Coast District is -0.0161. For example, a one percent increase in the price of water on Lakeside District would result in a 0.60 percent reduction in the total on-farm water demand.

Demand for water in agriculture is known to be inelastic. However, linear programming assumptions may have underestimated the price elasticity. If so, the value of water and water demand may be overestimated at higher water prices. It is therefore desirable to determine how large an error may have occurred. The following analysis develops elasticity estimates from the farmer reaction curves and compares these results with those obtained from the derived demand equations.

No acreage goes out of production on Gulf Coast District in the lower leg of the derived demand curve where the price elasticity is estimated. Therefore, this elasticity may be equated with reductions in on-farm water use rather than acreage. The Lakeside elasticity estimate is higher than the Gulf Coast elasticity estimate, suggesting that water use will decrease in response to water price increases more quickly on Lakeside District. This is due to second crop acreage reductions below the price point at which the Lakeside District estimates are calculated.

This analysis first tests whether derived demand elasticity estimates can be equated with elasticity estimates based on the farmer reaction curve. Because the functional form of the farmer reaction curve may underestimate farmers' responses to increases in the marginal cost of water, the analysis then estimates a maximum price elasticity from the farmer reaction curve assuming a constant propensity to conserve water over all water prices.

The farmer reaction curve is discussed in Chapter 3 and given in equation 3.10. The equation is repeated in equation 6.10. It states that water use is a function of the amount of rainfall during the crop period, the number of days during the growing season, the price of water and the crop type:

$$W = \beta_0 + \beta_1 D + \beta_2 \ln(PE) + \beta_3 C + \beta_4 G + \beta_5 INTG \qquad \textbf{(Eq. 6.10)}$$

W	field-specific water use (acre-feet per-acre)
D	number of days between first and last water delivery (days)
PE	the effective price of water (dollars)
C	a dummy variable equal to 1 for observations from second crop rice fields
G	a dummy variable equal to 1 for observations from Gulf Coast Irrigation District
INTG	an interaction term equal to 1 times the ln (PE) for fields on Gulf Coast District
β	coefficients estimated by ordinary least squares regression.

Price elasticity based on the farmer reaction curve is calculated by first substituting the known price point of interest in place of the variable PE (equation 6.10) and subsequently calculating per-acre water use. Values of W will represent per-acre water use rather than total water use on the irrigation district. Therefore, these elasticity values do not reflect the loss of acreage as the marginal cost of water increases, only the reduction in on-farm water use. To obtain price elasticity by the farmer reaction curve the parameter estimate β_2 is multiplied by the inverse of the estimated on-farm water use at the price point of interest:

$$\varepsilon' = \beta_2 \left(\frac{1}{\hat{W}} \right) \qquad \textbf{(Eq. 6.11)}$$

ε'	price elasticity
β_2	parameter estimate from equation 6.10
$\hat{W}$	estimated W, field-specific water use (acre-feet per-acre), from equation 6.10

On Lakeside District, price elasticity at \$16.46 per acre-foot is -0.03025. On Gulf Coast District, price elasticity at \$10.87 is -0.02293.

If, as discussed above, price elasticity in the derived demand model for Gulf Coast District is strictly a function of the farmer reaction curve, the two estimates of price elasticity should be equivalent. There is a small difference in the two estimates for Gulf Coast District. This difference may have resulted from categorizing farmers' water use in the linear program according to individual water management styles. Elasticity estimates based on the farmer reaction curve will only be comparable to those of the derived demand equations if no acreage has dropped out of production.

Price elasticities based on the farmer reaction curve for Lakeside District differ significantly from those calculated from the derived demand equations. Because price increases result in second crop acreage reductions, the elasticity estimate provided by the farmer reaction curve represents that portion of the elasticity that may be attributed purely to farmers' adjustment in water use. The remaining portion of the original elasticity estimate, -0.57325, is the result of acreage reductions (-0.6035 - -0.03025 = -0.57325).

The following analysis is concerned with whether or not the elasticity estimates have been underestimated in the farmer reaction curve specifically. Elasticity estimates for the Lakeside and Gulf Coast Irrigation Districts reflect underlying assumptions about the functional form of the farmer reaction curve. The reaction curve imposes a nonlinear relationship to reflect farmers' diminishing propensity to conserve water. However, because this is a short-run estimate based on two years of data, the existence of a diminishing propensity to conserve water is difficult to test. Elasticity may actually be much higher at low water prices. Under the assumption that there is a at least some diminishing marginal propensity to save water, but the elasticity has been underestimated because of the lack of data, it is possible to estimate how big that error might be by fitting the farmer reaction curve using a linear form rather than a lin-log form.

To determine price elasticities based on a reaction curve with a linear form, equation 6.10 must be re-estimated. Equation 6.10 becomes linear when the effective price of water (PE) is transformed from a logarithm to its original value:

$$W = \beta_0 + \beta_1 D + \beta_2 PE + \beta_3 C + \beta_4 G + \beta_5 INTG \qquad \textbf{(Eq. 6.12)}$$

All of the variables are the same as discussed above in equation 6.10. Regression results for equation 6.12 are given in Table 6.9. A maximum elasticity is calculated by substituting the price point of interest into equation 6.12, estimating per-acre water use, $\hat{W}$, and solving for ε'' using equation 6.13. The calculation is:

$$\varepsilon'' = \beta_2 \frac{P}{\hat{W}} \qquad \textbf{(Eq. 6.13)}$$

ε''	maximum price elasticity
P	price point at which elasticity is to be estimated
$\hat{W}$	estimated W, field-specific water use (acre-feet per-acre), from equation 6.10
β_2	parameter estimate from equation 6.12

At the price \$16.47 on Lakeside District, the price elasticity is -0.3528. At the price \$10.87 on Gulf Coast District, the price elasticity is -0.1753.

Estimates of maximum price elasticity are substantially higher than those obtained from the lin-log reaction curves. They measure the percent change in on-farm water use that will result from an increase in water price with no concurrent reduction in irrigated acreage. At these prices, they may be interpreted as maximum elasticities related to non-acreage variables under the following assumptions. The first assumption is that the farmer reaction curve would not change if it were based on more than a two year span of data. The second assumption is that farmers do have at least some diminishing marginal propensity to conserve water in response to increases in water price.

Table 6.9
Parameter Estimates and T-Statistics for the Linear Farmer Reaction Curve

Variable	Coefficient	Eq. 6.12
Intercept	β_0	1.4183
Days Watered (D)	β_1	0.2018
		(8.017)*
Effective Price (PE)	β_2	-0.0466
		(-4.205)*
Crop Type[†] (C)	β_3	-0.4098
		(-3.796)*
District[‡] (D)	β_4	0.7139
		(4.758)*
Interaction Term (D * ln PE)	β_5	-0.0236
		(-0.858)
R-squared		0.2427
Adj. R-squared		0.2384
Model F		56.6080

Source: Calculated by the author based on data in: Lower Colorado River Authority, 1993a. Water Accounting Database for 1992 and 1993. Lakeside Irrigation District, Eagle Lake, Texas. (Computer File.); and Lower Colorado River Authority, 1993b. Water Accounting Database for 1992 and 1993. Gulf Coast Irrigation District, Bay City, Texas. (Computer File.)

Note: T-statistics given in parenthesis. (*) Asterisks indicate significance at the 95 percent confidence level. (†) Crop Type is a dummy variable indicating equal to one for the second crop. (‡) District is a dummy variable equal to one for Gulf Coast District.

Summary

The results provided in this analysis of on-farm water demand will be useful in determining an appropriate direction for volumetric pricing and water measurement components of LCRA's water conservation program. The results provide answers to many questions about the effect of the districts on the supply of water, and the economic benefits associated with water conservation. The method has its weaknesses as well as its strengths. Among its principle weaknesses is the need to explicitly describe the conditions in the farming area. Errors in measurement or judgments about conditions on the districts could lead to inaccurate results. On the other hand, it is possible to test how big these errors might be by making slight changes to the data on which the model is based.

Perhaps one of its biggest strengths is the ability to manipulate conditions on the districts by changing assumptions about water use and farmer behavior. Results of sensitivity analysis enables water managers to test different management options and evaluate their impact on water use. For example, it is possible to examine changes in the demand for water in response to changes in crop prices, and it is possible to examine the impact of LCRA's drought management plan. Given the necessary information, it is also possible to examine the potential impact of infrastructural investments that might reduce field water use. Results provide a basis for evaluating policy options and drawing conclusions about management alternatives. These are discussed in the following chapter.

Chapter 7
Conclusions

The impetus for this linear programming model was a series of questions about how water rights influence the availability of water in the river basin. Of particular interest is the question of whether or not the existing allocation of water in the river basin is inefficient, and whether or not the allocation of water presents an impediment to water conservation efforts. Results provide insights into how a water conservation effort might work within the constraints of an existing legal framework that establishes water rights. Applications of model results for water resources planning and management include the evaluation of policy options, and estimation of economic benefits associated with water conservation programs. The model could be restructured to estimate the impact of drought management policies.

Economic theory provided a normative framework for structuring the analysis and estimating derived demand and the value of water. Because competitive markets for water do not exist on the irrigation districts or in the river basin, demand for water is based on the demand for farm products. This is not an entirely satisfying approach because the demand for farm products and irrigated acreage are not themselves rooted in competitive markets. All else equal, the value of water used to irrigate subsidized crops will be higher than water used to irrigate unsubsidized crops.

Linear programming methods and farm budget analysis require a rigid specification of conditions on the irrigation districts. Results in this report are based on the best information available at the time, but a detailed survey of farm characteristics was beyond the scope of the study. One advantage of the linear programming model is that it is easily updated to reflect changing conditions. New information can be added to the model as it becomes available.

The first section of this chapter discusses the effect of water rights on farm water use. These considerations could prove useful in providing some more direction to water conservation programs. The second section discusses goals of water conservation programs and assesses alternative water conservation tactics. The linear programming model can be manipulated to provide some answers to these questions. Finally, this paper concludes with a brief discussion of what institutional changes might increase the economic benefits associated with the distribution of run-of-river water.

The Impact of Water Rights on Farm Water Use

The conventional view of water conservation may be limited. Many see it as a necessary evil to increase water supplies when they are scarce, and some see the institutional changes associated with the redistribution of access to water resources as a deliberately rent-seeking activity. Somehow, those who live in the river basin must find ways of doing more with less so that they can continue to support their standard of living as the population and the volume of goods and services produced expands in the future. Water conservation is a long-term process. Preparation and planning for most water development projects begins many years before they become a reality. If water conservation is an alternative source of water supply, then it is also appropriate to begin that process many years before the water is actually needed. Water conservation requires substantial technical change and innovation in existing industries to ensure that water is available.

When Texas was a young state, perhaps it made sense to allocate water rights to agricultural interests in order to advance the economic development of particular regions. Water rights were necessary to guarantee the availability of water when river flows were low during drought years, thereby improving the prospects for long-term investment in those regions. In particular, the location of the LCRA irrigation districts at the lower end of the river basin required some sort of protection to ensure an equitable distribution of water. There was a danger that upstream interests might divert all of the water and prevent any water from reaching these irrigation districts during critical periods of low flow.

Despite any good reasons for having institutionalized farmers' rights to water in the first place, the primitive irrigation practices and the inefficient use of water in Texas' gulf coast region reflect this elimination of risk to rice farmers. The consequence of eliminating this risk is analogous to what happens in other subsidized industries. Performance in subsidized or protected industries is characteristically low because they are protected from market competition. Similarly, senior water rights protect and subsidize farmers' access to water. Agricultural water use becomes inefficient because there is no incentive to manage the risk of suspended access to water or compete economically for water supplies. This can be accomplished by increasing the value of water and farmer's willingness to pay relatve to other uses.

Water rights have come back to haunt us because they now make implementing water conservation in agricultural areas more difficult. Irrigation technologies and cultural farming practices have not developed to use water efficiently. Water rights are only one of the many subsidies available to agricultural interests, and these have also stifled technological change. Agricultural Stabilization and Conservation Service programs subsidize farm output at guaranteed price levels and U.S. trade policies have protected farmers from foreign competition. When LCRA tries to implement a water conservation program on its irrigation districts, the problems it faces are the result of a long history of poor technological development.

While making water available when and where it is needed in the future is an appropriate goal of water conservation, it may be a limited objective. Water conservation not only makes water available for the production of more goods and services, it also increases the value of water in its existing use. If the value of water may be defined by the farm budget residual in agriculture, it may also be defined by the budget residual in other industries. If the producer uses less water to produce the same output, the marginal product of water increases as less water is used. Because this producer has reduced his demand for water, he has increased the amount of run-of-river flows that may be diverted by others. If this reduces the volume of stored water purchases, there is an increase in the net returns to water in the river basin as a whole. The inefficient use of water by any one sector in the river basin is an externality that affects all others who might make use of that water otherwise, even if stored water remains available in the Highland Lakes under current conditions.

The economic benefits of water conservation can be seen today. In the absence of a competitive market in which water is distributed on the basis of its marginal value, a surrogate water conservation goal might be to raise the average value of run-of-river water above the price of stored water. This is accomplished by reducing water use and altering the input ratio, or increasing yields without increasing water use. The simple re-allocation of water from the districts to other sectors of the economy is not necessarily a satisfactory goal because it does not ensure that other sectors are necessarily efficient in their use of water. For example, re-allocation of water to uses for which the marginal product of water is less than rice irrigation produces a net loss to the economy in the river basin.

Water Conservation Alternatives

In practice, agricultural water conservation programs can seek to achieve several goals. One goal is to increase the volume of run-of-river flows during periods of low flow. This may be accomplished through acreage reductions. Another goal is to evenly distribute the economic benefits of water use to all water users in the river basin. This may be accomplished by increasing irrigation efficiency and eliminating marginal water uses. Yet another goal is to maximize the net returns to water use within the river basin as a whole. This requires the elimination of all existing water rights and the distribution of water among users according to its marginal product. The marginal product of water on the LCRA districts is known, but not the marginal product of water in alternative uses; thus, it is not possible to evaluate the impact of this alternative.

Conclusions about water conservation alternatives can be drawn from derived demand model results. Proposals for reducing water use and increasing the volume of run-of-river flows include transfer payments to farmers and volumetric water rates. Two forms of transfer payments have been proposed. The first is to pay farmers not to raise a second rice crop, and the second is to make technological investments in laser levelling or other infrastructural improvements that reduce water use. Although there are several means of increasing the supply of water in the river basin, which alternative LCRA might choose to pursue will be a matter of its program objectives.

Transfer Payments to Reduce Second Crop Acreage

If the objective of water conservation is to increase the volume of run-of-river flows, transfer payments that create incentives not to divert water make sense. The model shows that Lakeside District needs about 47,369 acre-feet of water for 22,655 acres of second crop rice. The total on-farm value of water diverted during the second crop is approximately $351,002, and the short-run average on-farm value of this water is $7.41 per acre-foot. Under the assumption that 60 percent of 25,371 first crop acres are second cropped in Gulf Coast District, and this acreage has a water requirement of 39,187 acre-feet, the on-farm value of water delivered to Gulf Coast District fields during the second crop is approximately $515,405. The short-run average value of this water is approximately $13.15 per acre-foot.

The cost per acre-foot of incentives to reduce second crop water use would differ from the average value of water. LCRA would probably have to pay farmers for each first crop acre of land on which they did not grow a second crop. The average value of one acre of land during the second crop period is equal to the value of water divided by the number of acres farmed. The short-run average value of one second crop acre is $13.38 on Lakeside, and $33.85 on Gulf Coast. These estimates are made on the basis of model acreage parameters and 1993 crop and water prices. Changes in acreage would not affect estimates of average value, but changes in crop and water prices would.

Because farmers do not pay a per-acre charge during the second crop, and there are no crop alternatives available that late in the season, the value of water is equal to the entire profit farmers make from growing rice during the second crop period. In addition, water values are the value of water delivered to the fields, and do not represent instream values because estimates do not account for canal losses. Accounting for canal losses would lower estimates of the average value but would not affect acreage values. Potential on-farm water savings equal 86,556 acre-feet. The increase in run-of-river flows would be higher due to corresponding decreases in canal losses.

One problem with incentives to reduce second crop acreage is that LCRA has no mechanism to determine on which acreage farmers would raise a second crop. To pursue this alternative, it is conceivable that LCRA would have to pay farmers for each acre on which they raised a first crop. In addition, this would only increase the volume of run-of-river flows during August, September, and October, after farmers raise their first crop. If LCRA emphasized the reduction in water diversions exclusively during the second crop period, part of their objective must include increasing run-of-river flows during this period.

If the water conservation objective is to maximize the economic benefits associated with water in the river basin rather than increase run-of-river water flows, this is no solution at all. The cost of buying farmers acreage, approximately $1.22 million a year, is calculated by multiplying first crop acreage by the average value of second crop acreage. This cost would fall directly on those who purchase stored water from the Highland Lakes. The program would redistribute the cost of any market inefficiencies related to senior water rights to those who continue to rely on stored water supplies.

Transfer Payments to Implement Water-Saving Technology

Rather than paying farmers not to raise a second crop of rice, LCRA could make investments in irrigation technology. However, LCRA should be cautious about making large investments in such things as laser-levelling. Results from Chapter 4 indicate that investment in irrigation technology is not a substitute for good water management. The most appropriate technologies and the largest water savings are likely to be those that farmers decide to implement on their own behalf, particularly if they have adopted these technologies as a result of increases in the price of water. The reason is that each farmer is the best judge of what technologies and input mixes maximize profits. LCRA could conceivably adjust the price of water to encourage farmers to adopt specific technologies if the cost and water savings are known.

Raising the marginal cost of water to farmers would induce adjustments in technology and input ratios. The linear program can be manipulated to determine what price of water would induce farmers to adopt these technologies. This is accomplished by adding the operational cost of implementing the technology to the farm budget residual. Capital costs are excluded because this model reflects demand for water in the short-run. However, the operational costs of implementing some technologies appears to be low and the resistance to new water-saving technologies may be related to cultural farming practices. Cultural biases may be a barrier to farmers' rational adjustment of input ratios to maximize profit.

Average Cost per Acre-Foot Pricing Strategies

Laws governing water use require that state water sold for irrigation be sold on a volumetric basis (Texas Administrative Codes, 31 TAC 297.46). The law states that:

> "Persons supplying state water for irrigation purposes shall charge the purchaser on a volumetric basis. The [Texas Water] Commission may direct suppliers of state water to implement appropriate procedures for determining the volume of water delivered."

Volumetric pricing has not been adopted on irrigation districts, perhaps because it is difficult to reliably measure water deliveries in open canal systems and the state has never enforced the law (Boyd, 1992). LCRA adopted volumetric water rates during the 1993 crop season as a water conservation tactic. The agency established the rates to encourage water conservation by raising the marginal cost of water to farmers. Water prices are set to recover the variable costs of operating the districts. A fixed per-acre irrigation charge supplements the volumetric water rate and is designed to cover each irrigation districts' fixed costs.

The higher the volumetric water rate, the less water farmers will use. How much LCRA might raise the price of water as an incentive to adjust technology and input ratios is limited. Because LCRA is a public utility, district revenues must reflect the cost of supplying irrigation water. Average cost per acre-foot prices described in Chapter 6 replace the fixed per-acre irrigation charge and do not lead to an increase in district revenues; thus they allow LCRA to raise the marginal cost of water within its revenue constraint. Estimates of derived demand and district costs show that prices would stabilize at $36.42 per acre-foot on Lakeside District, and $26.05 per acre-foot on Gulf Coast District. Only 1,848 first crop acres would go out of production on Lakeside District, and only 220 first crop acres would go out of production on Gulf Coast District.

Model results show that average cost per acre-foot pricing eliminates second crop acreage and reduces per-acre water use. Farmers could only continue raising a second crop by increasing the value of water. This may be accomplished by increasing rice yields or by reducing the quantity of water used in the production process. On Lakeside District, farmers would have to raise the average value of water above $22.79 per acre-foot, which would be LCRA's cost of delivering 108,937 acre-feet of water.

Farmers on Gulf Coast District would have to raise the average value of water above $19.36 per acre-foot, which would be LCRA's cost of delivering 127,985 acre-feet of water.

LCRA's concern over average cost per acre-foot pricing has been that farmers would respond by greatly reducing *first and second* crop rice acreage rather than by adopting water-saving technologies during the first crop period. First crop acreage reductions would reduce water use much more than moderate reductions in per-acre water use. If the demand for irrigation water decreases too much, LCRA districts could not meet their fixed costs. This analysis shows that not much acreage drops out of production and that LCRA can meet its fixed costs.

Although LCRA can meet its fixed costs, there remains a risk that average cost per acre-foot prices prescribed by the linear programming model would not produce enough revenue to cover total cost on the districts. Water price prescriptions are sensitive to model parameters LCRA cannot control such as crop acreage, crop price, ASCS program parameters, and elasticity estimates.

Water price prescriptions are sensitive to rice acreage variables. Factors other than water price influence rice acreage, and these factors are not included in the linear programming model. In particular, rice acreage shifts from year to year in response to ASCS program parameters and crop prices. Estimating derived demand using acreage projections based on these variables (equation 3.1) alleviates this problem, but does not resolve the issue.

Water price prescriptions are sensitive to elasticity estimates which project decreases in per-acre water use. Model results show that the elasticity of demand for water, the percent change in water use relative to a percent change in price, is very low after controlling for acreage reductions. Only small decreases in per-acre water use can be expected. Analysis of model assumptions indicate that some assumptions may have contributed to this low estimate.

Reductions in per-acre water use are based on the farmer reaction curve (equation 3.9). Data used to estimate the farmer reaction curves were collected over a two-year period and a narrow range of prices. The functional form of the farmer reaction curve reflects a diminishing marginal propensity to conserve water. This is consistent with economic theory, but because the amount of data is limited, data do not confirm this assumption. Moreover, maximum elasticity estimates based on a model that assumes constant propensity to conserve water are much higher.

Because elasticity estimates are based on two years of data, they are short-run elasticities. Short-run elasticities tend to be lower than long-run elasticities because there is a lag time between price increases and consumer responses. Farmers need time to adjust to increasing water prices by developing technology and input substitutes. On-farm water demand will probably become more elastic in the long-run.

Although risks exist, it is not clear that the expected cost of these risks is any greater than the risk of not meeting district costs when average costs are distributed among farmers on a per-acre basis. LCRA charged farmers on strictly average cost per-acre basis for many years. Acceptance of the revenue risk is an investment in water conservation. Because LCRA has expressed a willingness to invest in other water conservation efforts, it should be willing to absorb or carry any operational losses on the districts if volumetric rates increase irrigation efficiency. However, carrying the operational costs of water savings may simply be another method of subsidizing farmers' water use. A more cost effective method of managing this risk would be to make capital investments on the districts that reduce fixed costs, thereby reducing the risk of acreage reductions.

Irrigation Technology Requirements as a Condition for Irrigation Service

Empirical studies of technology transitions have applied multinomial logit models to describe irrigation technology transitions. Farmers adopt new irrigation technologies in response to several market signals. Among the principal signals to which farmers respond are crop and water prices. These studies show that production costs rather than potential increases in farm revenue appear to be the more significant factor that induces technological change (Cason and Uhlaner, 1991). In addition, farmers appear to adopt technologies for crops that are not subsidized by Agricultural Stabilization and Conservation Service (ASCS) farm programs much more readily than ASCS program crops (Schaible *et al.*, 1991). Probably as a result of their water rights, farmers do not appear to adopt technologies in response to regional water shortages. These authors conclude that water savings through technology transitions in agriculture will be slow to develop in the absence of more sweeping policy changes.

Policy changes are an alternative to adjustments in water price. LCRA or the state could require that farmers adopt specific irrigation technologies as a condition of irrigation service. For example, infield laterals require only a low capital investment and appear to have almost no operational cost. One advantage to this alternative is that the districts could effectively implement and enforce this measure. This alternative assumes that farmers will make effective use of those improvements. As in the case of laser-levelling, infrastructural improvements are not a substitute for water management. However, one concern that needs to be addressed here is why, for example, the Gulf Coast District has not successfully implemented a program that prohibits the use of holding streams. It may be that management practices are simply more difficult to enforce than infrastructural improvements.

Institutional Change in Water Rights

What is apparent in this analysis is that the initial allocation of water rights was created to satisfy policy objectives that are now inconsistent with public policy goals. The existence of agriculture's property right in water makes agricultural interests immune or insensitive to changing public needs. Yet this insensitivity produces costs that lead to a suboptimal economy in the river basin. It generates conflict between farmers and others over the allocation of resources. Solutions to creating technical and institutional change in these property rights can be resolved through two methods. Pareto efficient conflict resolution, in which the public compensates farmers for giving up their property rights is accomplished through bargaining. Institutional changes in the property rights themselves are considered a Pareto non-comparable conflict resolution tactic that the public resorts to when Pareto-efficient bargaining fails to produce results (Larson and Knudson, 1991). If the cost of a Pareto-efficient outcome is large, or the ability to enforce the agreement is too difficult, the public is forced to resort to institutional changes in order to rectify the inefficiencies.

Several options for institutional change exist. The simple reallocation of a portion of the agricultural water right has already been discussed. A better solution may be the introduction of temporal restrictions on when the irrigation districts may divert water. However, these options do not promote technological adjustments and increases in the economic value of water. Another alternative is to redefine the property right. For example, water diversions under existing water rights are restricted to beneficial use. Beneficial use is defined in engineering terms as the average quantity of water used to irrigate one acre (TWC, 1988a; TWC, 1988b). It would be possible to define beneficial use in economic terms. Although such a definition would be hard to identify, and even harder to enforce, the potential improvement associated with the equitable distribution of water and the economic returns when run-of-river flows are scarce is worth considering.

It is probably true that the larger the scope of a policy change, the more difficult it is to implement. Management decisions on a local level may be more effective than state-wide policy changes. LCRA can manage the districts to achieve on-farm water savings in addition to savings from canal rehabilitation and operational improvements by increasing the marginal cost of water through average cost pricing and other technology forcing measures.

What this study has shown is that farmers can reduce their demand for water through input substitutes and technology investment. Farmers will withstand increases in the marginal cost of water, if not the total cost. Studies of technical change in agriculture show that conflict over shortages of water in a river basin will not reduce on-farm water use locally as long as farmers are protected by a water right. Increasing the marginal cost of water to farmers relays the cost associated with their use of water to others. Transfer payments to farmers in the form of technology investment or compensation for the second crop do not appear to solve the problem of an uneconomic distribution of water in the river basin.

Recommendations for Further Research

Additional work could provide answers to some questions raised during the course of this study. Resolving questions about the role of water in the production process, the potential reduction in on-farm water demand, and the hydrology of water in the river basin could lead to improved estimates of the economic impact associated with the allocation of water and the potential water savings associated with water conservation. The following section describes some possible approaches to these questions.

Data envelopment analysis provides information on the location of the efficiency frontier for water as an input in the rice production process. The results presented in this paper are sensitive to the variables and methods selected for analysis. These data need more scrutiny to determine whether or not selected non-water input variables are the most appropriate. Additionally, the analysis might be conducted against a series of categorical variables relating to irrigation technology or soil type. Any expansion of the number of variables under analysis, however, will require a larger sample size for analysis. There is also an opportunity to explore the use of DEA as a tool for identifying best irrigation practices.

It is not clear how the mechanics of river flow would change if the irrigation districts reduced run-of-river water diversions. Some run-of-river water not diverted by the districts might not be available for diversion by less-senior owners of water rights. If this is the case, the cost associated with allocating water to the districts could be considerably less than the estimates presented in this paper. Estimates might be obtained through the use of time series models that analyze changes in stored water sales since 1988 in relation to the LCRA's water conservation program. Existing hydrologic models of the river might also provide some clues as to the potential re-distribution of water savings among users in the basin. This knowledge could suggest at what point in the growing season on-farm water conservation efforts might produce the greatest benefit.

Run-of-river water saved through conservation must be available when and where it is needed to produce a benefit. There is only a benefit if the individual that diverts water would be willing to pay more than the potential value of that water in rice irrigation. Therefore, it is important to determine the relative impact of reductions in the supply of water at different times during the growing season. A multiperiod linear program might be a useful means of accomplishing this task.

Economic theory suggests that the water produces the greatest benefit within a region when it is allocated according to its marginal product. The linear programming model presented in this paper suggests possible values for the marginal product of water in rice irrigation. However, it is not possible to deduce what a more productive distribution of water might be if there is no information on the marginal value of water in alternative uses. Therefore, it would be useful to know what the marginal benefit of water is in its existing uses and in its potential uses. For example, it may be that other uses of water within the river basin are actually less efficient than rice irrigation.

Finally, estimates of the elasticity of demand presented in this paper were developed before much data on water use and water prices were available on the irrigation districts. Information regarding on-farm water deliveries in the future will provide better estimates of how farmers react to changes in the marginal cost of water, particularly if LCRA adjusts the variable price of water from year to year. A similar analysis done two or three years from now could significantly improve derived demand estimates.

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