Irrigation for Sale:

A Case Study of Water Marketing and Conservation in the Rio Grande Valley of Texas

by

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For Ruth,

my partner in life

and in spirit

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Most literature on water marketing focuses on the expected increase in economic efficiency, but there is little that examines a market's effect on conservation and overall water supplies. It is argued here that a water market, rather than encouraging conservation with the lure of being able to sell saved water, instead encourages more water-intensive farming, thereby causing reservoir levels to fall faster during drought. To test this hypothesis, this study examines one of the most active water markets in the United States: the Lower Rio Grande Valley of Texas. A linear regression analysis shows that a trend towards greater water efficiency in the farm sector stopped in 1986, the same time rules for a regional water market were promulgated. Possible reasons are investigated by simulating farmer crop choices and irrigation use with quadratic and mixed-integer linear programming models run recursively with actual data on inflow and precipitation for 1993 to 1998.

The results suggest that when holders of irrigation rights can lease some of their water to others, overall economic benefits increase; reservoir levels fall faster and farther during drought, the economic incentive to irrigate more efficiently is reduced, and there is a stronger economic push to plant high-profit, water intensive crops.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Water markets have been in vogue among policy makers since at least the early 1990s. Some states — most notably California — have experimented with market-based responses to drought, and have met with a measure of success. In other places where scarcity is the norm (Colorado, Utah, and Idaho, for example), state legislatures have created various forms of water banks to transfer supplies to those willing to pay and to compensate those willing to sell.

Conservation is a potential benefit sometimes mentioned in the literature on market-based water resource management.[1] By allowing water users to trade their entitlements amongst themselves at prices they negotiate, scarce supplies should move from low-valued to high-valued uses, and waste should be reduced. As excess water becomes valuable, users have an incentive to invest in water-saving technologies or cut back on activities that consume water inefficiently. The market then

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1 Ronald Kaiser, "Texas Water Marketing in the Next Millennium: A Conceptual and Legal Analysis," *Texas Tech Law Review*, vol. 27 (1996). See also Richard W. Wahl, *Markets for Federal Water: Subsidies, Property Rights, and the Bureau of Reclamation* (Washington: Resources for the Future, 1989); Terry L. Anderson, *Water Crisis: Ending the Policy Drought* (Baltimore: Johns Hopkins University Press, 1983); James Winpenny, *Managing Water as an Economic Resource* (London: Overseas Development Institute, 1994); Charles W. Howe, Dennis R. Schurmeier, and W. Douglas Shaw Jr. "Innovative Approaches to Water Allocation: The Potential for Water Markets," *Water Resources Research*, vol. 22 (1986), pp. 439-445.

“rewards the conservor with the right to sell the fruits of his labor – namely that amount of water saved through conservation practices.”[2] Water prices usually rise, but as Anderson notes,

> At higher prices people tend to consume less of a commodity and search for alternative means of achieving their desired ends. Water is no exception.[3]

Most of the authors who talk about water marketing’s conservation effects, however, do so in the context of other issues more central to their concerns. Usually, these scholars focus on the reallocation of scarce supplies in a way that doesn’t require the government to take a heavy hand in rearranging water rights. Issues related to entitlements are explained in detail; conservation is treated as a residual issue rather than as a policy goal with its own virtues. As a result, assumptions about the conservation effects of water marketing far outnumber the studies actually undertaken to explore the question.

The experience of the Lower Rio Grande Basin of Texas suggests that a water market’s propensity to encourage conservation is not straightforward. This is especially interesting given the fact that the area has one of the most ideal and active water markets in the United States. It is very easy to buy and sell permanent water rights, and even easier to sell quantities under a water right to others without giving up the right itself.

This study focuses mainly on short-term water markets — those in which the seller enters into a contract to provide a certain volume of water for a certain period of time but retains the permanent water right.

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2 Kaiser, p. 194.

3 Anderson, p. 5.

In this type of a water market, negotiations have a very short time horizon, quantities reflect immediate needs, and prices tend to respond to today's economic conditions. Deals happen more often and more quickly among more parties, permitting a market to find its equilibrium more easily than is the case with infrequent sales of permanent water rights.

The data show that despite a very active water market along the lower and middle Rio Grande, overall conservation (at least as it is defined by some) is not happening. The agricultural sector — which typically consumes around 85 percent of the basin's water on the U.S. side of the border[4] — is using more water per acre, not less. On the other hand, an acre-foot of water typically produces more economic benefit now than before the days of water marketing. While this trade-off is hardly surprising to natural resource economists, it goes against the intuition that is evident in writings by political scientists and legal scholars who discuss water marketing in the context of property rights.

There are other related trends in the area:

- The amount of surface water that has migrated from agricultural use to municipal use has been small compared to the movement of irrigation from small farms to large ones.
- An increasing share of acreage that is planted in cotton and sorghum, the Valley's two largest crops, is being dry-farmed. At the same time, cultivation of water-intensive crops such as sugarcane is expanding.

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4 Texas Water Development Board, *Water for Texas* (Austin, Texas: 1997), p. 3-181. The figure 85 percent refers to demand in the Texas part of the Rio Grande Basin proper, including areas upstream from the Valley. It also includes irrigation water diverted by irrigation districts in the Valley itself that are technically interbasin transfers.

- After more than a decade of water marketing, very few drip or precision-application irrigation systems are in place. The predominant method of irrigation is still by furrow, which is one of the least efficient practices.

In short, large farms are planting more water-intensive crops and are taking a larger share of the available irrigation supplies. While some irrigation districts have cut conveyance losses by lining canals, few farmers have made any radical switch to water-conserving irrigation methods. Smaller farmers are "conserving" by switching to dry-farming, fallowing, or in some cases getting out of the business altogether.

For drought management, a consequence of this rather skewed picture of conservation under water marketing is that accumulating water reserves is more difficult. Each month, an average irrigated acre requires more water for its crop, making it less likely that rainfall will meet crop needs sufficiently. More irrigation will be used, sustained demand will be higher, and less residual inflow will be available to build up reservoir storage.

Similarly, conservation storage will be depleted faster whenever drought hits. Not only does the average irrigated acre require more water, the economic penalty of using less than the required amount is greater, as each incremental decrease in yield entails a greater marginal loss in revenue. The higher water demand and the higher consequences of scrimping on water (and thus yield) mean that when inflows to the entire hydrological system are down, agriculture will draw down its water reserves at a fast pace.

Does water marketing "work," then? If the goal is to increase economic benefits to the agricultural sector (i.e. farm profits), the answer is yes. If the goal is to reduce water consumption, the answer is no. That, at least, is the experience of the Lower Rio Grande Valley. But as the following chapters will show, what has happened in the Valley is no local aberration. It is argued here that sound theoretical reasons underlie the trends evident in the Rio Grande water market. Water managers and law makers in other areas who are contemplating a water marketing regime may therefore learn much from what has happened in the Rio Grande Valley. Higher consumption has accompanied higher profits in the farm sector because the area's water market has acted as water markets are wont to act.

The question, and the neoclassical answer

Is the ability to buy water actually *replacing* the incentive to irrigate more efficiently? The argument put forward in this study is that to some extent, it has. The Valley's short-term water market (in which a water right holder sells a specified quantity under a 12-month contract while retaining the permanent right) seems to have reduced the risk of irrigation shortage during times of drought, bolstering the confidence of large farming operations to go out on a limb with more cultivation of high-return, water-intensive crops.

Why might this be? One could pursue explanations based on water's marginal product. The key questions along this line of inquiry would have to do with how water figures into the agricultural profit function, and the effect of incremental changes in farm inputs on the value of output. The important variables would be the price at which water can be obtained, the technological efficiency of irrigation, and the capital cost of upgrading to water-conserving technology.

With no water market and no investment in efficient irrigation technology, the basic profit function for a simple one-crop farm would be

Eq. 1-1: $$\prod = p \times f(\text{water}) - C - K$$

where Π represents the crop's per-acre profit margin, *p* is the harvest price (plus government subsidy, if any), *C* is variable operating costs, and *K* is fixed capital costs. Per-acre crop yield is represented as a function of applied water, *f(water)*.

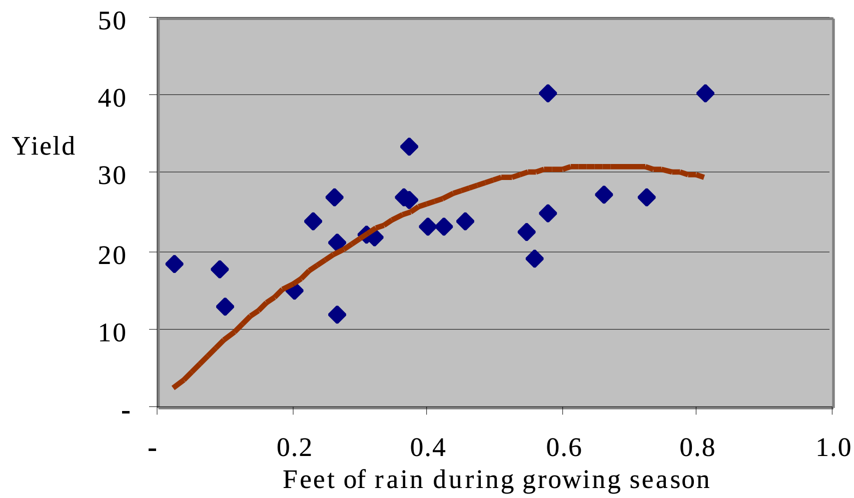
Assume that the crop's yield may be approximated by the general quadratic equation $\alpha\, water - \beta\, water^2$. Figure 1-1 depicts the yield curve for unirrigated sorghum based on historical data from the Valley; for this crop, water is solely a function of precipitation and natural soil moisture. For irrigated crops, water is actually a combination of rain and applied irrigation, $rain + \varphi irr$, with φ representing the technological efficiency of the irrigation method used. (As φ approaches 1, irrigation is more efficient.) The expanded profit function for irrigated crops is then

Eq. 1-2: $$\prod = p \times [\alpha\,(\text{rain} + \varphi\text{irr}) - \beta\,(\text{rain} + \varphi\text{irr})^2] - \omega\text{irr} - C_o - K$$
$$\textit{subject to } \text{irr} \leq W$$

with ω the average cost of applying one acre-foot of irrigation, and *W* the amount of irrigation legally controlled by the farmer. All other operating costs are represented by C_o. Irrigation's marginal contribution to profit is found by taking the partial derivative in the usual way:

Eq. 1-3: $$\frac{\partial \Pi}{\partial \text{irr}} = p\alpha\varphi - 2p\beta\varphi^2\text{rain} - 2p\beta\varphi^2\text{irr} - \omega$$

Figure 1-1. Water-to-yield curve for unirrigated sorghum in Hidalgo County



Yield is in hundredweight per harvested acre. Curve was estimated by regression from seasonal rainfall and historical yields for unirrigated sorghum in Hidalgo County from 1976-97, using the zero-intercept quadratic model $y = \alpha\ rain - \beta\ rain^2$. Both parameters are significant at the 99 percent level. Data sources: National Agricultural Statistics Service, "Crop County Data" database (Washington: U.S. Department of Agriculture, 1999), tables for sorghum; National Climatic Data Center, "Monthly Surface Data" database TD-3220 (Washington: U.S. Department of Commerce, 1999), tables for McAllen, Texas.

The economically optimal amount of irrigation is found by setting the first-order condition equal to zero. This resolves to

Eq. 1-4:

$$irr = \frac{\alpha}{2\beta\varphi} - \frac{rain}{\varphi} - \frac{\omega}{2p\beta\varphi^2}$$

In plain language, this equation says the economically optimal amount of irrigation — *irr** — is the amount required by the crop to obtain the best yield (the first term on the right-hand side), minus rain's contribution (the second term), minus an increment of irrigation whose marginal contribution to yield is so minuscule that the extra revenue it would generate would not be worth the cost of applying the additional water (the third term). Graphically, this last component corresponds to the flattest part of the upward-sloping half of the water-to-yield curve, as shown in Figure 1-1. At just less than the optimum, more water gives only a small boost in yield.

Taking the derivative of Equation 1-4 with respect to φ shows that increasing technical efficiency reduces the amount of irrigation required to obtain the best yield and also reduces the amount of irrigation that is replaced by an inch of rain (because irrigation is more productive). Increasing efficiency also makes it harder to scrimp on irrigation, as the amount of marginally unprofitable irrigation decreases.[5]

The effect of water trading may now be captured by revising Equation 1-2. The new profit function becomes

Eq. 1-5: $$\prod = p \times [\alpha(rain + \varphi irr_m) - \beta(rain + \varphi irr_m)^2] + \tau(W - irr_m) - \omega\, irr_m - C_0 - K$$

where irr_m is irrigation used under a water market, and W is no longer a constraint but a parameter. A positive value for $W – irr_m$ describes the surplus water a farmer may sell. A negative value indicates the amount of irrigation in excess of W a farmer purchases. In either case, W itself does not enter into the first-order condition of the new profit function.

5 These inferences come from the signs of the three terms after taking the derivative. The sign of the first term is negative (thus reducing *irr**), while that of the other two are positive (pushing *irr** higher).

The value τ represents the average opportunity cost of water — exclusive of its delivery costs — as represented by the open-market price of irrigation. It is what a farmer must pay for irrigation in excess of his entitlement, and what he foregoes by not selling any portion of *W* he does not use himself.

The marginal profit contribution of irrigation under a market regime is

Eq. 1-6: $$\prod' = p\alpha\varphi - 2p\beta\varphi rain - 2p\beta\varphi^2 irr_m - \tau - \omega$$

and the optimal irrigation is

Eq. 1-7: $$irr = \frac{\alpha}{2\beta\varphi} - \frac{rain}{\varphi} - \frac{\omega + \tau}{2p\beta\varphi^2}$$

Note that the first two right-hand terms of Equation 1-7 are identical to those of Equation 1-4. The third term differs only in the numerator. This suggests that if water has any market value at all, a farmer holding a water right will benefit by reducing irrigation (and consequently yield) slightly and selling what he saves to someone else at a price of τ. The ability to buy or sell — embodied in the value τ — represents an additional option for the use of the farmer's lowest-valued water, an option which (at some point for some measure of water) would be more lucrative than using the water himself and realizing only a trace of a profit. What the farmer loses in that small portion of harvest value is more than offset by the benefit of selling (or not buying) the corresponding increment of irrigation.

Equation 1-7 dominates Equation 1-4 regardless of the crop, commodity prices, or rainfall. This suggests less individual use of irrigation under a water market. But what about investment in water-conserving technologies?

A farmer will have an economic incentive to invest if the discounted stream of savings on irrigation costs is greater than the additional capital costs that would be incurred. Mathematically,

Eq. 1-8:
$$\frac{\partial \mathrm{irr}}{\partial \varphi} \omega > \frac{\partial K}{\partial \varphi}$$

where the left-hand term represents the amount of irrigation saved multiplied by the per-unit cost of delivery (i.e. a change in variable irrigation costs) and the right-hand term is change in fixed capital costs due to changing the efficiency of irrigation. (Because both sides are discounted, the discount rate effectively cancels out.)

Comparing how the condition expressed in Equation 1-8 is satisfied under both market and no-market assumptions involves taking the derivatives of Equation 1-4 and Equation 1-7 with respect to irrigation efficiency, φ. The derivatives are identical except for the presence of one positive term in the market scenario:

Eq. 1-9:
$$\frac{-\alpha\omega}{2\beta\varphi^2} + \frac{\mathrm{rain}}{\varphi^2} + \frac{\omega}{p\beta\varphi^3}$$

Eq. 1-10:
$$\frac{-\alpha\omega}{2\beta\varphi^2} + \frac{\mathrm{rain}}{\varphi^2} + \frac{\omega}{p\beta\varphi^3} + \frac{\tau}{p\beta\varphi^3}$$

Because the additional term in Equation 1-10 containing τ will never be negative, its effect is to increase the expected economic benefit of upgrading irrigation technologies, thereby making the investment more attractive when water marketing is allowed. As was the case in the previous market to nonmarket comparison, Equation 1-10 dominates Equation 1-9 regardless of crop, rainfall, or commodity price. This is the crux of the neoclassical argument in favor of a water market.

A different answer

As with most analyses of this nature, the farm decision maker is placed in a static slice of time at which the variables are somehow resolved and an equilibrium condition either does or does not obtain. The assumption is that water users try to maximize the profit they receive from what they consume, and make rational decisions based on input costs and expected commodity prices at harvest.

But months pass between the time a farmer makes production decisions and the time that the harvest goes to market. And there are many uncertainties in this lag between costs sunk and benefits realized. Consequently, a static framework is not always the best way to proceed with an analysis.

Consider, for example, the question of water's cost. For a farmer, the real cost of using water is more complicated than simply the price of the water or the cost of getting it to the field.

Each acre planted with a particular crop has a certain amount of water that will result in the best possible yield. (Recall Figure 1-1.) Beyond that optimum, simply buying and applying more water without expanding acreage will actually reduce yield. Getting more benefit from using more water requires planting more irrigated acres at the beginning of the season, and planting them differently. (An irrigated crop is usually planted more densely than the same crop dry-farmed.) So for a farmer to increase water use by, say, 10 percent may involve other expenses — the extra cost of plowing, planting, and fertilizing an additional portion of acreage, as well as the cost of additional borrowing. Most of these other factors must be decided in advance and cannot be revised up or down later as prices change.

Typically, water purchases make up only 7 percent of a cotton grower's cash expenses, and around 1 percent of a sugarcane grower's expenses.[6] This tends to make a farmer's demand for water relatively inelastic with respect to water's going price. That is, factors unrelated to water may determine a farmer's planting decision, and once the decision is made, it matters little how the price of water changes. A particular quantity — whatever the price — is needed for all the previously made cropping decisions to work; more is not necessarily better, while less may be disastrous. In such a case, a farmer may be willing to pay well above the present marginal product of water if it ensures that the required minimum supply will be available a few months later.

Absent alternative sources of water that can be purchased on short-term contract, a farmer may hedge against a water shortage by investing in modern irrigation technology. Because such an investment usually requires financing, the expected value of future gains in yield plays a large part in the investment decision. A sequence of expected values of

6 Economic Research Service, "Cotton Production Costs, Southwest, 1975-97," database (Washington: U.S. Department of Agriculture, 1999), and ERS, "Sugarcane Production Costs, Louisiana/Texas, 1992-96," database (Washington: USDA, 1999).

annual harvest yields and prices is projected into the future and rolled up into one discounted value that is compared to the easily measured amortized cost of financing the new equipment. The higher the present value of expected yield gains, the more likely it is that the farmer will modernize.

There are important differences between the decision to invest in modern irrigation, and (if permissible) the decision to buy water as needed. Investing in new irrigation technology involves raising the threshold of risk-exposure for all years equally. But a threshold still exists, thus even after the investment and incurring the debt, the farmer will still face some degree of drought risk. If water is severely scarce during a particular season, the new irrigation technology might not save enough water to ensure a crop's profitability, or even its survival. During years when rainfall is unusually high and less irrigation is needed, the farmer will have overpaid for water security because the same debt payment will be due.

In contrast, buying additional water *ad hoc* every season is a variable cost that fluctuates according to the drought risk for any given year. There is no overpaying for security, because if water is sufficient for a particular season, no purchase contract is necessary. On the other hand, given the inelastic nature of water demand, a farmer is likely to keep pursuing contract water during a drought as needed with relatively little regard for the price. Even if the price of a contract is high during the current year, it will have little bearing on the farmer's cost of risk-avoidance the following year.

Relying on spot market contracts as a strategy of risk hedging can be done with any method of irrigation in place. If a farmer continues to rely on furrow and flooding to irrigate, then long-term average water use per irrigated acre will remain high even though the water market reduces the risk of loss due to drought. Over time, the water actually taken from the system by the irrigator will remain high, and conservation will not be achieved.

There is yet another possible response to the risk of drought: deciding at the outset to reduce the level of output so that less water is required. This “minimax” hedge—minimizing the maximum likely loss at the expense of reducing the probable output—would reduce the amount of water needed for the season. If the grower’s water entitlement is then more than sufficient for that year, the farmer could enter the water market as a seller rather than a buyer.

A possible difficulty with reducing production levels is the problem of returns to scale. In most cases, small farming operations are less profitable than large ones, thus the greater the reduction, the more difficult it is to keep the entire enterprise feasible. What is likely under this scenario is closing the farm and permanently selling the water rights, converting the land to dry crop or some other activity not dependent on irrigation. Instead of comparing the present value of future gains against the cost of modernizing, as is done when deciding whether to invest in new irrigation technology, the farmer would compare the present value of future expected profit against the risk-free proceeds from selling the water rights and discontinuing irrigated farming.

The framework

Because time and uncertainty are important dynamics influencing the farmer’s decisions, it is essential to follow an analytical framework that takes risk into account. Within this framework, one must then ask a number of crucial questions. What institutional conditions are required for various risk-minimizing decisions to be feasible? Are market behaviors and conservation behaviors complementary or antithetical? Are the conflicts (if any) between marketing and conservation an inherent part of risk avoidance, or are they artifacts of their institutional environment?

In examining the conservation effects of water marketing, farmers are not simply profit-maximizers. They simultaneously want to maximize profit *and minimize uncertainty*. Risk-avoidance and profit maximization are not mutually exclusive, of course, but the contention here is that the behavior of a water market can be explained more fully by looking explicitly at risk in conjunction with expected profits.

Here, water conservation will be operationally defined as a reduction in the number of acre-feet of water used per acre of farmland. This definition excludes notions that equate conservation with economic efficiency, and does so by design. Maximizing profit and reducing use both are important aims in water management policy, but they are not the same. So to keep the concepts clear and distinct, this study will use the convenient term "economic efficiency," not conservation, to describe economic efficiency. Water conservation will refer to an absolute reduction in water use by a particular sector, with the savings either going elsewhere (from agriculture to cities, for example) or remaining as augmented in-stream flow for ecological or other purposes. Chapter 3 will more fully discuss the various definitions of conservation and demonstrate why this operational definition is valid. For the time being, the reader should note that no definition of conservation is accepted by everybody, that non-economic definitions are common, and that what matters ultimately is that the phenomena at hand not be confused with other things.

If the policy variable is the presence of market-based water management mechanisms, then two alternative hypotheses may be put forward.

- *A neoclassical hypothesis*: When a water market exists, water-conserving irrigation technology tends to be adopted and water consumption per acre decreases.
- *A risk-avoidance hypothesis*: When a water market exists, water-conserving irrigation technology tends not to be adopted and water consumption per acre increases.

An adequate treatment of markets and conservation is necessarily eclectic. A number of academic disciplines can cast light on different aspects of the relevant issues. Because the ultimate aim of this study is to provide insights for policy-making rather than for any single discipline, it is necessary to place this research in legal, economic, and water management contexts.

Chapter 2 provides an overview of water marketing research to date. Even though this study follows a so-far untrodden path in the relatively young literature on water marketing, it builds on the theoretical and empirical work that has gone before. It is here that the basic economic foundations of water marketing will be introduced and explained. The chapter then examines the reasoning behind the advocacy of conservative political scientists, and the cautionary notes sounded by natural resource economists. Chapter 3 discusses and defines two concepts that are central to this investigation: drought and conservation. Both of these concepts have a number of interpretations, and the differences can affect the inferences and conclusions one may draw.

Ever since the civil law of the Roman Empire, legal codes have recognized the right and the need for the state to set rules by which water is divided among users. Chapter 4 examines the predominant legal regimes that have governed water allocation in the Lower Rio Grande Valley throughout its colonial and modern history: under Spanish civil law, under riparian law, and under the doctrine of prior appropriation. Each of these three regimes will be examined in the context of economic issues raised in Chapter 2.

Chapter 5 carries forward the background of Chapter 4 into a description of how water is managed in the Lower Rio Grande Valley today. The political and legal history of the regime is described, with an explanation of how the current watermaster system came about. As will be seen, the fact that the region's water law system is not cut from the usual pattern contributes significantly to the viability of the area's water market. This chapter details the rules by which the watermaster allocates water among users, and how the market for irrigation leasing works.

It is often argued within Texas water law that the uniqueness of the Valley's hydrology prevents the watermaster system from being compared with the rest of the state, or anywhere else. But the argument in this study is exactly the opposite. Chapter 5 will show that the Valley's hydrological and legal uniqueness is concomitant with an ideal water market, so lessons from this case study *do* have applicability to other places. The Valley is a true water market in that both the volume and price of each trade are determined by the buyer and seller themselves. If water marketing doesn't achieve conservation in the ideal setting of the Lower Rio Grande Valley, it probably won't do so in a quasi-market where the ideal does not obtain.

Chapter 6 will paint the area's empirical picture, describing past and present patterns of agricultural water use in the Valley. This exploratory data analysis describes the phenomena that need to be explained, the most important of which is the lack of any discernible trend towards water conservation in the farm sector.

Chapters 7, 8, and 9 offer an explanation, justifying it by way of a recursive mathematical programming simulation. The institutional description of Chapter 5 provides the rules for alternative structures of the simulation; half of the scenarios model the Rio Grande watermaster's current rules of operation in which water trading is common, and the rest modeling alternative scenarios that preclude trading. The historical data introduced in Chapter 6 provide the inputs for the simulation runs.

Although the simulations results reported in Chapter 9 suggests cropping patterns under the different regimes and how much irrigation would be used over time, these are not the results of interest. The simulations contain a number of decision variables, coefficients, and constraints that remain the same across each run. The model's computational output includes measures of how the underlying pressure on each crop choice changes as the rules change to permit the free buying and selling of irrigation amongst those holding water rights.

Finally, Chapter 10 offers conclusions and policy recommendations about water markets and water conservation.

Limitations of this study

It should be emphasized that the focus of this study is on the value of water marketing as a tool to promote water conservation; it does not profess to go further than that. Policy makers and water managers have additional objectives to which they must attend, and these other aims are beyond the scope of this study. Thus the purpose of this study is not to pass a thumbs-up or a thumbs-down on water marketing, but simply to elucidate one aspect of market-based institutions that should be taken into account by policy makers. Clarifying the conservation effects should contribute to a better-informed policy discussion that deals with economic benefits in a more accurate manner.

Regardless of its conservation effects, water marketing does provide an effective way to ensure that water is put to its highest-valued use; virtually *any* purchase involves moving water to higher-valued use, almost by definition. As Saliba and Bush point out,

> Market transfers occur because the buyer expects the private benefits of the transfer to outweigh the price paid to the seller plus any cost the buyer incurs in implementing the transfer; so the answer to the question "Are market processes moving water to higher valued uses?" will nearly always be positive.[7]

Whether or not all economically feasible transactions happen — and why they don't — is the subject of most water marketing research to date. But it is not the subject of this study. Also, the protection of public-interest values that are hard to express monetarily is beyond what is being investigated here. The policy importance of wildlife habitat is

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[7] Bonnie Saliba and David Bush, *Water Markets in Theory and Practice* (Boulder, Colo.: Westview Press, 1987), pp. 240-241.

something to be determined politically, not by models of risk aversion, and benchmarks for success are rooted in the natural sciences rather than the social sciences. The ecological ramifications of water marketing are set aside for other inquiries.

Even within its intended context, however, this study has important limitations. The fact that the rules governing short-term water contracts prohibit shifting water to a different use means that the spot market for water excludes agriculture-to-municipal transactions. This is an important exclusion, because one of the most politically charged issues of water management is figuring out how to draw water from the agricultural sector to meet the domestic demands of growing cities. What the Valley's contract market can show, however, is what happens within the agricultural sector itself when water can be freely bought and sold short-term. Seller characteristics in the Valley would likely still obtain in a market open to irrigator-to-municipal contracts, while buyer characteristics would indicate who might be competing with municipalities as buyers.

At this point in time, however, the cross-sectoral limitation on trading is of academic rather than practical importance. Irrigation and municipal use constitute freely operating markets within themselves, and there have always been excess municipal supplies even during the worst droughts. Cities haven't really *wanted* to lease water from irrigators, because abundance in the municipal sector has kept contract prices relatively low — only slightly higher than irrigation contract prices.[8]

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[8] A few cities, most notably Laredo and Brownsville, have been active purchasers of permanent water rights, however. Other municipalities have entered into long-term contracts with irrigation districts, which have converted some of their water rights to municipal use.

Another limitation of this study is that the Valley's allocation regime does not take into account water quality. A number of studies — including some of the earliest — include water quality as a variable in their marketing models, under the assumption that higher salinity means less yield. When buyers and sellers in the Valley negotiate a water contract, the variables are quantity, price, time, and point of diversion, but not water quality. The reason quality is not an important trade variable is that water is a far more fungible commodity in the Valley than it is along a free-flowing river. All water right holders from Falcon Dam down to the Gulf of Mexico have storage accounts in Falcon Reservoir, and just as a dollar is a dollar in a bank account, so too is an acre-foot an acre-foot in the reservoir. There is no physical distinguishing between an acre-foot released and charged to a water right holder in Starr County just below the reservoir, or an acre-foot released and charged to a water right holder in Cameron County at the salty mouth of the Rio Grande, if the water is diverted by a purchaser in Hidalgo County in either case.

Offsetting these limitations, however, is the plain fact that the Valley's water market has been extremely active. There is a wealth of data on buyers, sellers, quantities, prices, and uses from which some qualified general insights can be drawn.

Contribution

This study will expand the understanding of market-based water management by viewing its effects as a function of farmer response to the risk of shortage, thus adding a new dimension to the literature on water marketing. Much of the existing literature treats water marketing as a marginal product problem, and this has provided a good theoretical background from which to proceed. Most of these other efforts have focused on the institutional requirements for a water market to happen, and the reasons such a market might not function ideally. This study, being less concerned with determining economic efficiency, relaxes the concern over market imperfections. Its concern is with what actually happens in a water market with respect to conservation, and whether those effects are a function of market failure or of market forces running as they are wont to run.

This will also be one of the few studies of a functioning water market to go beyond a simple description of the institutions. Studies of the Central California water bank and of water trading in the Colorado-Big Thompson project have been rich in description but have not yet provided rigorous analysis of time-series data. This study draws on abundant data from a historically active market. It takes advantage of one of the few opportunities currently available to empirically test hypotheses about water marketing behavior.

Finally, by attending to the institutional factors that influence how the Valley's water market works, this study will provide additional information to policy makers and water resource managers. Ever since the mid-1980s, the drive towards using market-based methods to manage natural resources has gained momentum. The political impetus for such policy changes, however, have been driven by property rights ideology rather than by drawing economic lessons from previous experience. In Texas, for example, the political glamour of establishing a state water bank stands in stark contrast to the fact that the bank has been moribund ever since its creation. A rigorous examination of the state's one unequivocally successful water market may suggest new directions for Texas Water Bank in particular, and for Texas water law in general.

Chapter 2: Literature

Before looking at the Rio Grande Valley and its particular characteristics, it will be helpful to look at the current state of research on water markets in general. This chapter will describe the theoretical principles behind water marketing and clarify the terms to be used in the discussion, drawing on previous research in the field. Chapter 4 will extend the discussion to an analysis of the economic principles embedded in various kinds of water law regimes, with the purpose of describing in general terms the reasons a water market might function well or poorly in each regime.

The organization of this chapter is as follows. The first section begins with an overview of the limited academic literature on water marketing that specifically addresses the Rio Grande Valley. The discussion then turns to the classical issues raised by economists, describing the theoretical principles common to most economic literature on water marketing and then looking at some of the main economic concerns.

The next section then describes how political theorists have carried the economic discussion into their own discipline. It looks at some of the issues of rights and responsibilities that have come into the political discussion, and briefly touches on water development policy in the western United States.

Finally, this chapter will look at some of the ways risk has been incorporated into agricultural economics research. While largely a discussion on methodology, this section will also show how previous work on risk in agricultural choice can be extrapolated to a theoretical model of water marketing.

The economics of a water market

There exist extensive bodies of literature on water conservation, technological transformation in agriculture, and risk. These areas are also integrated by numerous authors who draw on more than one field to research their empirical questions. But these well-developed areas have only begun to extend in the direction of water marketing. Consequently, much of the literature on the subject is descriptive and anecdotal; there is little empirical work designed to test theoretical propositions about water markets.

Theorists who write about water marketing generally fall into three camps: advocacy scholars who argue from a standpoint largely guided by political ideology and institutional values, a more cautious group of economists who are concerned about how water deviates from a pure market model, and legal scholars concerned mainly with the regimes within which water marketing can occur. For the most part, the economists recognize the gains to be had from market-based allocation as compared with command-and-control allocation. They say the "public good" attributes of water require some policy adjustments in order for a market to work efficiently, and that where such adjustments can be made, the market will allocate scarce water such that society as a whole will be economically better off.

Neither the political nor the economic thread is rich in empirical analysis; anecdotes constitute most of the vision on the real world. Among the descriptive studies of different water markets are two that look specifically at the Lower Rio Grande Basin at different times: Schoolmaster's 1991 study, and 1996 overview by Jonish, Terry, and Yoskowitz, the latter being an atheoretical description of water trading in the Rio Grande Valley.[1] Schoolmaster provides a geographer's perspective on how the water market affected allocation in the Valley during its early period (from 1971 up to 1990). He concludes that whereas water management elsewhere in the United States is usually a matter of conflict between interests competing for scarce resources (regulatory) or of friendly coalitions lobbying the government for public investment in water infrastructure (distributive), the Rio Grande water market more closely fits redistributive policy making in that government institutions act to move existing resources from one segment of society to another with minimal conflict.[2]

Jonish found that on the short-term water contract market from 1991 to 1993, municipal water traded at prices somewhat higher than did irrigation water, while prices of water traded between mining accounts were even higher. Contract water traded largely between irrigators,

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1 F. Andrew Schoolmaster, "Water Marketing and Water Rights Transfers in the Lower Rio Grande Valley, Texas," *Professional Geographer*, vol. 43 (1991) pp. 292-304; James E. Jonish, Neil Terry, and David Yoskowitz, "Water Marketing along the Rio Grande," Universities Council on Water Resources 1996 Conference Proceedings, San Antonio, 1996.

2 Schoolmaster employs a model of policy making formulated by Lowi. For more on this four-sector model, see Theodore Lowi, "Four Systems of Policy, Politics, and Choice," *Public Administration Review*, vol. 32 (1972), pp. 298-310; and Robert H. Salisbury, "The Analysis of Public Policy," in *Political Science and Public Policy*, ed. Austin Ranney (Chicago: Markham Publications Co., 1968).

while permanent water right transfers went mostly from irrigators to municipalities. Prices for permanent water rights transfers were roughly 30 times higher than short-term contract prices.

Clearly, there is a water market in the lower and middle Rio Grande, especially for short-term contract trading. For many political advocates of market-based management, this is enough; the simple existence of widespread trading is regarded as proof of its viability, and nothing else of interest remains to be explored. Unfortunately, the mere fact that buying and selling occurs proves nothing about *how* a water market works, or about whether the theories behind them are indeed accurate descriptions of what is happening.

The following sections review the existing literature on water markets, choice of irrigation technologies, and agricultural risk. It will be seen that much of this literature carries certain embedded assumptions and policy values about what ought to be accomplished with market-based water management. These implicit policy values—one of which is the need to conserve scarce water resources—suggest questions that can be tested only in the presence of a functioning market. Thus the inquiry doesn't end when water trading proliferates; rather, it segues to a new level.

Theory of water markets

The primary theoretical concept behind water marketing is the notion of economic efficiency. This is not to be confused with how water managers and other non-economists understand the word "efficient." In fact, concepts of efficiency that have to do with reducing physical waste of water (conveyance efficiency, for example) have little direct bearing on how economists understand efficiency.[3] In a classical economic framework, allocative efficiency is obtained when it is no longer possible to reallocate water such that the net benefits to society increase. If it is possible to make someone better off without making someone else worse off, then the system is considered inefficient until such a reallocation occurs.[4]

For a water right holder, the marginal product of water with respect to output is the value of what would be given up by surrendering just one increment of water (an acre-foot, for example). For the person needing water, it is the value of what would be gained with one additional acre-foot. If the prospective buyer's marginal valuation of water is greater than that of the prospective seller, there is economic room for a deal at some price between the two marginal valuations.

Consider a simplified economy with only two water users, whose partial demand curves are depicted in Figure 2-1. Assume that the two demand curves are such that they both slope downward near the point at which all of their water endowments are used; this means that the

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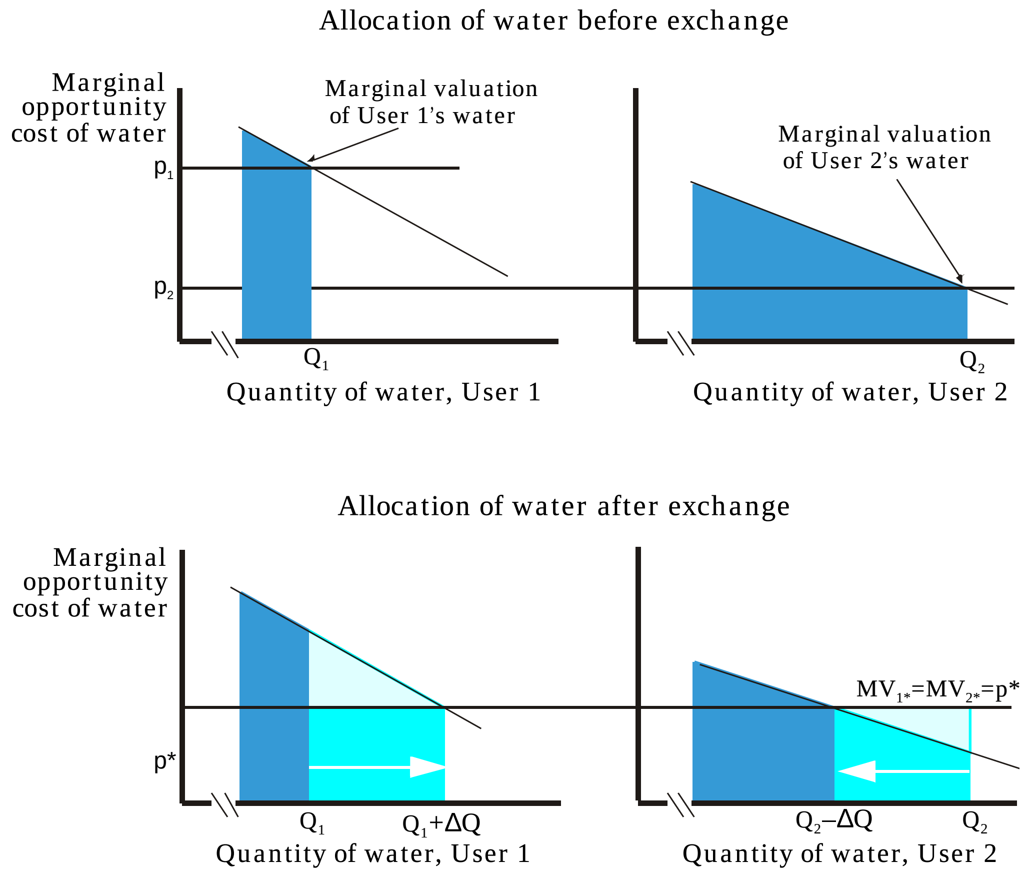
3 Charles W. Howe, Dennis R. Schurmeier, and W. Douglas Shaw Jr., "Innovative Approaches to Water Allocation: The Potential for Water Markets," *Water Resources Research*, vol. 22 (1986); James Winpenny, *Managing Water as an Economic Resource* (London: Overseas Development Institute, 1984), Terry L. Anderson, *Water Crisis: Ending the Policy Drought* (Baltimore: Johns Hopkins University Press, 1983).

4 The Hicks-Caldor Compensation Principle carries the reasoning a step further: If it is economically possible for gainers to still come out ahead after compensating losers for what the latter give up, then a reallocation is considered to be efficient *even if the compensation does not in fact take place.* Extremely controversial outside the realm of neoclassical economics, the Compensation Principle in essence splits policy questions between their economic and institutional elements. Whether or not gainers have the means to compensate losers is an economic issue; whether or not they actually do so is an institutional question that becomes relevant only after economic efficiency obtains.

Figure 2-1. Initial endowments in a potential water trade



ΔQ: Quantity of water exchanged

benefit derived from using one additional measure of water — and consequently, their willingness to pay for it — gets progressively smaller. The user with the steeper curve is said to have a more inelastic demand, because a relatively slight change in water availability would result in a relatively greater change in benefit obtained. At some point, each demand curve would reach zero, meaning that additional water would yield no additional benefit.

The quantity Q_1 indicates how much water User 1 has at the outset; Q_2 is User 2's initial endowment. It doesn't really matter, from an economic standpoint, how these initial quantities were determined.[5] What matters is that the marginal value of the quantity held by each user is different. In this example, the marginal value of User 1's endowment is greater than that of User 2's, meaning that in this state of affairs User 1 is more economically desirous of additional water than is User 2.

Let's say that there is no additional source of water other than the volumes controlled by the two users. If there are no other mitigating circumstances and both act in an economically rational manner, each user would accept from the other some price (call it p*) greater than the currently realized marginal value as an inducement to give up some quantity (ΔQ) of the water held. Similarly, each one would pay less than the marginal value to acquire more water. Referring to Figure 2-1, User 1 would sell water at some p* greater than p_1, and would buy at p* less than p_1. User 2 would sell at p* greater than p_2, and would buy at p* less than p_2.

The example depicted in Figure 2-1 shows that there is room for a deal between User 1 and User 2 at a price p* somewhere between p_1 and p_2 by which User 2 would sell some amount ΔQ to User 1. Adding ΔQ reduces User 1's marginal value of water, and vice versa for User 2, up to the point at which the marginal value is the same for both users (p*).

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5 This point was developed in Ronald Coase's seminal paper "The Problem of Social Cost," *Journal of Law and Economics*, vol. 3 (1960). Coase develops the theoretical proposition that "It is always possible to modify by transactions on the market the initial legal delimitation of rights. And of course, if such market transactions are costless, such a rearrangement of rights will always take place if it would lead to an increase in the value of production."

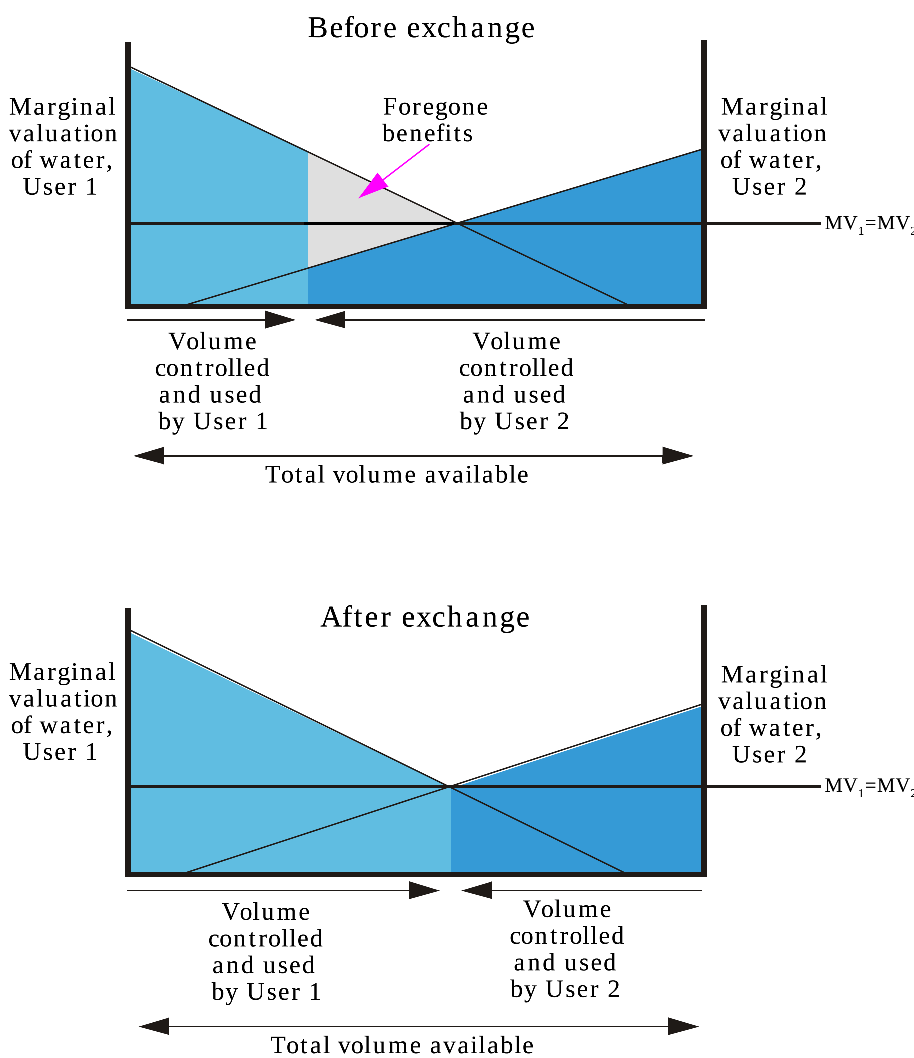
At that equilibrium point, any further exchange would fail to produce a mutual increase in benefit.

The amount paid by buyer User 1 ($p^* \times \Delta Q$) would be represented by the rectangle below p* and between Q_1 and $Q_1 + \Delta Q$; an identical area between Q_2 and $Q_2 - \Delta Q$ below p* represents the payment seller User 2 receives. User 1's incentive to buy — the additional benefit above and beyond what is paid — is represented by the triangle above p*. User 2's incentive to sell is represented by the triangle below p*. It is the difference between what User 1 paid for the water, and the benefit User 2 would have gotten had he kept the water and used it himself. Both are better off after the exchange.

The additional benefit to User 1 need not be the same as that of User 2. But the two profit triangles do represent an optimum; there is no other combination of p* and ΔQ that would increase one benefit area without decreasing the other. Nor is it the case that all combinations of initial endowments and demand structures would result in an economically feasible transaction. The key is whether the prospective buyer's marginal value of water is greater than that of the prospective seller. If so, there is room for a deal. A transaction is said to be economically efficient if the buyer and seller in the exchange have characteristics described above, if the transaction is relatively costless, and if there are no significant and uncompensated effects on third parties.

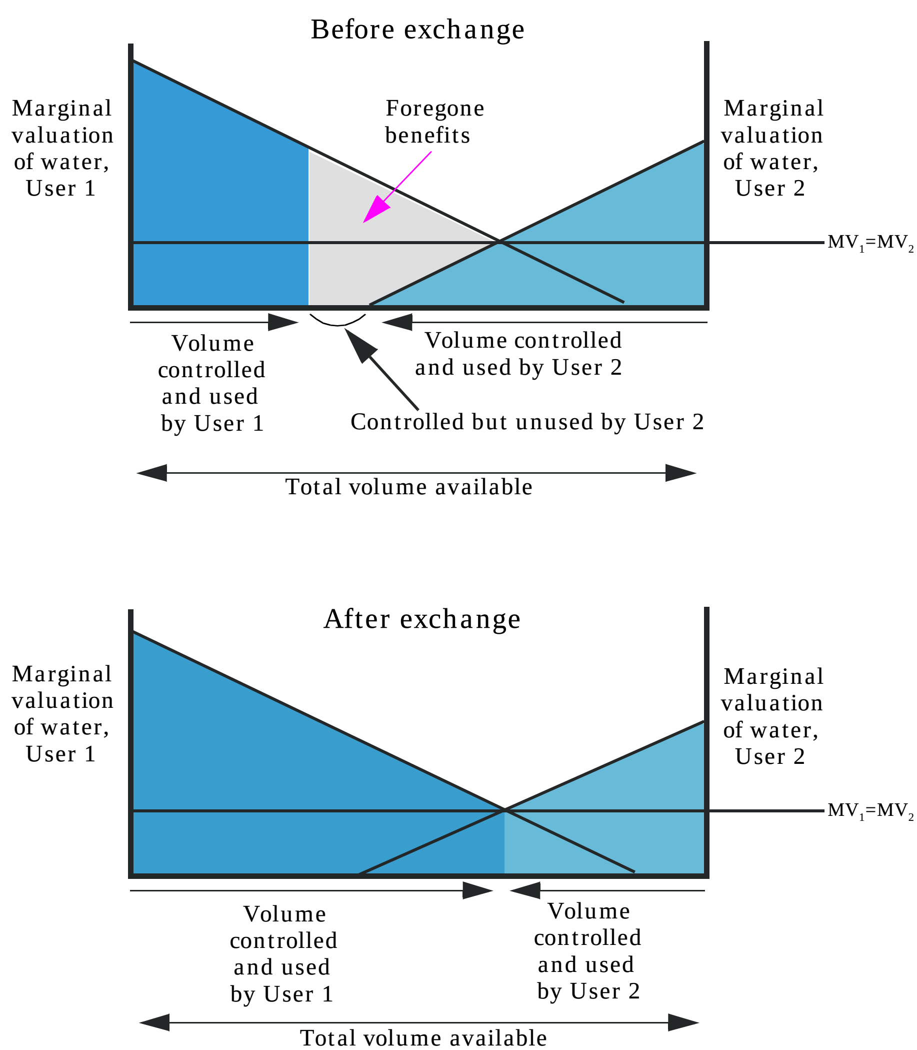
The exchange illustrated in Figure 2-1 may also be viewed from a slightly different angle. Assume that there are only two water right holders, and that all available water supplies are fully allocated between them. In Figure 2-2, the distance along the horizontal axis between the left and right vertical axes represent the entire volume of available

Figure 2-2. Exchange when water is fully allocated, fully used



water. User 1 controls the left portion of the axis, while User 2 controls the other. User 1's marginal valuation of water is depicted on the left vertical axis, with the most valuable water to the left and the least valu-

Figure 2-3. Exchange when water is fully allocated, partially used



able towards the right; User 2's marginal valuation is represented in an opposite manner on the right vertical axis.

The shaded triangle in the top portion of Figure 2-2 represents the economic inefficiency of the initial allocation. It results from User 1 having a high value on his least-valued water, and User 2 placing a low value on his least-valued water. This area of inefficiency also represents what may be gained by the two users if they were to exchange enough water to make the portions economically efficient. The part of the triangle above the horizontal line $MV_1=MV_2$ is User 1's net gain, the part below is User 2's. The point at which the two marginal valuation curves intersect ($MV_1=MV_2$) is where the allocation of water would be economically efficient. This point is labeled p^* in Figure 2-1.

Notice, however, that moving from the inefficient allocation shown in the top part of Figure 2-2 to the efficient allocation shown in the bottom part involves no net change in the total amount of water used; the entire supply of water is still consumed. Conservation has taken place only if one defines the term as increasing water's economic productivity. If it means reducing water consumption, then no conservation has taken place.

There is one scenario in which a market exchange would actually increase the amount of water consumed in aggregate. If in the initial allocation, one user had more than could be put to productive use and was actually allowing some of the entitlement to remain unused, then moving to an economically efficient state would result in unused water being used. This scenario is shown in Figure 2-3. This is a very unlikely scenario in places where water rights are governed by the rule of prior appropriation, however. Under such a regime, any portion of an entitlement that is unused for a prescribed period of time is usually subject to forfeiture and would then be available for appropriation by someone else.

This is the essence of the theory behind water marketing, an analytical framework generally applicable not only to water but also to widgets and workers. The success of a water market, according to many, is whether water moves from lower-valued to higher-valued uses—an indication of gains in social benefits. But as Saliba and Bush point out, given the assumptions behind the model, such a standard is almost tautological; a transaction will almost always entail such a movement, or else it would not take place at all.[6]

Generally, the role of the government changes from regulator to referee under a market-based regime. Rather than determine by command and control how water is to be divided among users, the government's main task is to promote and enforce rules for activity that are consistent, transparent, and fair. Spulber and Sabbaghi contend that if the state can ensure the stability of a market, then "the supply, demand, and pricing of water resources is self-regulating and results in the maximization of net economic benefits without the need for overall planning and management." They go on to develop an equilibrium model of transactions in a water service area to show how an artificially imposed price or allocation structure will lead to sub-optimal distribution of economic benefits to society.[7]

Howe, Schurmeier, and Shaw provide some of the earliest theoretical treatment of water marketing.[8] They enumerate six characteristics nec-

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6 Bonnie, Saliba and David Bush, *Water Markets in Theory and Practice* (Boulder, Colo.: Westview Press, 1987), pp. 240-241.

7 Nicolas Spulber and Asghar Sabbaghi, *Economics of Water Resources: From Regulation to Privatization* (Boston: Kluwer Academic Publishers, 1994), p. 57.

8 Howe, et al.

essary for achieving allocative efficiency through market-based mechanisms.

- It must be clear who is entitled to what portion of available water, and those entitlements must be reasonably secure from challenge;
- Water entitlements must be transferable;
- Using the available water must entail some real opportunity cost for both the buyer and the seller;
- The outcomes of the water transfer process must be predictable;
- The public must perceive the transfer process as fair; and
- The transfer process must be capable of reflecting public values that may not be adequately considered by individual water users. (This point is a departure from Spulber and Sabbaghi, who contend that valid public values constitute a locus of economic demand that can see to its own interests in a market setting.)

Saliba and Bush, who develop the general model in the context of water transfers between cities and irrigators, discuss the possible reasons a competitive water market might not work in the most efficient way from the standpoint of the economy as a whole. Many of the concerns they raise are echoed throughout the literature.

Water as a public good: Unlike with many commodities, the same water can serve many purposes and provide simultaneous benefits to many users. The characteristic of limited nonrivalry is why in-stream flows are important: water may provide recreational benefits while flowing on its way to an agricultural user. Similarly, the benefits of a water purchase often cannot be limited to the party buying the water, especially where surface water is concerned. Most often, purchased water is moved from the seller to the buyer by way of existing watercourses, and while in transit the water could enhance fishing, hydropower, or other benefits.

Externalities: A deal between a water seller and a water buyer could easily affect more interests than the two parties themselves. In welfare economics, these effects are called externalities. In the language of most state water codes, they are called third-party effects. While economists are concerned with both positive and negative externalities, state laws are concerned mostly with harmful third-party effects. For instance, if a downstream seller leases water to an upstream buyer, the net effect of the deal is to reduce the in-stream flow between the two parties' diversion points. All other water users in between could experience an increase in salinity and in the concentration of any pollutants being carried by the stream. This insult to water quality would impose an economic burden on in-between users outside the deal, yet their costs would not be reflected in a free, competitive market transaction price.

Imperfect competition: Equilibrium prices form when buyers have many independent sources, and when sellers have many independent potential customers. When either the number of buyers or the number of sellers becomes small enough to approach monopsony or monopoly, competition becomes lopsided. As a result, either the selling price would be set by a single dominant supplier, or the buying price would be set by a single dominant user. Without what Kaiser calls a "critical mass" of buyers and sellers, prices do not reflect the marginal benefits to the buyer and seller.

Risk: Water users have time horizons for decision-making that extend well into the future. Thus an important consideration for many farmers, water district managers, and municipal utilities is hedging against future shortages. Given the short-term uncertainty of annual precipitation and river flow, the long-term uncertainty of population growth patterns, and the capital costs of storing water, risk aversion may affect market decisions in non-economic ways. For example, a number of irrigation districts in the Lower Rio Grande Valley have policies prohibiting the sale of water to users outside the district, regardless of stored reserve levels. While apparently "irrational" from an economic perspective, such policies could be highly rational from a political or institutional standpoint.

From their survey of practices in the western United States, Saliba and Bush conclude that water marketing mechanisms have been fairly successful at allocating scarce water between agricultural, municipal, and industrial users. Where these systems are weakest, they note, is with regard to in-stream flows and other environmental considerations that are removed both from the opportunity costs guiding buyers and sellers and from state-mandated safeguards against detrimental third-party effects. If in-stream flow has value — and many states' water codes say it does — a sale that takes water out of the river sooner and farther up stream may involve social costs that render some transactions less than optimal. They also point to the considerable administrative costs of adjudicating and protecting water rights so that markets can function. Thus from a social standpoint, transactions are not costless.

Most often, the reasoning used to justify the conservation effects of water marketing is based on expected response to changes in the price of water. Caswell and Zilberman, for example, draw data from six counties in central California's San Joaquin Valley to estimate the likelihood of using water-saving irrigation technologies (sprinklers or drip systems) given particular crops and water prices. They conclude that raising the price of water by way of a Pigouvian tax would increase the adoption of the more efficient technologies across the board for all counties and all crops studied.[9]

Shah and Zilberman then extend this reasoning to the question of using a water market to reduce per-acre water use in a region's agricultural sector.[10] Using the parameters estimated earlier by Caswell and Zilberman, they simulated the transition from a prior appropriation regime to a water market in a hypothetical agricultural area growing cotton. They conclude that in the case of decreasing water availability, the transition will result in more land being irrigated as farmers modernize, and as a consequence both the water-to-land ratio will go down and the amount of irrigated acreage will increase. They estimate that even with a 25 percent reduction in water supplies (which would presumably be transferred to municipal use), the well-being of the agricultural sector would remain about the same.

Zilberman, MacDougall, and Shah look particularly at water allocation in California's Central Valley and conclude that assignments based on prior appropriation laws discourage conversion to modern irrigation technology and fail to reflect the true value of water.[11] They demonstrate that higher water prices induce farmers to invest in modern, water-conserving irrigation technologies. But when water allocations are based on priority of right and there is no mechanism for transferring water from

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9 Margriet Caswell and David Zilberman, "The Choices of Irrigation Technologies in California," *American Journal of Agricultural Economics*, vol. 67 (1985), pp 224-234.

10 Findings presented in David Zilberman, Neal MacDougall, and Farhed Shah, "Changes in Water Allocation Mechanisms for California Agriculture," *Contemporary Economic Policy*, vol. 12 (1994), pp. 122-133.

11 Zilberman, et al. (1994).

one user to another, the tendency is for farmers to use as much water as possible.

The parties in a water transaction can be individuals, or they can be countries. Dinar and Wolf apply essentially the same theoretical model described above to a conceptual water market among countries in the Middle East, with the added dimension that water technology can also be sold (thus changing the technology buyer's demand curve). Each country has its characteristic set of domestic demands, natural supplies, and water institutions that determine that country's demand elasticity for water.[12] The authors simulate a four-player game involving Israel, Egypt, the West Bank, and the Gaza Strip and conclude that water trades at the national level would increase regional benefit overall if the political and technological obstacles could be overcome. Key to their conclusion is Israel's advanced irrigation technologies, which translates into a higher demand elasticity than that of its neighbors. In Dinar and Wolf's game theory model, the different elasticities mean that additional water will affect productivity faster than is the case in neighboring areas that are less technologically intensive.

The public-good character of some water resources does not necessarily make a water market impossible. Griffin and Hsu, for example, develop a more complex model for assigning water when in-stream flows are assumed to have value. Not only are in-stream flows seldom counted in most economic models of water marketing, they exemplify the complicating aspects of public goods. Griffin and Hsu show that unlike money,

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[12] Ariel Dinar and Aaron Wolf, "International Markets for Water and the Potential for Regional Cooperation: Economic and Political Perspectives in the Western Middle East," *Economic Development and Cultural Change*, vol. 43 (1994), pp. 43-66.

grain, or most private commodities, water is not entirely fungible; an acre-foot of water "here" is not necessarily exchangeable in value for an acre-foot "there."[13] Say, for example, a water seller is upstream and a water buyer is downstream. A sale means that amount of water stays in the river longer, between the seller's and buyer's points of diversion, and in-stream flow increases. Higher flows increase the stream's capacity to sustain aquaculture, provide hydropower, absorb biological waste, and disperse pollutants and salinity. Conversely, if the buyer is upstream and the seller is downstream, water is taken out sooner than would normally be the case, reducing in-stream flow.

Colby notes that water seldom has the same economic properties as widgets and workers, thus it is important to temper pure theory by taking these differences into account.[14] Water — especially surface water in riverbeds — more closely resembles a public good rather than a privately held stock of widgets. Water is not exclusive (many can enjoy some benefit to the water without necessarily paying for it) nor is it rival (many can derive benefit from the same water).

Some of the most ardent proponents of water markets are not economists, but political scientists. For them, the issue is not so much one of economic efficiency as of preservation of rights and the reduction of command-and-control management of natural resources. Although they

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13 Ronald C. Griffin and Shih-Hsun Hsu, "The Potential for Water Market Efficiency when Instream Flows Have Value," *American Journal of Agricultural Economics*, vol. 75 (1993), pp. 292-303. See also Griffin and Fred O. Boadu, "Water Marketing in Texas: Opportunities for Reform," *Natural Resources Journal*, vol. 32 (1992), pp. 265-287.

14 Bonnie G. Colby, "Markets as a Response to Water Scarcity: Policy Challenges and Economic Implications," in Darwin C. Hall, ed., *Advances in the Economics of Environmental Resources*, vol. 1 (London: JAI Press, 1996).

accept the economic arguments about water moving to uses with higher social value, they generally focus on institutional issues affecting water rights, water development, and water transfers.

Anderson advocates decentralizing water allocation planning in favor of market mechanisms. He is even skeptical of applying marginal utility models for the purpose of setting water prices or optimal allotments. Citing the same externality problems economists themselves explore, Anderson concludes that equilibrium models cannot practically derive accurate and efficient water control parameters (such as price and allotment).

While agreeing with the idea that externalities can distort the neoclassical economics model, Anderson further suggests that having regulators compensate for these distortions is hardly an improvement. Lacking price information — and thus lacking any reliable indicator of how to value such externalities at the margin — government regulators must rely on political criteria to determine when to rein in profit-motivated entrepreneurs.

Key policy variable in Anderson's framework is the construction, enforcement, and transferability of property rights. He suggests that all so-called "externalities" can be taken into account by some market response if water rights are stable. Citing the purchase of water rights by groups such as the Nature Conservancy, Anderson contends that most externalities can be internalized by the formation of some social group willing to pay its marginal cost of water.

> "Responsibility for opportunity costs is crucial. … As the rules of the game determine who has access to and use of resources, the property rights structure will determine who is responsible for which opportunity costs. … If authority

can be linked to responsibility through private property rights, self-interest can be linked to efficiency. In the absence of such a link, nothing in the economic process will push the system toward efficiency."

Ingram describes a darker side of Anderson's point — resource allocation divorced from opportunity cost — in her study of water development legislation passed by Congress in the late 1960s.[15] She shows how the "project paradigm" — water management by building dams and other major construction works — dominated federal water policy and how the direction of policy making at the congressional level was determined more by the distribution of political capital rather than the findings of cost-benefit analyses. She concludes that economic arguments were invoked when they supported local political interests with congressional influence, but did not lead policy determination.

Winpenny draws similar conclusions in his study of water development projects worldwide.[16] He argues that present and future water shortages are due largely to policy makers treating water as a supply problem rather than a supply-and-demand problem. Spending on new water projects, he argues, often becomes a *de facto* surrogate for changes in the way existing supplies are managed. The result is that users do not regard water as a commodity that entails an opportunity cost to provide, and demand for new (costless) water becomes insatiable, a conclusion that closely complements Ingram's findings about federal water policy in the 1960s.

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15 Helen Ingram, *Water Politics: Continuity and Change* (Albuquerque, N.M.: University of New Mexico Press, 1990).

16 Winpenny.

In Winpenny's policy prescription, government is actually more active and more involved than when it merely builds new water projects. Even though his "enabling conditions" include privatization and reform of water utilities (as well as institutional and legal changes), the state still directly intervenes in some areas intended to facilitate conservation. Government would invest in canal lining, leak detection, and programs to increase the use of water-efficient appliances and industrial water recycling. Mainly, the state would be responsible for providing market and non-market incentives for voluntary trading to take place.

Empirical studies

Perhaps the most-studied water market has been the Central California Water Bank, which was created in 1991 in response to prolonged drought conditions in the southern part of the state. As the drought progressed, it became apparent that critical needs in the water-short south could be met by using excess water in the north. Rather than risk running crossways against the state's complicated system of water rights, California water managers instead tried to encourage voluntary transfers that compensated those who chose to temporarily give up their water claims.

MacDonnell, Howe, Miller, Rice, and Bates provide a detailed description of the California Water Bank as it operated in 1991 and 1992.[17] The bank was created as a closed institution comprising cities, water supply corporations, and others responsible for delivering water

[17] Lawrence J. MacDonnell, Charles W. Howe, Kathleen A. Miller, Teresa A. Rice, and Sarah F. Bates, "Water Banks in the West," Natural Resources Law Center, University of Colorado School of Law, Boulder, Colorado, 1994.

to various kinds of users. But no exchanges ever took place between water bank members. Instead, members could sell water to the bank, either by entering into a contract to fallow or dry-farm, by pumping more groundwater, or by releasing reservoir storage. Other members could purchase water from the bank, limited by the amount of reserves the bank had acquired.

The purchase price and the sales price were set by the bank, and were the same regardless of whether the parties involved were cities, irrigation districts, or farmers. During its first year of operation, the bank bought water at a price of $175 per acre-foot and sold at $125. This resulted in a $33.2 million overpurchase of water by the bank—about 265,000 acre-feet more than it was able to sell. As the drought persisted into 1992, the bank reduced its buying price to $50 and its selling price to $72. The excess volume dropped by 90 percent, and at the lower price, the cost of the surplus fell to $1.2 million.

All transactions through the California water bank were temporary, in that at the end of the contract with the bank the seller would retain rights to the entire original entitlement. This is similar to how the contract water market works in the lower and middle Rio Grande, as operated by the Rio Grande watermaster.

Dinar, Sunding, and Zilberman model three possible scenarios for transferring water use from one part of the Central Valley basin to another.[18] They conclude that reliance on market mechanisms can

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[18] Ariel Dinar, David Sunding, and David Zilberman, "Changes in irrigation Technology and the Impact of Reducing Agricultural Water Supplies," in *Advances in the Economics of Environmental Resources*, vol. 1 (London: JAI Press, 1996), pp. 167-183.

increase the quality of water flowing into the downstream estuaries, and do so in a way that moves water from its lowest-valued uses.

Cairncross and Kinnear found water demand to be extremely inelastic for the poor and middle class. In their study of water demand in two low-income areas of Khartoum, Sudan, they found that price made no apparent difference in the amount of water used by typical households.[19] Where prices were higher, households spent a larger proportion of their income on water. Virtually all who have written on water demand patterns say that municipalities have more inelastic demand than do agricultural users; the results from the Cairncross and Kinnear study raise a further question of how household income affects urban elasticity of demand. The importance of their findings for water marketing is that consumption—and therefore conservation—may be relatively unresponsive to the price of water, at least as far as municipalities may be concerned.

Nieswiadomy and Cobb, using data from 109 U.S. cities, found that one reason municipal demand tends to be inelastic is that urban users tend to respond to average costs rather than marginal costs.[20] The implication of this finding is that variable-rate water pricing structures that charge more per gallon for higher volumes of consumption might have only a diluted conservation effect. That is, if the next 100 gallons used is to be charged at a rate 20 percent higher than the previous 1,000 gallons, a typical user will not look at the additional incremental cost, but rather

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19 Sandy Cairncross and Joanne Kinnear, "Elasticity of Demand for Water in Khartoum, Sudan," *Social Science and Medicine*, vol. 34 (1992) pp. 183-189.

20 Michael Nieswiadomy and Steven L. Cobb, "Impact of Pricing Structure Selectivity on Urban Water Demand," *Contemporary Policy Issues* vol. 11 (July, 1993), pp. 101-113.

at how that higher rate affects the average rate paid for all water consumed.

Technology

Shah, Zilberman, and Chakravorty examined the question of technological diffusion with regard to the adoption of water-conserving irrigation methods. Intuitively, it would seem that the prospect of water shortage would encourage the quicker adoption of modern water-saving irrigation technologies, and this is indeed often advanced as a benefit of water marketing. Shah and his colleagues find, however, that when access to an aquifer is open and competitive, the spread of new technology is in fact rather slow, due largely to the capital costs of conversion. They suggest that a tax on old irrigation methods, a subsidy on modern technologies, or a combination thereof could compensate for this tendency. Such an approach is in keeping with natural resource economics based on welfare economics.[21]

Purvis, Boggess, Moss, and Holt go a step further in concluding that irreversibility and uncertainty also contribute to the delay in adopting modern technologies.[22] They note that "the discrepancy is greatest for decision makers applying lower discount rates and more for uncertain investments." Their study of investment decisions by Texas poultry farmers suggests that at any given decision moment, the expected value

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21 Farhed A. Shah, David Zilberman, and Ujjayant Chakravorty, "Technology Adoption in the Presence of an Exhaustible Resource: The Case of Ground Water Extraction," *American Journal of Agricultural Economics*, vol. 77 (1995), pp. 291-299

22 Amy Purvis, William G. Boggess, Charles B. Moss, and John Holt, "Technology Adoption Decisions Under Irreversibility and Uncertainty: An Ex Ante Approach," *American Journal of Agricultural Economics*, vol. 77 (1995), pp. 541-551.

of waiting dominated the expected value of investing once the effects of risk and irreversibility were taken into account, even if a strict neoclassical analysis indicated that the investment was technically in the best interest of a utility-maximizing firm or individual. This was especially true of decision makers with lower discount rates and of more uncertain investments. Their prescriptions were also Pigouvian: compensate producers willing to invest in new technologies.

Risk

Various approaches have been developed and used in agricultural economics to examine questions of risk. The most common are mean-variance analysis, dynamic programming, and regression modeling. As each method has its particular strengths and weaknesses, evaluating them is largely a matter of choosing the right tool for the job. When decisions resemble a portfolio problem (such as choosing a crop mix that both maximizes expected profit and minimizes risk exposure), mean-variance analysis is often the most useful method of estimating risk. When the question is one of choosing a strategy that over time will result in the highest likelihood of the best outcome (whether or not to fallow a field in exchange for a conservation subsidy, for example), dynamic programming may be the tool of choice. If it is necessary to estimate how the use of various farm inputs might change among farmers with different degrees of risk aversion, regression models are often the most useful.

Just and Pope have proposed a general framework for analyzing farm behavior that permits the estimation of risk in the contest of a regression analysis. This model, put forth in 1978, was tested with a static analysis by Meyer in 1987, and revised by Leathers and Quiggin in

1991.[23] The Just and Pope production function postulates that a farm input has both a direct production effect (which will be designated *f*) and a risk effect (*h*). Fertilizer, for example, has a direct effect on crop yield that varies with soil characteristics. But it also has a risk effect in that chemical burning may occur if rainfall is too little. The Just and Pope production function is

Eq. 2-1: $$y = f(x) + h(x)\varepsilon$$

where ε is a random variable that scales $h(x)$ so that it is comparable to $f(x)$. This basic model is then revised by Leathers and Quiggin into a state-space model that takes into account inputs other than the one being tested, as well as variations in a farmer's aversion to risk.

Leathers and Quiggin do not set out to address questions related to water marketing, but two of their conclusions are germane here. In their words:

- A subsidy on water use will not cause all risk-averse farmers to increase water use or expected output, and
- A reduction in prices received by farmers will not necessarily lead to a reduction in use of water or agricultural chemicals.[24]

In their analysis of the revised production function's statics, Leathers and Quiggin conclude that if a farmer has constant absolute risk aversion (when risk aversion is the same regardless of the level of out-

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23 R. Just and R. Pope, "Production Function Estimation and Related Risk Considerations," *American Journal of Agricultural Economics*, vol. 61 (1979), pp. 276-83; Howard D. Leathers and John C. Quiggin, "Interactions between Agriculture and Resource Policy: The Importance of Attitudes toward Risk," *American Journal of Agricultural Economics*, vol. 73 (1991), pp. 757-64.

24 Leathers and Quiggin, p. 762.

put) prices will exert an effect on how much purchased water is used. But for those with decreasing absolute risk aversion, which is the more common assumption, the effect of price changes for either inputs or output is ambiguous.

Dynamic programming represents a fusion between linear programming and game theory, using iterative procedures to determine the optimal strategy (or strategies) of a sequence of decisions given a vector of probable outcomes. Johnson uses a dynamic programming model to examine the effects of risk on an irrigation-related farm decision: fallowing.[25] Specifically, she examined different scenarios affecting a farmer's decision to participate in the Conservation Reserve Program, in which the federal government pays farmers not to cultivate acreage that is vulnerable to erosion. This extreme option of soil conservation has an obvious although not completely transferable effect on irrigation.

The dynamic programming model makes it possible to explicitly include in the decision process a sequential series of probable outcomes. Johnson concludes that by regarding the problem of technology choice not as a static situation but rather as a sequence of decisions under changing conditions of uncertainty yields different predicted results. If the returns from not enrolling in the fallow-land program are stochastic, then during a bad year, farmers with a longer planning horizon (those planting sugarcane, for example) will tend to avoid enrollment and bet on the chance of better harvests. Farmers who don't have as pressing a need to think about the long run will tend to enroll when times are hard.

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[25] Celia Ahrens Johnson, "Optimal Participation in the Conservation Reserve Program," chapter in *Applications of Dynamic Programming to Agricultural Decision Problems* (Boulder: Westview, 1993).

Another approach to estimating risk operationally is through mean-variance analysis, which is also used in estimating investment portfolio risk. Selley concisely describes different applications of mean-variance analysis and shows how the concept can be changed for various structures of risk as well as for different methods of mathematical analysis.[26]

Say, for example, there are three planting options for a piece of land. Yield (or alternatively, net profit) will vary over time, and this variance can be measured for each crop alternative. The fluctuations can be arrayed in a variance-covariance matrix:

$$\begin{bmatrix} \sigma & cov_{2,1} & cov_{3,1} \\ cov_{1,2} & \sigma & cov_{3,2} \\ cov_{1,3} & cov_{2,3} & \sigma \end{bmatrix}$$

To minimize uncertainty, a farmer would want to choose the mix of crop acres a_1, a_2, and a_3 that, when taken as a scalar and multiplied by the variance-covariance matrix, yields the smallest sum.

Eq. 2-2:

$$\min \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \times \begin{bmatrix} \sigma & cov_{2,1} & cov_{3,1} \\ cov_{1,2} & \sigma & cov_{3,2} \\ cov_{1,3} & cov_{2,3} & \sigma \end{bmatrix} \times \begin{bmatrix} a_1 & a_2 & a_3 \end{bmatrix}$$

A risk parameter λ scales the outcome of the risk matrix so that it is comparable to the profit portion of the utility function. The full form of the objective function then becomes:

[26] Roger Selley, "Decision Rules in Risk Analysis," in *Risk Management in Agriculture*, ed. Peter J. Barry (Ames, Iowa: Iowa State University Press, 1984).

Eq. 2-3: $$\max \sum_{1}^{3} a_i \times \text{margin}_i - \lambda \mathbf{A}\sigma^2\mathbf{A}'$$

where a_i is the acres to be planted in crop i, A is a vector comprising all a_i, A' is the inverse of vector A, σ^2 is the variance-covariance matrix of historical profit (all σ_i^2 and covariances between all pairs of i), and λ is the scaling parameter.

Because the matrix variables make the utility function quadratic (the risk component contains terms in which decision variables are multiplied by decision variables), this formulation works well with a quadratic programming model, but isn't much good with a simple linear programming model. A linear alternative, however, uses the mean of total absolute deviations (MOTAD) for each individual alternative and dispenses with the covariances.

Mussen, Mapp, and Barry lay out the MOTAD structure in detail and illustrate its application with an example of evaluating cash-crop enterprise.[27] The MOTAD formulation is

Eq. 2-4: $$\lambda \frac{\sum_{t} |\mu_x - x_t|}{n}$$

where x_t can be yield, net profits, or any other crucial variable for a crop over n number of instances t and μ_x is the mean of x over all instances t. (Again, λ is a scaling parameter.) If a farmer is considering cultivating cotton or sorghum, yield may be the greatest source of uncertainty,

[27] Wesley N. Musser, Harry P. Mapp Jr., and Peter Barry, "Applications I: Risk Programming," in *Risk Management in Agriculture.*

assuming that prices usually don't change enough between planting and harvest to affect the planting decision. This would suggest using MOTAD to estimate the risk associated with yield fluctuations. If prices are volatile, however, it may be more realistic to examine fluctuations in profits.

When the MOTAD profit-risk measure is added to the utility function (and after mathematical manipulation), it essentially mitigates the expected margin of the profit function. Taking the above three-crop example, the objective function would be:

Eq. 2-5:
$$\max \sum_{1}^{3} a_i \,(\text{margin}_i - \text{risk}_i)$$

where $risk_i$ is the result of Equation 2-4 calculated for crop *i*.

The MOTAD constant may therefore be interpreted as a risk premium: the larger the uncertainty, the more it adjusts the expected value of the profit margin downwards. The resulting objective function then tries to optimize land allocation according to a nicely linear risk-adjusted expected margin.

A major limitation of the MOTAD approach is that covariances between crop alternatives disappear from the picture. One can easily test the covariances to see whether the omission would matter. But in any case, omission of the covariance terms means that the cropping decision is no longer treated as a portfolio problem. Instead, it is a set of choices in which the risk associated with each option is independent of all other options. The choices are ordered rather than balanced, in that the model will usually tend to fully satisfy each option in decreasing order of attractiveness.

The discussion in Chapters 5 and 6 will show how the question at hand — whether risk-averse farmers tend to make different planting decisions if a water market exists — resembles a portfolio problem. It is assumed that farmers may want to spread their exposure among a diversity of crops, so it is important to keep between-crop covariances in the analytical picture. The classic mean-variance approach as generalized in Equation 2-3 is therefore the methodological approach taken here.

Before proceeding further, however, it will be necessary to clarify two concepts central to this study: drought and conservation. Although these terms may seem clear enough to a casual reader, there many ways of understanding their details and policy implications. The next chapter will discuss how drought and conservation have been variously treated by scholars and policy makers, and will then define the two terms in the context of this study.

Chapter 3: Concepts and Definitions

Scanning the literature on water marketing, drought management, and conservation, it quickly becomes apparent that the same terms can mean different things to different people. Economists and water management experts will both agree that efficiency is a high-priority goal, but as soon as one delves into the literature one sees that the two worldviews are far apart. The economic notion of efficiency described in the previous chapter does not imply using less to do more. Although the two concepts of efficiency and conservation are not mutually exclusive, linking them requires an explicit exposition of reasoning that is seldom done in the literature.

The ambiguity of crossing disciplines creates particular problems with two especially important concepts: drought and conservation. These crucial concepts will be defined here.

Water conservation and drought management are two wheels of the same cart. Systematic reduction in the amount of water normally used reduces the vulnerability to drought. If certain drought response mechanisms are triggered when available supplies fall below a threshold of need, then reducing the threshold will make a drought less likely.

Affixing both wheels to the same policy axle, however, is often a difficult task. Political change tends to respond to crisis, but drought tends to be a "creeping disaster" — the problem isn't recognized until the well has run dry, and by then, it's too late for many of the most efficacious options.[1] Conservation measures (canal lining, installation of precision-application irrigation technology, etc.) cost money today, and future hardships tend to be discounted relative to today's values.

Part of the difficulty in combining the two concepts arises from how they are defined. As an issue begins to evolve on the policy agenda, the parameters of what can and cannot be done are often determined early in the debate. Problem definition thus becomes an important strategic endeavor for the major stakeholders. Whether water conservation and drought management are defined as agricultural, economic, or environmental issues will have a crucial effect on how legislation and agency rules are drafted. In Colorado, for example, the nexus between conservation and drought management places the burden of adjustment more on municipal users rather than agricultural users.[2]

Problem definition can also reflect the political values that will guide policy selection. Among these values are the role of government, and how non-monetized water uses are to be weighed against agricultural productivity and urban development.

In the case of the Lower Rio Grande Valley, water conservation must happen in a policy environment created in 1969 by the courts. The landmark decision creating the area's present water regulatory regime

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1 For a more detailed discussion of forecasting and identifying drought, see Neil Grigg, *Water Resources Management* (New York: McGraw-Hill, 1996), p. 421.

2 Colorado's 1991 Conservation Act applies to "each municipality, agency, utility, including any privately owned utility, or other publicly owned entity with a legal obligation to supply, distribute, or otherwise provide water at retail to domestic, commercial, industrial, or public facility customers, and which has a total demand for such customers of two thousand acre-feet or more in calendar years 1989 or thereafter." The act does not apply to agricultural users. Colorado Revised Statutes, Title 37, Article 60, Sec. 126.

defined water use as primarily an agricultural issue, rather than an environmental issue. The provisions were for the interests of established water right holders.

Drought

Wilhite and Glantz surveyed water management literature and laws in the 1980s and found about 150 definitions of drought.[3] They broadly categorize them as follows.

- *Meteorological drought*, in which rainfall is below a chosen benchmark level;
- *Hydrological drought*, in which reservoir levels, water tables, river flow, or some other normally measurable aspect of the hydrological cycle drops far below a normal level;
- *Agricultural drought*, in which water (from any source) is insufficient to meet the demands of the region's most important crops; and
- *Socioeconomic drought*, in which available water supplies are insufficient to sustain current levels of municipal consumption, irrigation, and industrial output.

While of greater policy concern than the other three types, socioeconomic drought is the most difficult to define. Tangible indicators such as precipitation, reservoir levels, and river flow are easy to measure, and are often used to proxy socioeconomic drought and to trigger various response measures. But human demands on an ecosystem change over time, especially in an area with significant population growth. So even though the meteorological or hydrological indicators may be the same in dry periods separated by a span of wet years, the human effects might be greater if population has increased during that time.

3 Donald A. Wilhite and M.H. Glantz, "Understanding the drought phenomenon: The role of definitions," *Water International*, vol. 10 (1985), pp. 111-120.

Figure 3-1 and Figure 3-2 illustrate three different definitions of drought in the context of the lower Rio Grande. Rainfall and reservoir storage data illustrate the meteorological and hydrological dimensions of the 1994-96 drought in the Lower Rio Grande Valley. In terms of rainfall, the mid 1990s were no drier than the late 1980s. Storage in the system's two main reservoirs — Falcon and Amistad — was much lower during the more recent drought, however. In fact, the combined U.S. storage in the reservoirs during the 1994-96 drought was about half of what it was during the dry spell of 1989-90.

It can be seen from Figure 3-1 and Figure 3-2 that the region has experienced two droughts in recent years, one from 1988 to 1990, and another from 1994 to 1998. The unweighted trend line in Figure 3-1 indicates the meteorological drought, while the weighted trend line (which gives the heaviest weight to rainfall during peak irrigation months) may be taken as an indicator of agricultural drought. Figure 3-2 is a picture of hydrological drought, as the reservoir levels are a function of the water in the entire hydrological system. But because the water in the reservoirs constitutes most of the supply for everyone, this may also be regarded as an indicator of economic drought.

One interesting feature about a comparison of the two drought periods is that while the 1994-97 drought was not as severe as the 1988-90 drought meteorologically and agriculturally, it was much worse hydrologically and economically. Population in the Rio Grande Valley grew by 30 percent from 1990 to 1997, twice as fast as growth statewide.[4]

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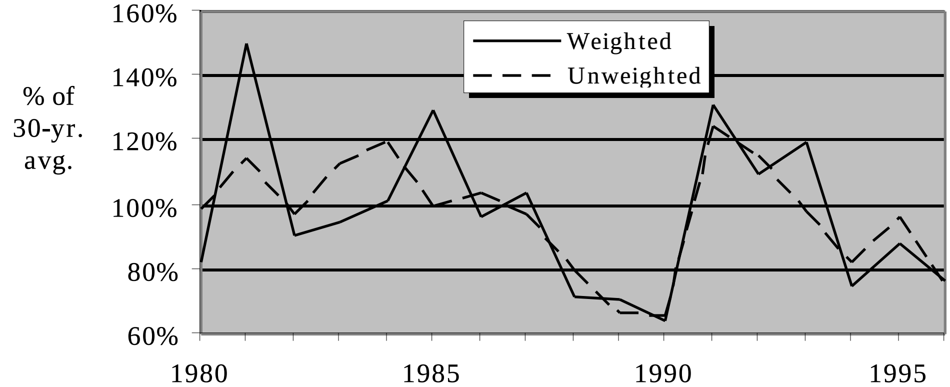
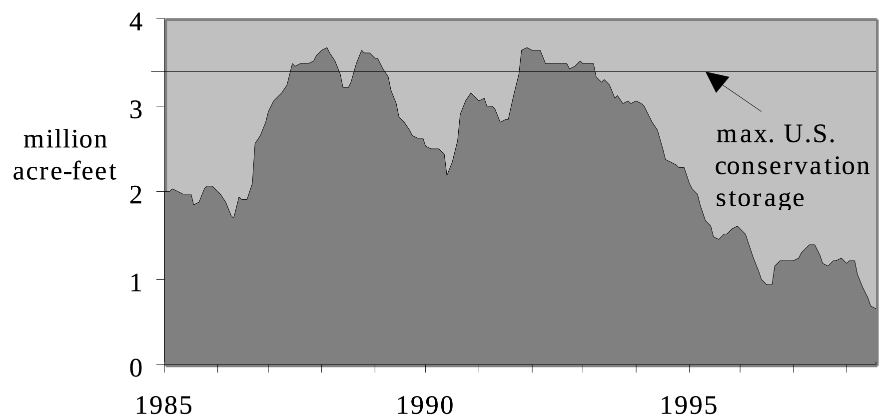
[4] Population Estimates Program, Population Division, U.S. Bureau of the Census, Washington, D.C., Internet Release 1998.

Figure 3-1. Meteorological drought: Annual rainfall



Source: National Climatic Data Center, "Monthly Surface Data" database TD-3220 (Washington: U.S. Department of Commerce, 1999), tables for Brownsville, Harlingen, McAllen, and Rio Grande City. The weighted trend line gives more importance to months of high irrigation demand, and excludes months during which no irrigation occurs. Weighted monthly figures are then summed by year and used to track changes in 30-year moving average.

Figure 3-2. Hydrological drought: U.S. storage in Amistad, Falcon reservoirs



Source: International Boundary and Water Commission, electronic data files provided by Kenneth Rakestraw, chief engineer, 1998-99.

For the purposes of this study, drought will be defined as an economic rather than a natural phenomenon. Ultimately, water policy is concerned not merely with how much water is in the hydrological system, but whether the water available is sufficient for the social demands placed on it. Simple rainfall and runoff data thus do not fit the purpose of this study.

Given the fact that agriculture uses most of the water along the lower Rio Grande, agricultural drought is also important. The sector's response to the possibility of shortage affects how much water is available for cities on an ongoing basis. Even though emergency allocation mechanisms give priority to municipalities when water levels drop, long-term, year-to-year availability will depend on how what happens within the agricultural sector.

Reservoir levels may be taken as an indicator of overall economic drought, due to the fact that Falcon and Amistad reservoirs store water for all users in the middle and lower Rio Grande. And as will be shown in Chapter 6, where the Rio Grande watermaster's rules of operation will be explained, water for municipal and other nonagricultural use can easily be deducted from total storage to derive an estimate of water in storage for irrigation.

Weighted rainfall will be taken as another indicator of agricultural drought, one especially relevant to unirrigated crops. In constructing this indicator, we use twelve coefficients to weight precipitation for each month of the year. The weights were derived from an ordinary least-squares regression of total monthly irrigation use:

Eq. 3-1: $$\text{irrigation} = \beta_0 + \sum_{m=1}^{11} \beta_m \text{month}_m + \beta_{12}\text{rain} + \varepsilon$$

where *irrigation* is the total amount of irrigation diverted by all users in the Lower Rio Grande Valley each month, *m* designates dummy variables corresponding to 11 months of the year, *rain* is monthly precipitation, and ε is the regression error. Any coefficient β that failed the test for significance at the 95 percent level was assumed to be zero. (The method used to derive the weights will be described in detail in Chapter 7.) Weighted annual totals were then expressed as a percentage of a moving average for the 30 previous years.

Conservation

Most people agree that water conservation is a worthy goal, at least until they have to clarify exactly what it entails. The concept is not as easy to define as one might think, and how it is defined often determines what will be done to make it happen. What constitutes water conservation (and similarly, how it is to be measured) depends on the political values used in the definition, and on the policy genre in which it is placed. As with other policy issues, the strategy of definition is "to place the burden of adjustment elsewhere, and to avoid changing your own pattern."[5]

Water is the lifeblood of the land it nourishes. This ecological fact forms the basis of the kind of conservation practiced by many conservation professionals in the public sector. In this comprehensive paradigm,

5 John Kingdon, *Agendas, Alternatives, and Public Policies* (New York: HarperCollins, 1995), p. 110-112.

conservation means natural resource management practices which value the self-renewal of the land and its biotic systems. Groundwater is not pumped faster than the aquifer can recharge. The flow at the mouth of a river is not allowed to fall so low that estuaries lose the fresh water needed to dilute salt water. Sewage return flows are treated so that biological oxygen demand and fecal coliform counts do not pose health hazards or kill marine wildlife.

Forestry biologist Aldo Leopold and soil scientist Hugh Hammond Bennett were the first to articulate this value through federal agencies (Leopold in the U.S. Forest Service, Bennett in the Soil Conservation Service).[6] Their ecologically derived conservation ethic is echoed in the more mathematically structured conclusions of pioneer land economists, most notably Richard Ely and George Wehrwein.[7] Rather than treating land as an ordinary commodity, Ely and Wehrwein regard it as a factor of production with attributes distinct from either labor or capital. Problems of land are problems of (among other things) tenancy in city and country, public ownership, community ownership, open ranges, large land holdings, the congestion of urban populations, and (of significance here) conservation.

The values and theories described by Leopold, Bennett, Ely, and Wehrwein have become the core of the sustainable development paradigm. In the meantime, however, the term "conservation" made a lexicographical pilgrimage to rather new meaning: supply augmentation. The

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6 Aldo Leopold, *A Sand County Almanac* (New York: Oxford University Press, 1966).

7 Their approach to economics is that "Land policies must be based on the operation of nature's laws as well as the economic drives of man." *Land Economics* (Madison: University of Wisconsin, 1984), p. 25.

expressed policy of the United States in the late 19th and early 20th centuries was to populate the western frontiers. With scarce and erratic water supplies, however, expansion faced a severe constraint. The policy challenge was to find ways to regulate stream flow in places most conducive to agriculture and settlement.

Gradually, water resource development became the dominant conservation paradigm, squeezing out the more ecologically oriented approach of Leopold and Bennett. The U.S. Bureau of Reclamation became the lead U.S. agency for water conservation, a task which it interpreted as building dams, levees, and other public works designed to reduce the risk of flooding and to ensure reliable supplies of water. Congress, under powerful local lobbying, channeled large amounts of public funds to the construction of dams and other large water works.[8]

More technical definitions of conservation exist, each reflecting different political values. In Colorado, for example, conservation is often gauged by how many times water in a river is used. This approach takes into account return flows — water that is returned to the stream after diverted and used. The logic of this indicator is that as water is used more efficiently, more water will be returned to the river for downstream users.

If these two definitions of conservation—using less water, and finding more water—seem dissimilar, it's because they are. State law is not helpful in clarifying the matter. In fact, the Texas Water Code says conservation involves both obtaining more water ("the development of water resources") as well as "those practices, techniques, and technolo-

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8 Helen Ingram, *Water Politics: Continuity and Change* (Albuquerque, N.M.: University of New Mexico Press, 1990).

gies that will reduce the consumption of water, reduce the loss or waste of water, improve the efficiency in the use of water, or increase the recycling and reuse of water so that a water supply is made available for future or alternative uses."[9]

Other definitions are particular to irrigation. *Irrigation efficiency* refers to the amount of water used by the crops in evapotranspiration as a proportion of the water taken from the stream or aquifer. *Application efficiency* is similar to irrigation efficiency, referring specifically to the amount of water retained in the roots of a crop.[10]

Here, conservation will be used to refer to policies and practices that, in general, reduce the amount of water used. Developing additional water supplies is excluded from the definition, mostly for the sake of keeping the current discussion focussed but also because the policy strategy of continually augmenting supplies is necessarily bounded. Water is a finite resource, so at some point, there is simply no more water to capture. On the other hand, there is always room to do more with less. While there may be physical obstacles to efficient use, many times the obstacles are social and can be addressed by public policy.

The indicator of irrigation conservation used in this study will be water applied per acre-foot of land. If over time farmers use less water to irrigate the same land and produce the same level of output, then water use per acre falls and conservation is happening. A number of things could cause this index to change, all of which would be indicative of water conservation: the installation of more efficient irrigation sys-

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[9] Texas Water Code, Title 2, Sec. 15.001.

[10] Grigg, p. 421.

tems, switching to crops that are less water-intensive, or even deciding to leave some acreage fallow for a season.

The next chapter will examine the legal environments in which water users must deal with drought, and through which policy makers try to encourage water conservation. The discussion will focus on those aspects of water law that most affect a potential water market. With conservation defined and the legal issues identified, we may then take a detailed analytical look at how a water market might affect conservation.

Chapter 4: The Economics of Water Law Regimes

One cannot fully understand water markets without some understanding of water law. Indeed, the legal regime governing the allocation and ownership of water is one of the most important factors determining whether market-based water management can work. Water law determines who owns water, who is entitled to use it, how it can be transferred, and how its quality is protected.

A common mistaken notion about Texas water law is that because the Rio Grande Valley is such an exception to so many rules, experience there can have no relevance to what could happen with water management elsewhere. But this is not true, at least as far as water marketing is concerned. The things that make the Valley exceptional — in particular, the fact that the Rio Grande is not a free-flowing river — also make it the kind of legal environment that is ideal to a flourishing water market. If there is a political desire to create water markets elsewhere, then a comparative study involving the Valley can help identify what rules may stand in the way of a well-tempered water market. If an anticipated benefit isn't happening in the Valley, one cannot reasonably expect to find it in another region where market conditions are less than ideal.

It will be shown in this chapter that the legal impediments need not be explicit. The experience of Texas has shown that even though there may be political and administrative intent to let market forces reallocate water, the goal is often undermined by ignoring the less-apparent but more fundamental elements of a state's water law that render a market ineffective.[1]

In most parts of the United States, surface water codes follow one of two general doctrines: riparian law, in which water rights inhere with land adjacent to a watercourse; and prior appropriation, in which older claims have preference over newer ones. Other parts of the world — including Mexico — follow a state-centered model in which the government retains full ownership of the water and directly administers its allocation and uses. The Rio Grande Valley has seen all three kinds of regimes over the past three centuries, and each has its particular strengths and weaknesses with regard to water marketing.

After outlining the economically relevant aspects of surface water law in general, the chapter looks at how the economic ideal plays out under each of these three kinds of water law. Each section describes its system's key features and historical origins, and then looks at the legal concepts through an economic lens. The purpose is to sketch what water law needs to do in order to allow market mechanisms to allocate water efficiently, highlighting the kinds of inefficiencies and social welfare losses that can result when the legal regime allows market-based institutions but does not adapt itself to the idea fully. Only then can there be a meaningful discussion about the potential economic and conservation benefits of water marketing.

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1 The intent to encourage water marketing may be found most explicitly in the creation of the Texas Water Bank (Texas Water Code, Sec. 15.701 to 15.703). Any portion of a water entitlement deposited in the water bank is protected from cancellation. (Texas Administrative Code, Sec. 297.71).

Unless explicitly stated otherwise, references to water law throughout this chapter will refer to statutes and constitutional provisions governing the use of surface water, not water from an aquifer. This is to aid clarity in explaining the economic dimensions of basic water law. As will become evident, ground water can add a confounding element to a water market, especially in states such as Texas where the right of capture is the legal doctrine governing ground water. The discussion in this chapter will turn specifically to ground water later once the market economics of surface water law have been fully described.

Economic elements of water law

It is generally accepted among natural resource economists and legal scholars that a precondition for a water market is a stable regime of enforceable rights.[2] But all three of the regimes that preceded the modern watermaster system in the Rio Grande Valley had stable rights, too (taking the riparian and appropriative systems separately, not as components of a dual system). Water trading took place under some of those systems, but not all of them. One may therefore infer that simple stability of rights may not be enough. *How* those rights are stable is important, too.

Water rights must be stable in two general ways. First, the opportunity cost of obtaining water by litigation, coercion, or disregard of legal entitlement must be sufficiently high to discourage any rational would-

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2 See James Winpenny, *Managing Water as an Economic Resource* (New York: Overseas Development Institute, 1994); Bonnie Saliba and David Bush, *Water Markets in Theory and Practice* (Boulder, Colo.: Westview Press, 1987); and Ronald A. Kaiser, "Texas Water Marketing in the Next Millennium: A Conceptual and Legal Analysis," *Texas Tech Law Review*, vol. 27 (1997), pp. 181-261.

be user from taking water without the rightful owner's consent. It is to be expected that a water seeker attaches some value to water, and that implies a willingness to pay. The question is whether the person wanting the water compensates the rightful owner in a consensual contract, or pays court costs, attorney fees, and other administrative expenses to seize title to the water. The stronger the legal precedent supporting existing entitlements, the lower the probability of success and the lower the expected value of that alternative. Similarly, if there is a high probability of being prosecuted for water poaching, then the opportunity cost of simply disregarding legal entitlements would be too high for that to be a viable option.

Second, the quantity of water controlled must be as stable as the basic entitlement itself. The right of access to a river is one thing; the right to take a specific amount of water out of the river is something more. Underlying this market requirement is the concept of economic scarcity. Markets do not function well without stable prices, and market prices do not form with any stability if (all other things being equal) the degree of scarcity is not known within a reasonable interval of confidence. Consequently, if a water right does not quantify the holder's entitlement in some predictable way — that is, if holders don't know *how much* water they control — water users won't know how badly they need to buy or how much they can sell. This is especially crucial when overall water supplies are scarce; it is the legal regime of water rights that must somehow allocate the available supplies among all legitimate claims.

Also, the quantity held today must have some bearing on the quantity held in the future. It is not necessary to know exactly how much water will be possessed by the owner of the right at a future date, no more than it is necessary for a firm to know exactly what its cash reserves will be a decade into the future when making a long-term debt obligation. But just as a firm can manage its cash reserves by changing its current income and spending practices, so too does a water right holder need to be able to affect the size of future water supplies by managing current consumption. Conserving water today should result in more water tomorrow.

In addition to the stability of water rights is the need for some institutional mechanism for transferring water from a seller to a buyer. It is possible for neighbors to base a water exchange on nothing more than a handshake if there is sufficient personal trust between them. But such deals are by their nature singular and say nothing about the system as a whole. In order to look at the broader and more general possibilities, one must examine what provisions the legal environment has for endorsing temporary or permanent exchanges of water between willing parties. A common set of operating rules must be known to all potential players, and information about buyers and sellers most be reasonably accessible to all potential players.[3] If the rules do not facilitate exchange, then a market cannot come into being even though there may be isolated "handshake" deals here and there.

An issue related to institutional stability is forfeiture. In states where water rights follow the doctrine of prior appropriation (discussed in detail below), a water right holder who consistently uses less than the amount of his entitlement may be required to permanently surrender

3 Saliba and Bush; Kaiser; Charles W. Howe, Dennis R. Schurmeier, and W. Douglas Shaw Jr. "Innovative Approaches to Water Allocation: The Potential for Water Markets," *Water Resources Research*, vol. 22 (1986) pp. 439-445.

the unused portion of his right. Unless the water code somehow exempts leased water from the rules of forfeiture, a farmer will have a disincentive against conserving water and selling what he saves.

Finally, the physical means to move water from seller to buyer must be practical and cost-effective. The cheapest conveyance, of course, is the riverbed itself. Most states, including Texas, permit the riverbed to serve as a means of moving water from seller to buyer, and provide safeguards prohibiting seizure by other appropriators while the water is in transit.[4] And while not necessary, storage facilities such as reservoirs can greatly enhance the viability of a water market. The economic role of a reservoir is an important one: it transforms water from a flow commodity to a stock commodity. This makes it possible to accrue water just as one would accrue money, allowing a more stable base for market transactions. The two dams regulating river flow through the middle and lower stretches of the Rio Grande were financed and built by the U.S. and Mexican governments, and that capital cost is not passed on to users. Consequently, the only transaction costs associated with water conveyance involve pumping, and because water right holders already have their equipment in place to service their own water entitlements, even these costs are very small.

Most surface water entitlements in Texas and elsewhere in the western United States are made on a priority basis in which quantities are set but are arranged in a time-priority sequence. In places governed by the riparian model, surface water is allocated by law on a balancing

[4] TWC Sec. 11.042.

Table 4-1. Comparison of three water law regimes

Spanish law	Riparian law	Prior appropriation
1. Public water owned by the crown, dispensed by royal grant; basis was benefit of the community. Heavily administered at local level.	1. Water itself is owned by no one; right of usufruct is incident to ownership of riparian land. Disputes settled judicially.	1. Public water is owned by the state. Administration is exercise of state's police powers for public welfare.
2. Quantity was usually a function of time. Quantity determined by grant, by investment in acequía, or ad hoc by major domo.	2a. *Natural flow doctrine*: quantity is irrelevant. 2b. *Reasonable use*: quantity is balanced fairly among all riparians.	2. Quantity is measured in acre-feet per year or cubic feet per second. Quantity set by permit, all-or-nothing appropriation in order of seniority of permit.
3. Generally, permissibility of trading depended on lack of harm to community. Time in rotation could be leased.	3. Rights transfer with sale of land; other transfers binding only between buyer and seller, not other riparians.	3. Permanent sales, contract leases subject to state approval conditioned on no-harm rule.

basis: a water right holder gets an amount that is fair to all riparians at the time, as determined by a court.

Table 4-1 summarizes the relevant differences between the water law systems examined in this chapter. Of particular note is the similarity between the nature of water ownership under the Spanish and appropriative regimes. The state retains ultimate ownership of the water under both systems, providing the foundation for a system of administration to determine how public waters are to be used. Under the riparian system, water is indirectly yet privately owned by virtue of its appurtenance to land. Water rights controversies are largely issues of property ownership, and the role of the state is mostly limited to the judiciary.

Texas surface water law has gone through four distinct periods:

- the Spanish-Mexican period up to 1840, when Spanish law (picked up by Mexico upon independence from Spain in 1821, and by Texas upon independence from Mexico in 1836) governed the creation and administration of water rights;
- the riparian period from 1840 to 1889, when water rights were regarded as derivative of English common law principles adopted by the Texas legislature in 1840;
- a period of wishful incongruity from 1889 to 1967, when state law attempted to combine the riparian and appropriative systems; and
- adjudication, from 1967 up to the present.

Ground water rights were taken into account by the Spanish and riparian systems in much the same way as they are treated today in Texas: as private property. But as the doctrine of prior appropriation began to take hold in the 20th century, Texas water law bifurcated into different regimes for rivers and for aquifers. Statutes and court cases moved surface water firmly into the public domain as the state asserted its police powers, while ground water remained as it had been historically under the Spanish and riparian systems.

The Water Rights Adjudication Act of 1967 erased all remnants of the Spanish and riparian systems, transforming surface water rights that had vested under those systems into a form that could be regulated under a state permit regime alongside appropriative water rights. Ironically, the act did this by asserting, modifying, and expanding the same two principles that underlie Spanish water law: water in rivers belong to the state[5], and no one can use public waters without the state's express permission.[6]

The present-day water regime of the Lower Rio Grande Valley evolved from the Spanish, riparian, and appropriative systems, but it differs fundamentally from each of them. Still, detectable imprints of the prior systems remain, and examining them will shed light on how the watermaster system evolved. More importantly, a comparison of the old and the new will highlight those features of a water management system that are conducive to market principles, and those that are antithetical to them.

The following sections look at the Lower Rio Grande Valley's historical water rights doctrines through an economic lens. Aside from a descriptive comparison of the legal regimes, the key issues that will be clarified in each context are

- On what basis rights were created and sustained,
- To what extent water right holders knew how much water they had and would have, and
- How easily a water right holder could transfer a portion of that present or future quantity to someone else.

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[5] The Texas Water Code already established that "water of the ordinary flow, underflow, and tides of every flowing river, natural stream, and lake, and of every bay or arm of the Gulf of Mexico, and the storm water, floodwater, and rainwater of every river, natural stream, canyon, ravine, depression, and watershed in the state is the property of the state." TWC Sec. 11.021.

[6] The Water Rights Adjudication Act provides that "it is in the interest of the people of the state to require recordation with the commission of claims of water rights which are presently unrecorded, to limit the exercise of these claims to actual use, and to provide for the adjudication and administration of water rights to the end that the surface-water resources of the state may be put to their greatest beneficial use," and later declares that this law "is in the exercise of the police powers of the state in the interest of the public welfare." TWC Sec. 11.302.

The remainder of this chapter will examine the Spanish colonial system, the riparian doctrine, and the prior appropriation doctrine. The following chapter will examine in detail how the current watermaster regime evolved out of these systems and how it compares to what went before it.

The Spanish legacy

The first European legal system to affect water allocation in the Valley came from the Spanish colonial government of the sixteenth through the early nineteenth centuries. Many of the surface water rights claimed when the Lower Rio Grande Valley litigation began in the 1950s were based on Spanish and Mexican grants. But a large part of these purportedly ancient water claims were tenuous, due to the characteristics of Spanish water law and to the fact that the Spaniards had not contemplated irrigation in the Valley at the time the land grants were made.[7] When electrical and diesel-powered pumps made it possible to lift large volumes of water out of the Rio Grande and deliver it to fields, owners of land adjacent to the river claimed irrigation rights that in fact had not been given to them or their predecessors, and which did not inhere with anything that *had* been given to them.[8] This was the essence of the landmark 1961 court decision *State v. Valmont Plantations*, which held that (a) the nature of surface water rights under Spanish and Mexican grants is determined by the laws in effect at the time of the grants,

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7 Betty Dobkins, The Spanish Element in Texas Water Law (Austin, Tex.: University of Texas Press, 1959), pp. 107-8. See also *State of Texas v. Valmont Plantations*, 346 SW 2d 853 (1961).

8 *State v. Valmont Plantations*. The appeals court ruled that “the law of Spain and Mexico at the time of each grant is the law applicable.”

(b) these laws contained no implicit riparian rights, and (c) any later adoption of riparian principles by the Texas legislature did not change the nature of Spanish and Mexican land grants.[9]

Baade contends that recent history has severed any direct connection between modern water laws and the practices of the Spanish colonialists.[10] But as he and others point out, the hydrological facts of the western United States have posed challenges for every water law regime introduced to the area. While there may be no doctrinal continuity between the water laws of colonial New Spain and modern Texas, there are some striking similarities between the two systems, especially when contrasted with riparian water law.

Although the *conquistadores* and their successors had to adapt their legal system to what they found in the New World, the two main principles of Spanish water law were largely upheld in the Americas. First, all public waters remained the property of the Spanish crown, and could not be used for consumptive purposes without a grant from the king or his viceroys. Second, public waters were to be used for the good of the community, and the government always retained the authority to arbitrate between local interests and, when necessary, to rearrange water entitlements if it were in the interest of the community to do so.[11]

The term "public waters" must be qualified, however. Even though water running in rivers was largely regarded as part of the royal patrimony (or later, the public domain), Spanish water law also recognized

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9 *State v. Valmont Plantations.*

10 Hans W. Baade, "The Historical Background of Texas Water Law — A Tribute to Jack Pope," *St. Mary's Law Journal,* vol. 18 (1986), pp. 1-98.

11 Dobkins, *passim.*

private water holdings. As with many later regimes, springs, wells, or other sources of water that originated on private property were regarded as part of that property.[12] These were treated differently, and without regard to how they might fit into a larger hydrological system that included public waters.

Early Spanish water law differed in many respects from English and French water law of the same time. Many of the important differences may be traced back to the Moorish conquest of Spain in the eighth century. Limited irrigation existed on the peninsula prior to that time, largely due to the influence of the Visigoths who controlled the area after the decline of Roman power.[13] In the regions they eventually controlled, the Moors borrowed from their experience in the arid lands of Africa and the Middle East to develop new and ingenious irrigation systems, bringing more areas under cultivation.[14]

To manage the additional farmland and the water used to irrigate it, the Moors adapted Islamic water law both to the existing Spanish customs and to the technology they were using.[15] Under Moorish custom, water use was governed by the community, for the practical reason that its development required a community effort, and for the social reason that Islamic law carried strong injunctions against individualistic hoarding.

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12 Dobkins, pp. 96-97.

13 Thomas Glick, *From Muslim Fortress to Christian Castle: Social and cultural change in medieval Spain* (New York: Manchester University Press, 1995); Dobkins, *passim*.

14 Dobkins, pp. 63-70

15 Glick, chapter 4.

Because most land would not have water in the absence of the community irrigation works, Moorish law regarded water as a commodity completely separable from land. According to Dobkins,

> water, not land, was the important element in production of wealth.... [The Moors] recognized the importance of rights to water and granted perpetual rights to water for irrigation to those who were best able to use them.[16]

Irrigation systems in Moorish Spain were governed by the people who built and used them, a principle very similar to the modern-day concept of statutory irrigation districts. Those who had helped build the system and expected to irrigate from it hired a manager and decided tariffs. This was the beginning of the *acequía* system, which the Spaniards brought to the New World in the centuries after Moorish rule.[17] In some areas of Spain, water from the community system was allocated according to time shares. Each water right holder was assigned a time to irrigate.[18] In other areas, members of the canal cooperative received a fixed proportion of whatever was available, so the amount varied with the flow of the river at any given time.

Islamic law generally prohibited any kind of usurious practice with regard to water, but this principle was interpreted in various ways when it came to buying and selling water. A strict interpretation prohibited any trades, but often a transaction was considered permissible if voluntary and if not harmful to others. This even extended to ground water; new wells could be prohibited if there were the potential of harm to other

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16 Dobkins, p. 67.

17 In fact, the etymology of the Spanish word *acequía* shows its Arabic source. See Dobkins, p. 69.

18 Glick, pp. 76-87.

well owners nearby. In some tight-knit communities where most of the available water supplies came from an acequía, the water allocation system was so well-defined and well-policed that regular water auctions were possible.[19] It may be inferred, then, that the principle governing water trading in Moorish Spain was community benefit with no harm to others, rather than the exercise of a pure right of ownership.

Although mainstream Spanish history is a chronicle of conquests by caliphs and kings, municipalities were regarded as the most important unit of politics and social order, especially with regard to questions such as water use. The term “pueblo” designated a concentration of people that had well-defined institutions governing how local society operated. Local custom for allocating water varied from pueblo to pueblo. After the reconquest of Spain and the expulsion of the Moors in 1492, the crown and its courts saw the value of the irrigation works that had been created and often chose to preserve local customs rather than impose a uniform set of rules.[20]

Later decrees by Spanish kings, as well as judgments by the Spanish courts, borrowed extensively from both Moorish tradition and Roman civil law in the formation of Spanish water law.[21] Early Spanish water law defined rivers as common goods, not as privately owned factors of agricultural production. Any use of public waters that did not diminish the flow of the river required no permit because such uses neither diminished the royal patrimony of water nor prevented others from using it.

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[19] Dante A. Caponera, *Water Laws in Moslem* Countries (FAO Development Paper No. 43, Agriculture), cited in Dobkins, p. 69.

[20] Glick, chapter 4; and Dobkins, pp. 71-73

[21] Dobkins, p. 69

In these nonconsumptive uses — primarily navigation and fishing — water was a medium of economic activity rather than a factor of production.

The Spanish water law that evolved in the semi-arid climate of the Iberian peninsula was transplanted to the New World after the papal demarcation between Spain and Portugal in 1493.[22] However, the Spanish found that in some parts of the New World, the indigenous peoples had already developed systems of irrigation.[23] Despite the many conflicts between the Spaniards and the indigenous peoples during the conquest, some of the Spanish kings believed it valuable to preserve these irrigation systems. In some cases, separate and autonomous *acequías* were established exclusively for native use. In 1563 Don Felipe II issued a decree establishing water judges to allocate water to the indigenous irrigators, a decision that was affirmed later by Don Felipe IV. These water judges were instructed to

> apportion waters to the Indians for the irrigation of their farms, orchards, and seed beds, and to water their cattle. They are to be such as to offend no one and shall apportion waters according to need. ... We further decree that the judges shall not proceed at the cost of the Indians and in causes of which they take cognizance, if their judgments are appealed, that which the *audencia* [high court] determines shall be executed without regard to the appeal, in view of the brevity required by such cases.[24]

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22 *State v. Valmont Plantations*; Dobkins, pp. 85-87

23 Robert Dunbar, *Forging New Rights in Western Waters* (Lincoln, Neb.: University of Nebraska Press, 1983), pp. 1-4.

24 Recopilacion, Law 63, Title 2, Book 3; translation cited in *State v. Valmont Plantations*.

The expanse of unassigned land posed a challenge to Spanish peninsular law, which was codified after most land claims in Spain itself were settled. The viceroys and *audencias* responsible for the royal patrimony of land and water in the New World had to proceed carefully in the mass creation of new rights; it was a task the old law had not had to address since the days of the Moors.

In many areas of present-day Texas, Tamaulipas, Nuevo León, and Chihuahua, the assigning of land and water rights took place after a survey of the region. The surveys classified lands according to their most likely practical use, and grants were made according to the classifications. Although surveys varied somewhat in their definitions, each distinguished in some form or another between irrigable and nonirrigable land.[25] In some cases, water was explicitly included in a grant of land. In other cases (especially when towns were established) water was granted independently of land. One detailed historical account enumerates these categories[26]:

- Grants of land with general references to water (wording such as "and waters in these lands contained");
- Grants of land with specific reference to water ("waters necessary to irrigate the lands granted");
- Grants of land alone;
- Grants of water alone, such as for sugar plantations, factories, and mills;

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[25] A.R. White and Will Wilson, "The Flow and Underflow of Motl v. Boyd: The Conclusion," *Southwestern Law Journal*, vol. 9 (1955), 377-433; *State v. Valmont Plantations*; *State v. Hidalgo County WCID No. 18*, 44 SW 2d 728 (1969); Dobkins, *passim*.

[26] Andres Molina Enriquez, *Los Grandes Problemas Nacionales* (Mexico City: A. Carranza e Hijos, 1909), cited in *State v. Valmont Plantations*.

- Municipal water supply grants; and
- Irrigation grants.

The first survey of settlements in the Rio Grande Valley took place in 1757, with the grants made ten years later. Camargo, Mier, and Reynosa were the three established settlements, and the surveyors judged that irrigation was infeasible at the first two locations.[27] Grants emanating from this survey were not for irrigable land, but for *porciones* of arable land (without irrigation) and for pasture (*caballerías*). *Porciones* were smaller and more expensive, while *caballerías* were larger and less expensive.

Where irrigation was possible in New Spain, the Spanish missionaries often established *acequías* to develop and maintain the system. One of the earliest *acequías* in New Spain was on the San Antonio River. Surface water was often apportioned during shortages by time rather than by quantity of water, a practice that can be traced back to Moorish Spain.[28] Devising a fair plan was often left to a water judge or some other designee of the Crown. In San Antonio, for example, two major groups of irrigators took turns irrigating in the case of a drought. Similar practices were used in Chile and other areas governed by Spanish law.[29]

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[27] Due to illness, the engineer did not make a report on Reynosa's irrigation potential. About Mier he wrote: "[T]here is no canal nor does the land afford the opportunity to enjoy this benefit," except for a small strip where it was "not worth the work and cost which it would involve." About Camargo he wrote: "Here there is no canal nor can it be built due to the depth of the bank with respect to the surface of the water of the Rio de San Juan and due to the fact that its waters flow so fast that they appear dammed." Acta de Visita General, 1767.

[28] Glick, pp. 76-80

[29] Frank J. Trelease, "New Water Laws for Old and New Countries," in *Contemporary Developments in Water Law*, eds. Corwin W. Johnson and Susan Hollingsworth Lewis (Austin, Texas: Center for Research in Water Resources, 1970), p. 42.

The Spaniards dealt with drought by allowing a majordomo or some other arbitrator enough flexibility to improvise solutions appropriate to local situations. Administrative discretion was the first-order characteristic of drought management under the Spanish system, in that it was always a fundamental aspect of how business was conducted ever since the Moors. Strategies taken by the administrators constitute the system's second-order characteristics; they indicate what was permissible.

Conflict resolution strategies suggest the extent to which the Spaniards quantified water rights. Most often, water was measured not by volume but by time: how many days of watering a right holder was entitled to when there wasn't enough to irrigate any day without discretion.

Thus under the Spanish system, the sources of surface water entitlements were social. Legitimate rights in water were those that increased public rather than solely private well-being. Authority to determine whether a use was in the public interest was vested in either a despot (the Spanish Crown, or a Moorish caliphate) or in a self-governing local committee whose work and money had made the irrigation ditch possible. One could not self-declare a right to public water by claim or prescription, nor could one obtain one by accident or incident relative to some other acquisition of property. As Dobkins notes,

> It is important in considering the Spanish system to bear in mind that its primary concern was with the common use of waters, with their administration in such a fashion that the community interests were served and the fertility of the land preserved, rather than with prior and exclusive rights. To look at the Spanish system through the lens of individualistic property concepts is to miss its *raison d'être*.[30]

[30] Dobkins, p. 98.

Implicitly, surface water rights were governed by a "use it or lose it" rule. Obtaining a right presumed some beneficial use, some enterprise to which the water would be applied. This was usually irrigation or milling, both of which were on-going ventures in which the relationship between the amount of water used and the amount of profit produced could be reckoned to some degree. In the case of irrigation, farmers could develop a sense of how many waterings were required for a season of wheat.

Although there is some indication of water auctioning, there is little to indicate whether shares or watering rotations could be sold from one irrigator to another in Moorish Spain. In the Spanish colonies, however, water rights were on occasion bought and sold. As more settlers moved into the fertile area of the San Antonio River and established more (and competing) acequías, earlier residents who were already facing cutbacks had to "rent" watering days from other users. Colonial governors and local administrators sometimes took away irrigation privileges that weren't being exercised, an 18th century precursor to a provision of modern Texas water law.[31]

A significant doctrinal gap lies between the time Spanish water law ended and modern Texas water law began, however. Despite the many similarities between the two, the evolution of Texas water law took a detour from the mid-19th century up to the mid-20th century, a detour that proved to be very bumpy. Indeed, the conflicts generated by this detour set the stage for the legal battle that led to the regime now governing water use in the Lower Rio Grande Valley.

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[31] Dobkins, pp. 113-122

Riparian water law

The Spanish system of water law was carried forward largely unaltered when Mexico won its independence from Spain in 1821. The following years were tumultuous for the area: immigration increased, along with tensions between the northern Anglo-American settlers and the Mexican government. The Republic of Texas successfully broke from Mexico in 1836 and was annexed to the United States just 10 years later. The border between Texas and Mexico remained highly disputed throughout that turbulent time, however. Only with the Treaty of Guadalupe Hidalgo, which ended the U.S.-Mexican War in 1848, was the Rio Grande established as the border between the United States and Mexico from El Paso to the Gulf of Mexico,

To promote stability in the area between the Rio Grande and the Nueces River, the Treaty of Guadalupe Hidalgo provided that "all grants of land made by the Mexican government, or by the competent authorities, in territories previously appertaining to Mexico, and remaining for the future within the limits of the United States, shall be respected as valid, to the same extent that the same grants would be valid if the said lands had remained within the limits of Mexico."[32]

Neither that clause nor the similarly intended Relinquishment Act passed by the Texas Legislature in 1852 was enough to hold back the impending flood of controversy over surface water rights in the area, however. A key problem was the wording of the treaty, which specified "grants of land" but said nothing about grants of water. Under Spanish law, in which land and water were clearly distinct, the implication was

[32] Treaty of Guadalupe Hidalgo, Art. 10. (1848).

that ownership reverted to the State of Texas.[33] But the Texas republic had adopted an English common law standard in 1840 in which water was appurtenant to land; a grant of land meant a grant of water if a river ran through it or along it.

The riparian doctrine was itself a new feature of the English common law in 1840.[34] Prior to the 18th century, common law had by and large followed the rule of ancient possession: if water in a river had been used for a particular purpose as a matter of custom from time immemorial, the current proprietor of that farm, mill, or other activity was entitled to continue the enterprise. New uses that jeopardized the old ones were disallowed when water conflicts were litigated. Civil law enabled the extension of this principle to an early variant of the prior appropriation doctrine, in that a use need not be ancient as long as it began earlier than another newer use that threatened to take water away from the prior use.[35]

The priority system was eclipsed in the early 19th century by the riparian doctrine, in which English and U.S. courts began to hold that land fronting on a river or with a river running through it was naturally endowed with the ability to use the water, while land away from the river was not. An 1827 California court decision[36] significantly clarified the riparian doctrine and created a strong precedent that, along with

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33 An important provision of Texas' annexation to the United States was that the state retained its sovereignty over its water and other natural resources.

34 A. Dan Tarlock, *Law of Water Rights and Resources* (New York: C.Boardman, 1988 with loose leaf updates), ch. 3, pp 6-9; David H. Getches, *Water Law* (St. Paul, Minn.: West Publishing, 1997), pp. 18-20; Samuel Wiel, *Water Rights in the Western States* (San Francisco: Bancroft-Whitney, 1911), 740-747.

35 Wiel, 735-739; Getches, p. 17.

36 *Tyler v. Wilkinson* C.C.R.I. 1827

subsequent legal commentaries by the prestigious New York jurist James Kent, influenced further rulings in English courts.[37] A very similar principle had developed under the Napoleonic code just two decades earlier, where the rights of a *proprietaire riverain* in France were treated in much the same manner as those of a riparian landowner in England.[38] By the time the Republic of Texas adopted the English common law in 1840, the riparian doctrine was firmly (albeit recently) a part of it.

Wiel says that a proper understanding of riparian law rests on three fundamental principles[39]:

- The water running through a natural watercourse belongs to no one;
- While one may not own the water itself, one may possess a right to use it (the concept of usufruct); and
- Water taken out of a stream under the right of usufruct belongs to the person diverting it, but only so long as it remains in the possession of the diverter.

By nature, however, only those who owned land adjacent to a watercourse were in a position to exercise the right of usufruct, even though the water itself was a community resource. Put another way,

> while the riparian owner's right is negative as to the *corpus* of the water and not an ownership thereof, it is a positive right in respect to *the use of his land*. His riparian estate is made up of many elements, not alone the actual soil, but other natural advantages of situation without which the soil would not have its character and potentialities of use.... [T]he right to use the water flowing by one's land and to

37 The landmark case in the English courts was *Mason v. Hill* (Eng. 1833), six years after *Tyler v. Wilkinson*.

38 Getches, pp. 16-17;Wiel, p. 750.

39 Wiel, p. 758.

> receive its benefits remains inherent in the riparian land whether it is actually put to use by erecting irrigation or other works or not.[40]

What the law is ultimately contemplating with regard to riparian rights, therefore, is really land rather than water. Land can be owned, but not water, which is simply used as a consequence of owning the land. Water is regarded as a part of the "negative community" of things, a concept dating back to Roman law designating things too ephemeral to be materially controlled. Land, as part of the "positive community" of things that can be held, includes not only the soil, but also the natural resources (*ferae naturae*) on it, under it, and above it. Making land productive involves harnessing the land's resources, one of which is the water with which nature has endowed a parcel.

In both English and U.S. courts, the right to use a river's natural flow also meant that an upstream riparian's use of the water could not compromise the ability of downstream riparians to use water as it was wont to pass their lands naturally.

With irrigation, urbanization, and industrial development creating additional demands for water, the cases coming to the courts became more complex. By the mid-19th century, riparian law began to replace the concept of natural flow with the reasonable use doctrine: "every riparian owner has a privilege to use the water for any beneficial purpose if the intended use is reasonable with respect to other riparians."[41]

Defining "reasonable," of course, was often a highly litigious matter, and still can be in areas where riparian water law continues to domi-

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40 Wiel, p. 774.

41 William Goldfarb, *Water Law* (Boston: Butterworth Publishers, 1984), p. 8.

nate. In practice, most disputes were decided in favor of existing downstream uses and against new upstream uses, although Texas courts described ways in which upstream users could establish prescriptive rights at the expense of other downstream riparian claims.[42] Nonconsumptive use was also preferred to consumptive use, especially during drought.[43] Most often, shortages were resolved by limiting riparians' withdrawals on a proportional basis.

The riparian system, being concerned mostly with river access and correlative rights, never developed a clear concept of quantity. The reason is that what a riparian really owns is not measurable; it simply describes something that can be done with land by virtue of its proximity to a river. The doctrine is not concerned with how often this right is exercised, only that it be preserved for downstream riparians.

The California Supreme Court summarizes this point of riparian law by saying that the riparian water user "has no property in the water itself, but a simple use of it while it passes along."[44] The quasi-ownership that comes into being when a particular volume is diverted into a private system is neither durable nor transferable; it amounts to little more than a legal restatement of the physical fact that the same molecules of water can not be in two places at once.

If one were to express the riparian natural flow principle in mathematical terms, the quantity consumed by any given user is assumed to be less than or equal to what is replenished by nature.[45] With the net

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42 *Martin v. Burr* (1921) 111 T. 57, 228 SW 543; *Motl v. Boyd* (1926) 116 T. 82, 286 SW 458.

43 C. Davis, "The Right to Use Water in the Eastern States," in *Waters and Water Rights*, vols. 7, R.E. Clark, ed. (Indianapolis, Ind.: Allen Smith Co., 1978).

44 *Tyler v. Wilkinson*, 4 Mason 397 Fed. Cas. No. 14,312.

change in flow presumed to be equal to zero, each downstream riparian should have enjoyment of the stream in something close to its natural state, taking only what is needed to support a household and its livestock from the land owned. Large-scale irrigation was not contemplated, nor were water-consuming industrial complexes.[46]

With negligible consumption, the corpus of the water itself has little or no intrinsic value because it is treated as though it were never consumed as a factor of production. The locus of legal value is the land, and whether or not it is watered by a stream. The *ability* to irrigate has ownership value, but there is no distinguishing between 100 acre-feet of water, one acre-foot, or even zero in actual use. The presence of water — not its consumption — is assumed to have value.

Of course, this makes hydrological sense only if one ignores evapotranspiration. As a point of fact, water is consumed; as a point of fact, water does have value as a factor of production. The divergence between the legal world view and the economic world view is generally why riparian water rights, though clear as an aspect of land ownership, provide no stability for a water trading system unless modified by a permit system. Water is not owned, and what is not owned cannot be traded. The law is content to act *as though* consumption is negligible as long as no other riparian users are harmed by the quantity actually consumed.

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45 See, for example, the 1805 English decision *Bealey v. Shaw*: "The general rule of law as applied to this subject is that, independent of any particular enjoyment used to be had by another, every man has a right to have the advantage of a flow of water in his own land *without diminution or alteration*." [italics added] 6 East, 208, cited in Wiel, p. 742.

46 I am indebted to Prof. Joe Moore for helping clarify this aspect of riparian law.

To clarify the market problem, consider a potential water lease between riparians. The opportunity cost of a good is the value of what one has to give up in order to enjoy it. In the case of riparians, water's marginal opportunity cost (what it costs to consume one more increment of water) is zero, up to the point that actual consumption is so large that it harms other riparians or exceeds the amount available at the point of withdrawal. (At that point, the high-demand riparian would have to compensate all other riparians for doing without water they normally would have enjoyed.) Put more simply, if a riparian ever needs more water, all that is necessary is to take it, as long as it does not demonstrably disrupt the balance of other riparian uses. Extra water costs nothing to obtain under the law, so no riparian would pay another riparian for it. What is really at issue — and valuable — in a riparian system is the right to divert water, not the water itself.

Potential leases from riparians to nonriparians are also problematic because they are not binding on other riparians not party to the contract.[47] The lessee would have no standing in any legal challenge brought by other riparians with respect to water diversion. The lease contract itself could pose a great risk to a riparian lessor if he could held liable for damages incurred by the lessee were a court to enjoin diversions.

Permanent water rights can have an implicit economic value derived from comparing riparian and nonriparian land values.[48] But transfer-

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47 See, for example, *Duckworth v. Watsonville Water and Light* (Cal. 1910).

48 This procedure was used to estimate water values in the Ogallala Aquifer. See L. Allen Torell, "The market value of water in the Ogallala Aquifer," *Land Economics*, vol. 66 (1990), p. 163.

ring water from a current user to a new user is extremely difficult in a riparian regime. Strictly speaking, the only way to do so is to sell the land to which the water is appurtenant. This inseparability of land and water is a defining characteristic of the riparian doctrine — and a fundamental reason why a water market is virtually impossible under such a regime. It is possible in some states for a riparian to sell the land yet reserve the water rights.[49] But many states hold that such an agreement is applicable only to the buyer and seller.[50] If any conflict arises with other riparians, the nonriparian may have no standing to seek damages or injunctive relief.

A riparian water rights regime, then, differs significantly from the Spanish system it replaced in the Lower Rio Grande Valley when the area became part of Texas. The explicit emphasis on community benefit that was the foundation of the Spanish system is absent in the riparian system, in which private property rights are the supreme good. In addition, riparian systems have no clear way of determining how much water is covered in an entitlement. Indeed, the concept of quantity doesn't even exist. Transfers are also very difficult under a riparian system, and for the most part take place only when riparian land is transferred from one owner to another. The state also has a much smaller role in a riparian system than it did in the Spanish system. Whereas the latter was clearly administrative in nature, the state becomes involved in riparian rights almost solely through the judiciary, when rights are contested.

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[49] Getches, p. 63; Tarlock, Sec. 3.18.

[50] Getches, p. 63. For an early decision to this effect, see *Duckworth v. Watsonville Water and Light.*

Riparian rights are stable only so long as there is enough water in the hydrological system to satisfy all riparians. In that case, the only conflict is between riparians and nonriparians. When water is scarce, however, the riparian system can be inadequate. It was in the western United States that riparian principles were put to the test when dealing with shortage. The failure of riparian law in these arid states created an imperative to find another way to create water entitlements.

Prior appropriation

The fiction of negligible consumption points to the riparian system's ideal world which, not coincidentally, resembled the land where the legal doctrine began. The rivers that ran through the green hillsides of England and Wales were enough for the low-consumption demands of the 19th century. The legal issue was who had the right to use a stream, not how much water any individual had a right to use. A householder was reasonably sure of having enough water for his family's needs as long as had physical access to the river.

But the arid and semi-arid western United States does not resemble England; the natural flow of the Rio Grande, its tributaries, and other western rivers can fluctuate tremendously from month to month and from year to year. The lack of predictability made the question "how much" critically important, and the riparian doctrine's inability to provide a clear answer was one reason western states had to come up with another way of assigning water rights.

Initially, agriculture did not lure Americans westward in the 19th century; gold did. In 1850s California and later in 1860s Colorado, as easy-to-mine gold and silver soon played out, pans were replaced by sluice boxes — troughs in which gold or silver ore was washed clean of its lighter residue by a stream of water. Miners competed for water in the streams running past the mountain mines, and unlike the millers and yeoman farmers of England, it didn't matter whether they were on the river or not. When veins of gold and silver were away from the river, it was often more convenient to bring the water to the ore rather than vice versa.

The miners, working lands in the public domain of the United States, applied their own law to allocating scarce water. Mining claims were staked and perfected by two basic rules: "first in time, first in right," and "use it or lose it."[51] Prior claims superseded newer claims, so long as the earlier claims were being worked. This practice was codified in federal mining laws, which governed the administration of natural resources in the recently acquired western territories.[52]

The mining camps found it conceptually expedient to apply the same principles to allocating water, and thus evolved the doctrine of prior appropriation in water law. Trelease summarizes three principles underlying most forms of prior appropriation. (Table 4-2 shows how these same concepts are embodied in Texas water law).[53]

- The state claims ownership and control of the water, allowing private persons to acquire rights only by virtue of a state permit.
- Permitted uses of water must be reasonable and beneficial.

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[51] Dunbar, pp. 73-76

[52] See 1886 Mining Act, 30 USCA Sec. 51 and 43 USCA Sec. 661.

[53] Frank J. Trelease, "New Water Laws for Old and New Countries," in *Contemporary Developments in Water Law*, eds. Corwin W. Johnson and Susan Hollingsworth Lewis (Austin, Texas: Center for Research in Water Resources, 1970), p. 40.

Table 4-2. Prior Appropriation Elements of the Texas Water Code

State ownership	"The water of the ordinary flow, underflow, and tides of every flowing river, natural stream, and lake, and of every bay or arm of the Gulf of Mexico, and the storm water, floodwater, and rainwater of every river, natural stream, canyon, ravine, depression, and watershed in the state is the property of the state." (Sec. 11.021)
Beneficial use	"No right to appropriate water is perfected unless the water has been beneficially used for a purpose stated in the original declaration of intention to appropriate water or stated in a permit issued by the commission or one of its predecessors," (Sec. 11.026) and "A right to use state water under a permit or a certified filing is limited not only to the amount specifically appropriated but also to the amount which is being or can be beneficially used for the purposes specified in the appropriation, and all water not so used is considered not appropriated." (Sec. 11.025)
Priority	"As between appropriators, the first in time is the first in right." (Sec. 11.027)

The Texas Constitution provides the basis for the above statutes:
"The conservation and development of all of the natural resources of this State, including the control, storing, preservation and distribution of its storm and flood waters, the waters of its rivers and streams, for irrigation, power and all other useful purposes, the reclamation and irrigation of its arid, semiarid and other lands needing irrigation, the reclamation and drainage of its overflowed lands, and other lands needing drainage, the conservation and development of its forests, water and hydroelectric power, the navigation of its inland and coastal waters, and the preservation and conservation of all such natural resources of the State are each and all hereby declared public rights and duties; and the Legislature shall pass all such laws as may be appropriate thereto." (Article 16, Sec. 59)

- Water users have property rights protected against infringement from later users, existing in perpetuity, if used, and in most states transferable by the owner to another person.

If water is scarce, whatever is available is distributed to appropriators in the order of priority on an “all-or-nothing” basis. The most senior appropriators get all they need under their entitlements; when the available water is used up, the most junior appropriators get nothing.[54] Thus, even though a bona fide appropriator knows the exact quantity of the entitlement, there is a certain probability attached to that quantity that is a function of seniority.

The more senior the right, the greater the probability that what is actually taken from the stream will equal the face amount of the right; the more junior, the more the probability diminishes. Upstream rainfall exerts a further influence on the effective amount of water, making junior rights all the riskier as stream flow falls below normal. Because flow is more difficult to predict the further one looks ahead, estimates of future quantities under a water right are unstable.

Intent is an important dimension of the beneficial use requirement. In the absence of a permit system, an appropriator usually may claim a priority date based on demonstrated intent rather than the time beneficial use would actually begin.[55] This improves the seniority (and value) of the right. Intent is established by identifying a specific beneficial use for the water, locating a specific point of diversion, and the commencement of construction or some other preliminary activities needed to divert the water.[56] Permit filing requirements normally guarantee that

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[54] David H. Getches, Water Law (St. Paul, Minn.: West Publishing, 1997), p. 101.

[55] TWC Sec. 11.141; also see Getches.

[56] TWC Secs. 11.124 through 11.127-1, also see Getches, pp. 89-92

these conditions will be met during the course of filing an application. To discourage speculative hoarding of water rights, most states have provisions to weed out bogus claims of intent, such as time limits on the waiting period between filing and the commencement of diversion.[57]

Perfected appropriative water rights usually can be transferred from a seller to a buyer. Often the rights are appurtenant to the land or the enterprise using the water, but it is not unusual for water rights to be severed from other property rights.[58] By preserving both the seniority and the quantity of the entitlement, a right takes on a limited degree of predictability (the structure of the uncertainty is known and constant) that enables it to acquire a market value relative to other water rights. All other things being equal, a senior water right will be worth more and will sell for more than a junior right.

No state allows completely unregulated sales of permanent water rights. Most states have a "no-harm" standard that must be met prior to the approval of any transfer of ownership.[59] The buying and selling parties must establish that changing the point of diversion or the use will not reduce the water available to users in between the buyer and seller. Nor can the change in use affect the quality of water delivered to any other user.[60]

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57 TWC Sec. 11.146

58 In Texas, permanent water rights are appurtenant to land and pass with title of the land unless otherwise stated in the transfer document. TWC Sec. 11.040. For other appropriative rights, the TNRCC is authorized to amend permits with regard to ownership. TWC Sec. 11.122.

59 Getches, p. 155.

60 Getches, p. 155.

Some states will also allow water to be leased temporarily, subject to the same no-harm provisions as permanent sales.[61] Over the past 10 years, some states have enacted revisions to their appropriations statutes protecting leased water against forfeiture for nonuse.[62] These new laws specify that the lease of unused water does not constitute waste, thereby preserving beneficial use.

Texas opens the door to water trading indirectly by protecting conserved water against forfeiture. The Texas Water Code first defines beneficial use as "use of the amount of water which is economically necessary for a purpose authorized by [the Texas Water Code], when reasonable intelligence and reasonable diligence are used in applying the water to that purpose *and shall include conserved water*." The same section then defines conserved water as that which is saved "through practices, techniques, and technologies that would otherwise be irretrievably lost to all consumptive beneficial uses arising from storage, transportation, distribution, or application."[63]

In many appropriation states (including Texas), the seniority of a right itself may be leased to a junior water right holder. Even though no water is involved in the transaction directly, the good being leased is still quantifiable and stable, which enables it to acquire and retain a market value of its own separate from the water.

As more Anglo-Americans established towns and agricultural areas in the West, territorial and state legislatures adapted the miners' prior

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[61] Getches, p. 156.

[62] TWC Sec. 11.173, see also Texas Water Bank Act, TWC Title II, Sec. 15.704.

[63] TWC Sec. 11.002 (italics added). These provisions were added to the Texas Water Code in 1997.

appropriation principle to surface water rights. Colorado was the first western state to completely repudiate the riparian doctrine. The state constitution adopted in 1876 asserted Colorado's sovereignty over water resources, and swept away the riparian system in favor of prior appropriation. The Colorado Supreme Court elaborated on the constitutional provision in a 1882 decision:

> The common law doctrine giving the riparian owner a right to the flow of water in its natural channel upon and over his lands, even though he makes no beneficial use thereof, is inapplicable to Colorado. Imperative necessity unknown to the countries which gave it birth, compels the recognition of another doctrine in conflict therewith.[64]

Both California and Texas found a hybrid water rights regime difficult to manage.[65] Riparian rights and appropriative rights are conceptually irreconcilable; they can co-exist only when there's enough water to satisfy all needs, in which case the regime is irrelevant because there are no disputes to settle. But while such a happy state may exist in England, it does not exist in Texas or any other western state.

In its pure form, a riparian system cannot fit appropriative uses into its framework. The essential conflict is with the riparian doctrine's natural flow principle: appropriation implies diversion, and diversion implies disruption of the river's natural flow. Morphing natural flow into reasonable use and correlative rights is hardly an improvement, replacing an unequivocal irreconcilability with an irresolvable ambiguity. Moreover, the further one gets from the natural flow principle, the more

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64 *Coffin v. Lefthand Ditch Co.*, 6 Colo. 443 (1882). Cited in Dunbar, p. 81.

65 Dunbar, pp. 59-69

one needs to improvise decision rules (correlative rights, for example) if the riparian regime is to be retained.

Consider the dilemma under a reasonable use rule of a riparian municipality that increases ten-fold in population. A "reasonable" increase in the municipal entitlement would require taking water from other riparian uses that presumably are as reasonable now as they were when the municipality was small. Encroaching into the amount of water available to a riparian affects what can be done with the land, which undermines the premises of riparian water rights.

Texas showdown between riparians and appropriators

The riparian doctrine had been the law of Texas water for about five decades when the state began moving towards prior appropriation. In the Irrigation Act of 1889, Texas followed other western states in declaring that unappropriated water was state property, and that anyone regardless of physical location could file a sworn claim to put public waters to beneficial use. The new law was flying blind with regard to how much water could be appropriated under a claim, however. The state had established no agency to verify and quantify claims, nor were there any reliable data on stream flow.[66]

Significantly, neither the 1889 law nor its revision six years later did anything to reconcile new claims with already existing riparian rights. This posed a potential booby trap for Texas water law, with the courts maintaining the common law standard of riparian rights and the legislature propounding a new system based on sworn claims.[67] The courts

66 Corwin Johnson, lecture notes, CLE Conference on Texas Water Law, Dec. 12-13, 1996.

eased some of the pressure by abandoning the natural flow principle in favor of reasonable use, which essentially put a margin of additional usable water into the system.[68] (Natural flow permits no diminution of flow; reasonable use does.) But the fundamental conflict remained: how could an appropriator claim unused water if a riparian wasn't required to use that water in order to maintain the right to it?

The Texas Legislature attempted to patch the holes in state water appropriation laws in 1913 and again in 1917.[69] Sworn claims were replaced by a requirement to obtain permits for using state water. By creating a Board of Water Engineers, lawmakers hoped to provide for the ongoing intelligence necessary to administer a permit system. The board was responsible not only for administering water rights, but also for maintaining data on how much water was available in the state's streams and lakes.

The Board of Water Engineers was also given the task of reconciling riparian rights with rights granted under permit. In short order, however, this provision was struck down as unconstitutional by a state court decision in 1921.[70] As Johnson notes, "This was a devastating blow to efforts to clarify and stabilize water rights. Sixty years would pass before this enormous gap in Texas water law would be filled by enactment of a valid water rights adjudication act."[71]

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[67] Texas was not alone in this split between the legislature and the judiciary. Wiel noted in 1911 that "The law of riparian rights is almost wholly nonstatutory in the West." p. 746.

[68] Getches, pp. 18, 20.

[69] Irrigation Act of 1913, Chapter 171, Texas General Laws, p. 358; revised in 1917, ch. 88, secs 105-132, Texas General Laws 211.

[70] *Board of Water Engineers v. McKnight,* 229 SW 301 (1921).

[71] Johnson, p. 6.

In the meantime, the already murky state of water rights was made even muddier by a 1926 Texas Supreme Court decision that distinguished between "ordinary flow and underflow" and "flood waters."[72] Chief Justice Cureton extended the riparian natural flow principle by ruling that a river's normal flow belonged to riparians; any unusual flow or runoff in excess of the normal flow was available in its entirety to appropriators. What the court did not provide were criteria for determining unambiguously what was normal and what was excess.

The venue for the final showdown between riparian rights and appropriative rights was the Lower Rio Grande Valley, during the drought of the 1950s. The litigation over water rights lasted for more than a decade before it was resolved on appeal in 1969. In the meantime, however, the Texas Legislature made another attempt to establish appropriative rights as the role of the state. In 1967 lawmakers passed the Water Rights Adjudication Act, which explicitly affected "claims of riparian water rights" (listed first among various other kinds of claims) and provided a period in which such rights could be transformed into an adjudicated right.[73]

The implications for water marketing

Ultimate resolution of the conflict between the two doctrines had to await the outcome of the Lower Rio Grande Valley lawsuits. This will be examined more closely in the next chapter, but here it is important to note how the conflict proceeded from prior legal history, and the key fea-

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72 *Motl v. Boyd.*

73 TWC Sec. 11.003.

tures of these prior legal systems with regard to buying and selling water.

Howe, Schurmeier, and Shaw, who provide some of the earliest theoretical treatment of water marketing, enumerate six similar regime characteristics that are necessary for achieving allocative efficiency through market-based mechanisms.[74]

- It must be clear who is entitled to what portion of available water, and those entitlements must be reasonably secure from challenge;
- Water entitlements must be transferable;
- Using the available water must entail some real opportunity cost for both the buyer and the seller;
- The outcomes of the water transfer process must be predictable;
- The public must perceive the transfer process as fair; and
- The transfer process must be capable of reflecting public values that may not be adequately considered by individual water users.

Howe, Schurmeier, and Shaw contend that each of the two modern water rights systems has different market shortcomings, depending on the cost of transactions, the general variability of water supplies, and the similarities among users. They say that generally, a riparian proportional regime is easier than a priority regime for the routine operation of a market. The trade-off is between the ability of a market to minimize the risk of shortage, and the ease of making a market work. Although their idealistic conclusion is that water rights regimes must be tailored to local hydrological conditions before market mechanisms can obtain allocative efficiency, they also observe that usually "there is a great deal

74 Howe *et al*. 439-445.

of room to facilitate water market transactions before such basic changes become necessary."[75]

Quantification problems exist in all three models discussed here. For a water market, the most intractable problem is with the natural flow doctrine under a pure riparian regime; in this case, water effectively has no quantity because it is legally little more than a descriptive condition of land. Under a system of riparian correlative rights, disputes among riparians are settled by a court decree, but rights are rarely quantified. By contrast, the amount of water that may be taken under a regime of prior appropriation is fixed by the water right. What varies, however, is the probability of getting that amount. That probability is a function of the right's seniority.

Transfer of water and water entitlements are easier under an administrative or appropriative system than under a riparian system. Under the latter, no truly secure transaction can take place unless it also involves some permanent sale or temporary lease of the land to which the water is appurtenant. Under an appropriative system, it is possible to sell or lease seniority as well as an amount of water itself.

A note on groundwater law

Water markets under any system can be further complicated (if not rendered completely infeasible) by how the law handles groundwater. In Texas, for example, the constitutional provision that defines "natural resources" specifically includes surface water (streams and storm runoff both), but is resoundingly silent with regard to groundwater.[76] Thus

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75 Howe *et al*, p. 444.

76 Texas Constitution, Article 16, Sec. 59 (see text in Table 4-2).

while surface waters clearly are considered public, the status of groundwater is left largely to interpretation.

In recent decisions, the Texas Supreme Court has made it clear that — at least theoretically — it considers groundwater a natural resource covered generally by the Texas Constitution. Judicial limitations on groundwater use have been slow in coming, however.[77] Instead, the court has continued to uphold the rule of capture while deferring to the Legislature on how groundwater is to be controlled within that common-law constraint.[78]

Ironically, the rule of capture governing Texas groundwater is in some ways similar to riparian surface water law, which was expunged from Texas in 1967[79], except that the water is flowing under the land rather than through it or along side it. The right to drill a well is considered appurtenant to land ownership, and this right is burdened by no implicit quantities governing withdrawals. Unlike riparian surface rights, however, there are no correlative rights among Texas land owners who tap the same aquifer, unless those owners have voted to establish a statutory groundwater district.[80] Generally, a land owner can

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77 Even as it was establishing for Texas the common-law rule of capture in 1904, the court held that wasteful pumping of groundwater that maliciously injures another well owner could be enjoined by the state. *Houston & Texas Central Railway Co. v. East*, 81 S.W. 279 2d 279. In 1978, the court ruled that a landowner could be found negligent if excessive groundwater pumping caused subsidence on someone else's land. *Friendswood Development Co. v. Smith-Southwest Industries Inc.*, 576 S.W. 2d 21.

78 *Bart Sipriano, Harold Fain, and Doris Fain v. Great Springs Waters of America, Inc., a.k.a. Ozarka Natural Springs Water Co.* (Tex. May 6, 1999).

79 See the Water Rights Adjudication Act, TWC Sec. 11.301, and especially Sec. 11.303.

80 *Sipriano v. Ozarka.*

pump any amount of water from a well situated on his property without regard to the effects on anyone else.[81]

With respect to water marketing, the most serious problem arising from Texas' bifurcated water law has to do with the conjunctive nature of surface water and groundwater: What runs into and out of an aquifer affects the quantity of water in a stream bed. It is possible that well owner could withdraw enough water from an aquifer to significantly alter the natural discharge of groundwater into a river, diminishing the amount of water available to appropriators under a "first-in-time, first-in-right" regime of surface water rights. Moreover, Texas courts have upheld the private property rights of land owners over the rights of those holding permits in state-owned surface water, regardless of how much is taken from the aquifer and how depleted adjacent streams become.[82]

Texas stands as an extreme example of how rights in groundwater can undermine the stability of a water market. The potential third-party effects require no compensation, creating huge externalities that render a market economically inefficient. Most states have avoided Texas' dilemma by including groundwater in their regulatory regimes, or by judicial application of the reasonable use doctrine.[83] The economic effect

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81 If the property lies within a statutory groundwater district, the district can limit the number of wells drilled and may impose restrictions on pumping. One groundwater district, the Edwards Aquifer Authority, has special legislative authorization to issue permits for specific quantities. Significantly, the Texas Supreme Court found that the rule of capture itself provides no basis for a constitutional challenge to the legislative act creating Edwards Aquifer Authority. *Barshop v. Medina County Underground Water Conservation District*, 925 S.W.2d 618 (1996).

82 *Pecos County Water Control & Improvement Dist. No. 1 v. Williams*, 271 SW.2d 503 (Tex. Civ. App. El Paso 1954, writ ref'd n.r.e.).

83 See, for example, Alaska, Colorado, Idaho, Kansas, Montana, Nevada, New Mexico, North Dakota, Oregon, South Dakota, Utah, Washington and Wyoming. Getches, pp. 252-259.

of imposing some rules of liability are to provide some means of compensation for harmful third-party effects, adding a degree of stability to the a state's entire system of water entitlements.

Groundwater in the Rio Grande Valley tends to be saline and constitutes a negligible portion of irrigation supplies. The confounding effects of Texas groundwater law have therefore had little opportunity to inhibit the efficiency of the Rio Grande water market. Historically, the main conflict had to do strictly with surface water supplies that were in dispute between riparians and appropriators. The next chapter focuses on how the court resolved that conflict and on how the specific issues resolved by the court's solution opened the door to water marketing.

Chapter 5: Water Rights in the Valley Today

The appropriative and riparian doctrines of water rights, as was seen in the previous chapter, are fundamentally incompatible and can exist in harmony only when water is so plentiful that either regime would be superfluous. Riparian rights are based on location irrespective of time; appropriative rights are based on earliest use regardless of proximity to the river. When the river level goes down and there isn't enough water to sustain all riparians and all appropriators, space and time run afoul of one another. Claims of place and claims of date have no common ground on which they can be reconciled.

Texas' dual system of water rights collapsed in the Rio Grande Valley during the drought of the 1950s. This "drought of record" — so called because its severity is the standard against which water policy is measured today — created an anarchic water scramble that left state authorities powerless. The policy crisis therefore headed to the courts, which essentially rejected both doctrines in their pure form and created a regime unique to Texas.

This chapter will give a brief history of what happened during the adjudication process, giving special attention to the economically important issues discussed in the previous chapter. One important lesson that comes from the Lower Rio Grande Valley is that if the legal institutions governing water rights and water allocation are flawed, even the best technological improvements can fail to avert a water supply crisis. The discussion then will turn to a detailed description of what the watermaster's office does and how its functions differ from water management in the rest of the state. Particular attention will be paid to the system of accounting used by the watermaster to keep track of water use.

Finally, the chapter will describe how permanent and temporary water transfers take place under the watermaster regime. A detailed descriptive analysis of water leasing ("contract water") will be presented using primary data from the watermaster's office. The findings of this analysis, along with the descriptive analysis of agricultural trends to be presented in the next chapter, will form the basis of the theoretical model to be developed and tested in the final chapters of this dissertation.

The adjudication

The Valley's system of water rights arose out of one of the longest and costliest legal battles in Texas history. Municipalities lined up against irrigation districts and other agricultural interests in Starr, Hidalgo, Cameron, and Willacy counties, with the state (represented by the Texas Board of Water Engineers and the Attorney General) coming down on the side of the municipalities. The state and the cities alleged in their original petition in 1956 that the approximately 3,000 irrigators named in the petition had been taking water from the Rio Grande in such quantities that the health and well-being of residents in cities of the Valley were in jeopardy, and that state regulatory authorities lacked the power to stop it.[1] At one point, an entire release of water from Falcon Reservoir intended for the City of Brownsville was withdrawn by irrigators before it ever got to the city's pumps.

Drought was not the sole cause of the Valley's water crisis, however. In fact, if one defines "drought" strictly as a meteorological phenomenon, it can be plausibly argued that the drought itself had considerably less to do with triggering the crisis than did other factors. While rainfall reached unusually low levels in the 1950s, the crisis was actually one of demand rather than supply. It was severe only in its economic effects and its effects on urban domestic users, due to the rapid expansion of agriculture — and irrigation — during the two decades prior to the dry spell. The drought of record was an economic and agricultural drought more than it was a meteorological drought.

Recall a concluding point made in the previous chapter: that riparian rights and appropriative rights can exist side-by-side only if there is plenty of water available. What created the legal booby trap that exploded in South Texas the 1950s had actually originated in the 1920s, as increasing demands were made on the highly variable water available from the Rio Grande.

Irrigation that the water-wise Spaniards had deemed impossible in the Valley in the 18th century became feasible in the 20th century with the development of powerful diesel and electric pumps. As a result, cultivated acreage in the Valley doubled from 1922 to 1939, which is even

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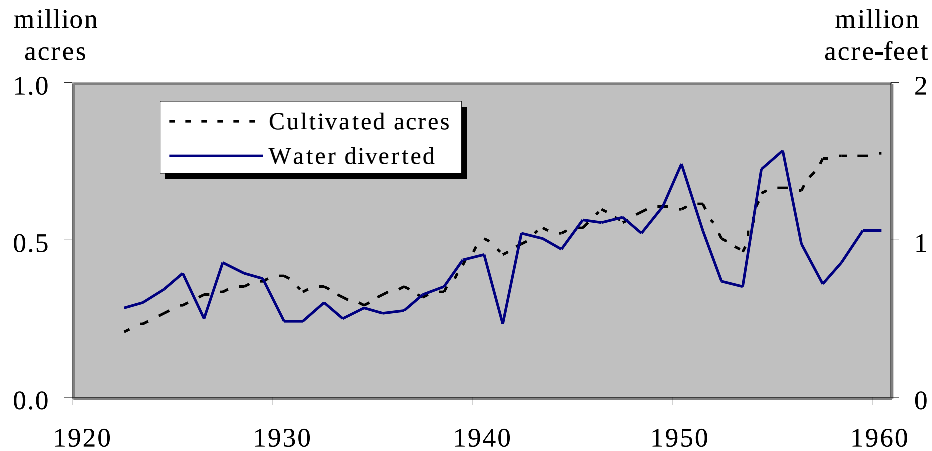
[1] A brief history of the conflict may be found in *State of Texas v Hidalgo County Water Control and Improvement District No. 18 et al.*, [hereinafter *State v. Hidalgo WCID 18*], 443 SW 2d 728 (1969); and in W.L. Matthews and P.H. Swearingen, Jr., "Water Rights in the Lower Rio Grande Valley," report prepared for the Falcon Water Compact by Matthews, Nowlin, MacFarlane & Barrett law firm, San Antonio, Texas, 1957.

Figure 5-1. Growth of agriculture in the Rio Grande Valley



Source: Tate Dalrymple, special watermaster, 93rd district court, "The Water Situation in the Lower Rio Grande Valley of Texas," report prepared for the court, Sept. 20, 1965, p. 22.

more impressive considering that the period was dominated by the Great Depression.[2] By the time of the Lower Rio Grande Valley water suit, cultivated acreage had almost doubled again. Figure 5-1 shows the extent to which agriculture had expanded by the 1950s.

Figure 5-1 also shows how water diversions increased commensurately with cultivation. After factoring out the effects of rainfall, the

[2] International Boundary and Water Commission/Comision Internacionale de Limites y Aguas (IBCW/CILA), *Flow of the Rio Grande and Related Data*, Water Bulletin Nos. 1-39 (Washington, 1930-69), "Diversions from the Rio Grande United States Side below Fort Ringgold, Rio Grande City, Texas," and "Diversions from the Rio Grande United States Side below Falcon Dam"; earlier data taken from Tate Dalrymple, "The Water Situation in the Lower Rio Grande Valley of Texas," McAllen, Texas, 1965.

demand for irrigation remained constant from 1922 to 1930, then increased by about 50 percent over the next two decades up to the time Falcon Dam was completed.[3]

As overall demand increased, the trend in water use intensity dropped from around five acre-feet of water per cultivated acre in 1922 to about four acre-feet by 1933, after which the trend remained steady up to the time of the drought.[4] (Actual data and the computed polynomial trend line are shown in Figure 5-2.) Due to ambiguities in the data, however, the water use intensity trend lends itself to a number of possible explanations. A plausible scenario is that much of the cultivated land added between 1933 and 1951 was not actually irrigated, and that plans to switch acreage from dry-farm to irrigated planting were temporarily stymied by the shortage of water.

These three data analyses clearly show that the Lower Rio Grande Valley's agricultural sector became a coherent economic force only after the Great Depression. The need for water conservation and augmented water supplies in the Valley was therefore very new when U.S. and Mex-

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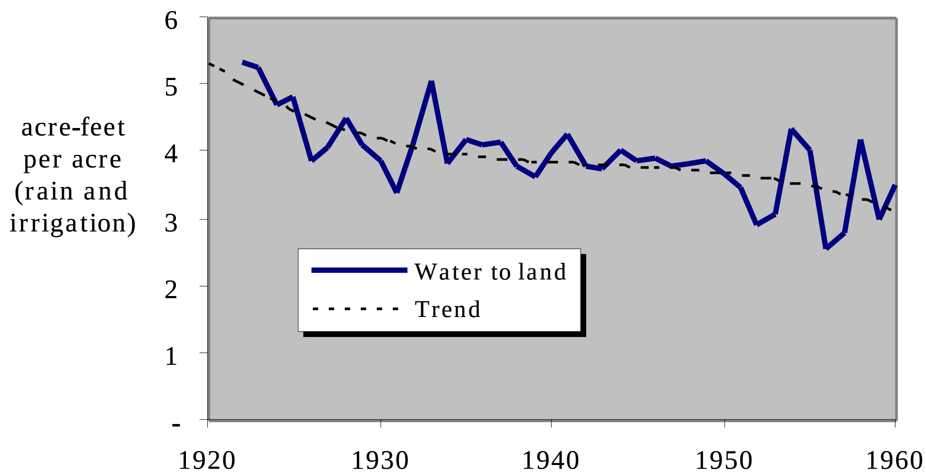
3 To allow for the possibility that different stages of the area's agricultural expansion had different dynamics, the water diversion trend was modelled polynomially, with actual annual diversions as the dependent variable. Independent variables included annual rainfall, a simple trend variable designating the year, a squared trend variable, and a cubed trend variable. All parameters and the intercept were significant at a 0.05 confidence level, with an overall adjusted R^2 of 0.53.

4 As with water diversions, a polynomial regression model was used to examine trends in water use intensity. The set of dependent variables was taken from Tate Dalrymple, special watermaster appointed by the court in the Lower Rio Grande Valley water litigation, who combined river diversions and rainfall into an aggregate index of water use. ("The Water Situation in the Lower Rio Grande Valley of Texas," McAllen, Texas, September 1965.) Dependent variables included a simple trend variable, a squared trend variable, and a cubed trend variable. All parameters were significant at a 0.01 confidence level, with an overall adjusted R^2 of 0.54.

Figure 5-2. Water per acre of cultivated land (U.S. only)



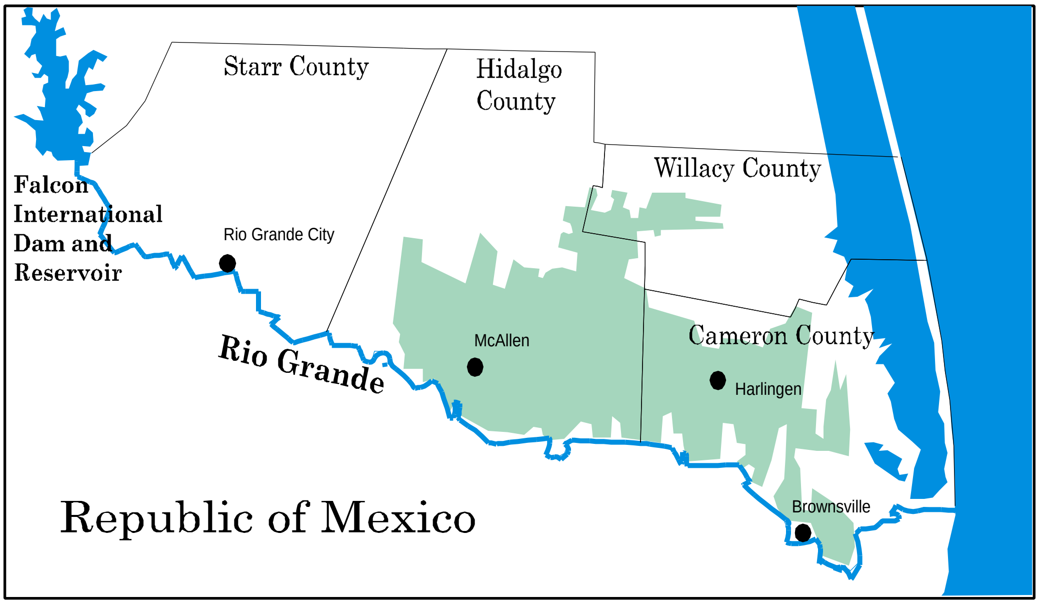
Source: Tate Dalrymple, special watermaster, 93rd district court, “The Water Situation in the Lower Rio Grande Valley of Texas,” report prepared for the court, Sept. 20, 1965, p. 22.

ican negotiators began working out the details of a water resources treaty in the early 1940s. Given the unprecedented pace of agricultural growth, however, the need was as acute as it was new. The wide variation in river flow imposed an increasingly significant risk to the area’s economy.

The U.S.-Mexican water treaty of 1944 was an attempt to deal comprehensively with most water issues involving the countries’ shared river basins: the Rio Grande along the Texas border, and the Colorado and Tijuana rivers in California and Arizona.[5] Under the treaty, the two countries agreed to build up to three dams on the Rio Grande to control

5 Surface water apportionment between El Paso, Texas, and Ciudad Juarez, Chihuahua, was governed by a 1906 treaty, which remains in effect today.

Figure 5-3. Map of Lower Rio Grande Valley



Shaded area indicate irrigation districts. Distance from Falcon Dam to the Gulf of Mexico is about 120 miles.

floods and (more important) to store water so that irrigation and municipal supplies would be less erratic.The first of these three projects was Falcon International Dam and Reservoir, at the upstream end of the Lower Rio Grande Valley (see Figure 5-3).

Although Falcon Dam (along with Amistad Dam north of Del Rio, finished in 1968) is a visible landmark of the treaty, the agreement also constituted a legal landmark. In it, the United States and Mexico mutually abrogated an agreement they'd made almost a century earlier in the Treaty of Guadalupe Hidalgo that neither country would compromise the navigability of the Rio Grande. Construction of irrigation and hydropower works on upstream tributaries had altered the main flow of the river so that it was largely unnavigable by the 1940s. The 1944 treaty affirmed the transformation of the Rio Grande from a stream to be preserved and navigated (an approach congruous with principles of the riparian doctrine) to a stream to be controlled and consumed (which fits decidedly with the doctrine of prior appropriation).[6]

Construction of Falcon International Dam and Reservoir was a binational project executed through the International Boundary and Water Commission (organized under the U.S. Department of State) and its counterpart agency in the Mexican government, the Comision Internacionale de Limites y Aguas. Finished in 1953, the reservoir was designed to store up to 2.8 million acre-feet of water for conservation purposes, 58.6 percent of which was for the United States and the rest for Mexico. The reservoir could also hold an additional 910,000 acre-feet of flood storage once the conservation capacity was filled.

Not only did the treaty provide for dam construction, it also established a system of water accounting between the two countries. Gauging stations are assiduously monitored and documented by IBWC/CILA on a daily, monthly, and yearly basis, with the data used to determine how much water comes into the river (and from where), and who is entitled to it. The physical river thus comprises two separate legal streams from Ft. Quitman south of El Paso all the way to the Gulf of Mexico, with the IBWC/CILA keeping careful account of how large each of the two legal rivers is. This system of international water accounting, along with the hydrological control afforded by Falcon and Amistad dams, has led some to refer to the 1944 agreement as an “engineer’s treaty.”

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6 This aspect of the treaty was emphasized by the court in *State v. Hidalgo WCID 18*.

When the floodgates of Falcon Dam were closed in August 1953 to begin filling the reservoir, the area was into the second year of what turned out to be a record five-year drought. However, unusually heavy rains during six of the next 13 months not only provided temporary relief from the drought, but also filled the reservoir so that U.S. storage quickly rose to 1.3 million acre-feet, near its full U.S. storage capacity of 1.6 million acre-feet. The dam famously accomplished its flood control objective during those unusually wet months of potential flash floods. It remained to be seen how well Falcon Reservoir would serve its water conservation purpose, but with a full supply in storage, it seemed poised for success.

That hope soon vanished as the drought settled in again as irrigators began diverting a record amount of water. Between June 1954 and January 1956, the U.S. store of water in the reservoir dwindled from 1.3 million acre-feet to 710,000 acre-feet. U.S. water users took about 2.6 million acre-feet from the reservoir during the 1955-56 calendar years, while only 1.8 million acre-feet (U.S. share) flowed into it. Appropriators and riparians alike were taking all the Rio Grande's water, leaving little — and sometimes nothing — for cities downstream.

It was against this background of voracious new irrigation demand, an almost-empty reservoir, and prolonged drought that the State of Texas moved judicially to come to the aid of cities in the Valley. While the Board of Water Engineers asked the IBWC/CILA to stop all further U.S. releases, the attorney general petitioned the court to take judicial custody of all the U.S. water in the river and accumulating behind Falcon Dam.

Although the suit was styled "State of Texas v. Hidalgo County Water Control and Improvement No. 18 *et al.*," the real conflict was between irrigators claiming riparian rights and water users claiming rights under state permits. At that time, most irrigation districts held water permits or certified filings, entitlements created under Texas statute. Most of these appropriative rights dated no earlier than 1889, when the Texas Legislature first established laws governing the allocation of surface water in arid areas. But land had been owned in the area from the time it was part of New Spain, and many landowners near the river had claimed riparian rights that predated and superseded any appropriative rights created after 1889.

In addition, both riparians and appropriators were concerned about the volume of upstream water use, particularly by the Maverick County Water Control and Improvement District. A number of water districts in the lower valley filed a cross-action suit against the Maverick district, claiming it was taking more water than its entitlement allowed.

All in all, the legal complaints filed between June and October 1956 documented a complex array of water conflicts: cities versus irrigators; riparian water users versus appropriative users; and downstream users versus upstream users. Texas water law was not up to the task of handling this tangled mass of conflict. The general inadequacy of the state's water law was well-known; former Texas Governor James Allred noted in a 1953 opinion that

> For years it has been a matter of common knowledge that the Texas water laws and decisions are in hopeless confusion; that even if they are as clear as some attorneys profess to believe them, their application and administration would be difficult for an agency clothed with ample authority; that the present state laws, which have been on the

> books without change for decades, confer little, if any, real authority upon the State Board of Engineers; ... that if riparian rights are given the full effect for which plaintiffs contend, practically every drop of water, normal flow or flood, is "bespoken"; that this is particularly true in the Rio Grande Valley...[7]

The crisis that reached a breaking point during the 1951-56 drought demonstrated, among other things, the weakness of water management strategies that rely solely on supply augmentation. International Falcon Dam and Reservoir had become operational a scant two years prior to the suit, making the last 270-mile reach of the Rio Grande about as controlled as any watercourse could possibly be. Indeed, the apportionment between the United States and Mexico was not in controversy, which is a testament to the fact that the "engineer's treaty" was effective as far as its authority reached.

The construction of Falcon Dam was consistent with engineering-oriented U.S. reclamation policies in the first half of the century. Recognizing that growth in the western United States was impossible without reliable water supplies, the federal government embarked on a long-term program of dam building throughout the West. This confidence in supply augmentation solutions to water problems was bolstered by the short-term success in reliably providing water for cities and irrigation. But with the exception of California, all western states had some variation of a purely appropriative system of water rights. The legal instability present in the Lower Rio Grande Valley was not present in most

7 *Martinez v. Maverick County Water Control and Improvement District No. 1*, cited in A.R. White and Will Wilson. "The Flow and Underflow of *Motl v. Boyd*: The Conclusion." *Southwestern Law Journal*, vol. 9 (1955).

projects undertaken by the U.S. Bureau of Reclamation or the U.S. Army Corps of Engineers.

Only after the Rio Grande's U.S. water became Texas water did the legal entanglement begin. The "hopeless confusion" of Texas water law cited by Judge Allred derives from the attributes of the water rights systems discussed in the previous chapter. Taking it a step further, the attributes of the riparian and appropriative water regimes that inhibit a water market are the same ones that led to the crisis in the Valley. This is especially clear when one considers some of the critical points described in the previous chapter: state power that can ensure the stability of claims, and the need to know how much water is controlled under a water right. An additional issue also comes into play: the propensity of irrigators to act on the basis of risk aversion.

State power

Clearly, Texas had little administrative power to avert the crisis; this was in fact why the state sought court adjudication. Although the problems of a water market were probably the furthest thing from the minds of the litigants and the court, the administrative flexibility that might have averted the crisis is also what is needed for an effective water market. What governs the big picture governs the narrower issues as well.

State impotence is in line with how the riparian doctrine contemplates the role of the water administration. Under the riparian doctrine, there is little or no administrative role for the state with regard to water quantity.[8] The issues that most likely arise between riparians have to do

8 Water quality, however, is a different matter. Many riparian states still have administrative rules regarding pollution and effluent discharge.

with whether one's water use is harming another's in some way, which is more a problem of tort than of administrative policy.

Under the doctrine of prior appropriation, the state has a somewhat greater administrative role, but it tends to be highly proscribed. Even though the state Board of Water Engineers was too weak to do anything about the water crisis of the 1950s, its power was essentially in line with what was expected of the state under the doctrine of prior appropriation: to keep account of when claims were filed, and how much water they included.

In a regime of nothing but water permits, the power to grant or deny permits is normally enough to deal with a water crisis because the decision rule — first in time, first in right — is built into the system. But when riparian rights are also present, the little power granted to the state under prior appropriation is insufficient to recover the system's stability when water runs short.

Compare this impotence of state authority with the Spanish system, in which the Crown retained unambiguous authority to delegate administrative power. By relegating individual property rights to a place of secondary importance behind community welfare, Spanish water law allowed audencias and majordomos ample authority to create *ad hoc* solutions in the event of serious shortages. The presence of a military detachment to enforce decisions underscored the ability of the state to exercise its police powers with regard to water.

The rapid agricultural growth that happened a mere two decades prior to the drought created an entirely new set of dynamics affecting water use in the Valley. What might have averted the crisis — and what was needed to guard against its recurrence — was some kind of administrative apparatus that could do what the old Spanish audencias, majordomos, and other arbitrators could do: invent solutions that fit the problem at hand, and enforce them. In the 30s, 40s and 50s, however, the state had no such power.

Questions of quantity

An important characteristic of the two decades preceding the suit was the fact that although the agricultural demands on the water increased for the Valley as a whole, there was no way of determining how an individual's entitlement increased if that person were withdrawing water as a riparian user. Recall that under the riparian doctrine, (a) a land owner may withdraw as much water as needed up to the point that it compromises the ability of other riparians to do the same, and (b) nonriparian uses don't figure into the riparian equation at all (with the exception of rights established by prescription).

But with so much demand coming from irrigation districts whose water rights were largely by virtue of state permits, it was virtually impossible to distinguish between the flows legally destined for the two types of users. This problem was made clear as mud by criteria set by the court in *Motl v. Boyd*, which divided waters between riparians and appropriators on the basis of "normal flow," "underflow," "base flow," "median flow," "flood flow," and similar concepts. Water engineers as well as later courts found the criteria to be unworkable, especially for runoff stored in Falcon Reservoir.

Yet unless the law can distinguish between the two, the inability of riparian rights to quantify entitlements inevitably spills over into permit rights. Although the face value of the quantity covered by a permit may be unchanged, the probability of getting that amount (which is a function of the permit's time priority) becomes utterly unknown. As a result, the expected value of a quantity ostensibly covered by a permit becomes just as ambiguous as a riparian quantity. Unless a riparian's diversion can be limited specifically (which was not the case in the Valley prior to the 1956 lawsuit), the question of quantity can be resolved for no water right holder when supplies are scarce.

Risk aversion

The stark economic risks posed by drought became a hard reality on the Valley's young agricultural sector in the 1950s. Figure 5-2 suggests a trend towards converting more cultivated land to irrigated acreage that was severely disrupted by the drought. Yet the disruption was involuntary; the history of withdrawals by irrigators during the drought show that farmers individually were unwilling to change their cropping plans, and instead attempted to pump as much as they could before the river ran dry.

The situation in the Valley in the '50s was a classic illustration of what Mancur Olson called the "logic of collective action."[9] Based on the Prisoners' Dilemma of game theory, Olson concludes that collective action is difficult to achieve because members of the group have an inherent incentive to willingly violate common rules if they can increase their own welfare by doing so.

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9 Mancur Olson, *The Logic of Collective Action* (Cambridge: Harvard University Press, 1971).

Figure 5-4. The Prisoners' Dilemma

		Choices and outcomes for Prisoner A	
		Don't betray partner	Betray partner
Choices and outcomes for Prisoner B	Don't betray partner	Both get a light penalty, both get the loot later	A goes free with the loot, B suffers a heavy penalty
	Betray partner	B goes free with the loot, A suffers a heavy penalty	Both suffer a heavy penalty, nobody gets the loot

The Prisoners' Dilemma is usually illustrated as a matrix similar to Figure 5-4. The dilemma is that either person is better off betraying the partnership, regardless of what the other partner does. Consider the possibilities and choices facing prisoner A, for example. Prisoner A does not know whether prisoner B will keep silent or betray their partnership. But A does know what the potential outcomes are:

- A knows that if B keeps silent, A will be much better off by betraying B, and
- A knows that if B betrays him, A will be no worse off by betraying B.

For either partner, the probable benefits of betrayal are greater than the probable benefits of remaining true to their partnership. If both follow a rational course of action, each will inevitably betray the other, resulting in what is the worst possible outcome from their combined standpoint: nobody gets the loot, and they both spend a lot of time in jail.

Often, the Prisoners' Dilemma is a metaphor for cooperative management of scarce natural resources. If there is little monitoring and if the penalties for defection are sufficiently small, an individual's self-interest will best be met by letting others carry the burden of compliance while appropriating a greater (and unfair) share of the benefits.

When water becomes scarce, individual users implicitly must weigh the benefits of cooperative drought management with the benefits of taking whatever they can out of the river when it's there. This involves anticipating (a) the likelihood that others would be equally restrained in what they pump, and (b) the likelihood of being penalized for breaking the rules. The lower the likelihood of either, the greater the likelihood of a pumping frenzy in which everyone takes all the water they can regardless of the harm to everyone else. If this is how a typical individual user assesses the situation, then the risk-avoiding strategy would be to jump into the frenzy and pump everything possible before the river runs dry. But collectively, it is the quickest path to depleting all the resources for everybody.

This is in fact what happened in the Valley. Even though mass pumping was the worst alternative, it was the inevitable outcome among a group of mostly new stakeholders trying to minimize individual risks.

Most empirical applications of game theory and Olson's theory of collective action conclude that the most reliable resolution to the dilemma involves: (a) small groups or (b) a strong government acting as a referee. As groups become larger, the need for a strong central enforcer is greater. This is so because individuals will act to minimize their risk. If the expectation is that chaos will dominate institutional rules, individuals will tend to appropriate all they can without regard to the collective good. In the Valley, the number of irrigators had exploded to more than 3,000 within two decades, with no corresponding increase in the power of the state to regulate their actions.

Ostrom argues that the propensity to defection can be overcome by the players without reliance on a strong government if the cost of self-enforcement is small. This describes what was done in Moorish Spain and the Spanish *acequias* of the New World, where members could reduce the risks of "free-riders" by agreeing on rules of behavior, and then hiring a major domo or some other kind of enforcer. But the social institutions that would have facilitated the kind of self-regulation necessary to avoid the water crisis never had a chance to form in the Valley. Most of the agricultural economy was too new. But more importantly, many of the water right holders were acting as riparians, and riparian law is the conceptual scion of individualism rather than community management.

Irrigators, then were not acting maliciously when they virtually drained the Rio Grande in 1955 and 1956. They were doing what any rational person would do in their situation: minimizing the risk of economic loss on the basis of what they knew. The inference: without institutional change to radically reconstitute the risk of various options, the crisis of the 1950s was destined to happen again.

The courts' solution

The approach taken by the district court in the Valley lawsuit was to appoint a special watermaster to sift through the maze of factual details so the court could render a technically informed final decree. It was a step back to the Spanish and Mexican practice of allowing courts the authority to rearrange entitlements based on community benefit and on an appraisal of the situation. Indeed, the watermaster appointed by the court stated a year after the initial ruling that the action of the court was intended to stabilize the economy of the Lower Rio Grande Valley. He noted that "Obviously there is insufficient water available to irrigate all acres wanting water, so some restrictions must be imposed," and further cited the need for a scientific basis of the decision.[10]

Perhaps the most important aspect of the court's role in the case was its refusal to consider itself bound by either riparian or appropriative principles. The appeals court affirmed this need, emphasizing the unprecedented nature of the Valley's water crisis and stating that "the equity arm of a court is not inoperative in the presence of an unprecedented situation."[11] Riparian claims in the Valley had already been invalidated by the *Valmont* decision. The appeals court in *State v. Hidalgo WCID 18* went further by stating that because rights acquired under permits or certified filings "were issued under laws which were adopted in contemplation of free flowing as contrasted with controlled rivers or streams," the "first in time, first in right" principle did not necessarily apply.[12]

The watermaster proposed — and the district court accepted — a resolution based on weighted priorities, taking into account the diverse origins of water rights being claimed. First priority was accorded to all rights originating from certified filings under the 1895 water appropriation law or the 1913 law creating the Board of Water Engineers. Second priority was given to permits filed with the Board between 1913 and the signing of the 1945 treaty that led to the creation of Falcon International

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10 Tate Dalrymple, special water master for the 93rd district court of Texas, "The Water Situation in the Lower Rio Grande Valley of Texas," McAllen, Texas, September 1965, p. 1.

11 *State v. Hidalgo Co. WCID 18*, p. 745.

12 *State v. Hidalgo Co. WCID 18*, p. 744.

Dam and Reservoir. Third priority was granted for a special class of rights arising from the treaty itself, while fourth priority was assigned to all permits issued by the state after the 1945 treaty. Finally, a fifth class of rights was given to miscellaneous claims that arose between the 1945 treaty and the beginning of construction on Falcon Dam at the end of 1950. About 90 percent of all agricultural land affected by the action (and virtually all land covered by irrigation districts) fell under the first two categories.[13]

Most of the water being used was for irrigation, and in most cases the acreage being irrigated was known and documented. The watermaster calculated that, after taking normal rainfall into account, the typical water-to-land ratio was 2.5 acre-feet of irrigation for every acre. Using this number as a basis, allocation to each user in each class was to be determined by a formula: after setting aside 60,000 acre-feet each year for cities and other domestic users, the remaining water would be distributed among irrigators according to weighted proportions, with the per-acre share gradually diminishing from first-priority to fifth-priority users.

The district court's solution factored out the "first in time, first in right" principle altogether. Although the classes designated by the court distinguished between rights acquired under the 1889 law, the 1913 law, and after the 1945 treaty, there was no time priority recognized within these classes. More significantly, the all-or-nothing allocation rule was completely eliminated in favor of a proportional formula that actually bore more resemblance to the riparian doctrine's notion of correlative

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13 *State v. Hidalgo Co. WCID 18*, p. 733.

Table 5-1. Timeline of Lower Rio Grande Water Adjudication

Date	Events
1945	Treaty between U.S., Mexico calls for construction of Falcon Dam and Reservoir; full conservation storage for both countries combined to be 2.1 million acre-feet
1953	Falcon Dam completed, gates closed
1954	Heavy rainfall fills Falcon Reservoir to near conservation storage capacity sooner than anticipated
January 1956	Drought continues; unauthorized pumping diverts an estimated 250,000 a.f. per year from releases
June 1956	Water released from Falcon Reservoir for City of Brownsville fails to reach city pumps because of unauthorized pumping; Texas Board of Water Engineers asks IBWC to close gates of Falcon Dam; state and municipalities sue water districts and other irrigators; court appoints watermaster
September 1956	Other water districts file cross-action asking court to take control of Rio Grande water and adjudicate all water entitlements
October 1956	Court takes jurisdiction of all water in Falcon Reservoir and in Rio Grande below Falcon Dam
1964	Lower court enters adjudication order
1969	Appeals court upholds lower court's adjudication order, with modifications
1971	Texas Water Rights Commission issues rights in accordance with adjudication order
1986	Watermaster's current rules governing the contract water market are incorporated into the Texas Administrative code

rights. Any other semblance of riparian rights, however, had already been rejected by the Texas Supreme Court, and nothing in the district court's formula attempted to revive any right based on river proximity.

Once the district court's decision was entered in 1964, nearly everyone involved appealed or filed countersuit. In 1969 the appeals court accepted the general principles followed by the lower court, making a few modifications to the details of the order. Instead of five classes, the appeals court allowed two: those based on legally executed claims and permits of any type as established by statute, and those awarded on the basis of good-faith use. This latter category, which the court termed “equitable” rights, was an *ad hoc* device designed to right what the court considered an injustice created in the Valley by prior laws. The appeals court maintained the 1.7-to-1 ratio between Class A and Class B users, while eliminating the three intermediate ratios that had been part of the lower court’s five-tier plan. The case was appealed no further.

The appeals court’s affirmation and modification of the lower court’s solution required a much stronger role for the state in the administration of water rights in the Valley. Up until the 1969 appeals court decision, this function had been done by the court-appointed watermaster. After the 1969 decision, the court transferred the watermaster’s office to the Texas Water Rights Commission, which began the process of issuing certificates of adjudication in accordance with the court’s guidelines.

The first of these certificates, which completely superseded any prior irrigation right, were issued in 1971. In all, 870 certificates of adjudication were issued, about 790 of which were for the irrigation of approximately 750,000 acres.[14]

As soon as the court transferred its watermaster operations to the Water Rights Commission, the commission established a deputy watermaster to oversee the middle Rio Grande from the newly completed Amistad International Dam and Reservoir near Del Rio downstream to Falcon Reservoir. The new office, which reported to the Rio Grande

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[14] Texas Water Rights Commission, Thirty-First Report (Sept. 1972 through August 1974), p. 20.; Texas Natural Resource Conservation Commission water rights database.

watermaster, was authorized by the Water Rights Adjudication Act of 1967. Recognizing the seriousness of the water crisis of the 1950s and its potential for happening again elsewhere, the Texas Legislature made a second attempt to adjudicate water rights throughout the state. But whereas the first attempt in 1913 was struck down by the Supreme Court as unconstitutional, the 1967 legislature had the guidance of the district court's decision in *State v. Hidalgo WCID 18* as a guide for the new law.[15] The act authorized the Water Rights Commission to designate a watermaster for a river basin and to adjudicate administratively all rights just as the court had done judicially in the Lower Rio Grande Valley.[16]

In 1986, the Texas Water Commission promulgated rules by which "verified owners of water rights in the Middle and Lower Rio Grande with the right to call on releases from the Amistad-Falcon system may contract for the sale of all or part of their annual authorized amount of use to other water rights holders or their agents in the Middle and Lower Rio Grande, as long as all of the contractual sales rules are complied with."[17]

The Rio Grande watermaster

Although administratively part of the Water Rights Commission and all it successor agencies up to the current Texas Natural Resource Conservation Commission, the Rio Grande watermaster's operations have

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15 The 1967 act withstood a constitutional challenge before the state Supreme Court in 1982. See *In re: Adjudication of the Water Rights of the Upper Guadalupe River Basin*, 642 S.W. 2d 438 (1982).

16 TWC, Secs. 11.451-11.458.

17 Texas Administrative Code, §303.51.

been guided more by the court decisions rather than by state policy. Indeed, given the fact that some of the most basic aspects of Texas water law do not apply in the Valley and the Middle Rio Grande, the office has for the most part operated on a quasi-independent basis.

Water rights operate differently in the lower and middle Rio Grande basin than elsewhere in Texas. These differences are summarized in Table 5-2. Surface water becomes a stock resource rather than a flow resource, meaning that water accumulates and is released on demand, and is not considered part of a continuous flow. The “first in time, first in right” principle ceases to apply because for the most part, the adjudication restarted the clock for everyone in 1971. Nor are senior water right holders guaranteed 100 percent of the amount on their right; all irrigators, even those in the middle basin whose rights were adjudicated later, always get a fixed proportion of whatever amount is available.

There are important differences in administration as well as in water rights. No water can be taken out of the Rio Grande without prior approval of the watermaster; elsewhere in the state, diversions must be reported at the end of the year but need not be approved in advance. Irrigation demand never supersedes municipal demand in the middle and lower Rio Grande; in the rest of the state, a senior irrigation right has preference over a junior municipal right.

The watermaster’s office rarely goes beyond the duties and responsibilities specified in the court decisions. It is concerned strictly with water quantity and allocation; issues of pollution are addressed by another division of TNRCC. Critics sometimes argue that this is a shortcoming of the watermaster program, but in the context of the original water crisis that led to the regime, such a narrow administrative focus

Table 5-2. How water law differs in the lower and middle Rio Grande

Lower and middle Rio Grande	Rest of Texas
Water is a stock resource.	Water is a flow resource.
No time priority.	First in time is first in right.
Burden of water shortage is carried by all irrigators proportionally; municipal water rights always begin each year at 100 percent of face value.	During shortage, senior water right holders get 100 percent of their entitlement, regardless of use, while junior rights are denied.
Municipal water rights are separate from and superior to irrigation rights.	Senior irrigation rights are superior to junior municipal rights.
All diversions from the Rio Grande must have the watermaster's prior approval.	No prior approval is needed; reporting is required at the end of the year.

provides an element of institutional stability that was entirely lacking in the 1950s.

Perhaps the clearest way to understand what the Rio Grande watermaster does today is to think of a bank. Water is the currency, and the depositories are Falcon and Amistad reservoirs. The watermaster acts as the central banker and chief accountant, determining by formula how U.S. share inflow for each month is allocated among water right holders and keeping track of who is entitled to how much of the U.S. water accumulated in the reservoirs.

Two factors enable the watermaster system to work well in the middle and lower Rio Grande. First, nearly all the flow in the Rio Grande below Amistad Reservoir is controlled. Especially in the agriculture-intensive Hidalgo and Cameron counties, virtually no new water enters the main stem of the river unless it is released at Falcon Dam. The hand on the faucet is the IBWC/CILA, but the word to turn it (at least, as far as consumptive use on the Texas side of the river is concerned) must come from the watermaster.

The second factor that makes the regime work is that the rights to the available water are unambiguously defined. Water right holders know on a monthly basis exactly how much water they are entitled to have released to them from the reservoirs. Not only does this pre-empt conflicts between users over who is entitled to what, it also enables users to plan ahead. They can be reasonably certain of how much water they will have over the next year, and so can make longer-term decisions with less uncertainty.

The IBWC keeps daily track of how much water flows into the two reservoirs, and also records the level of the reservoirs on a daily basis. Between these two flows of information, the commission knows with reasonable accuracy how much water is stored in the system at any given time, and how much new water has been added during any given period.

The commission allocates new water to the United States and Mexico according to a formula set by the 1944 treaty. It also keeps a running account of how much water has been released from storage at the behest of each country. At the end of each month, after recording the "deposits" into and "withdrawals" from the two water funds, the IBWC reports to each country how much water it currently has in storage.

By arrangement with the U.S. Department of State, the monthly reports for the U.S. side are sent directly to the Rio Grande watermaster. That same arrangement establishes the watermaster as the agent authorized to request releases of U.S. water held in storage in the two reservoirs.

How water accounting works

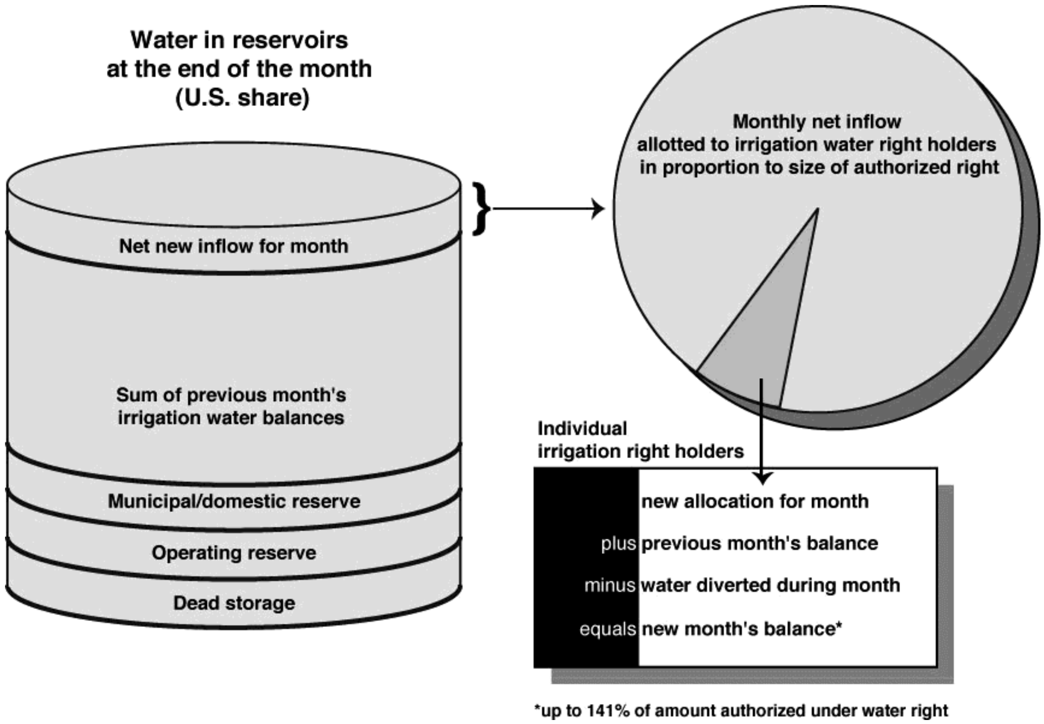
The Rio Grande watermaster's primary job is to keep track of water ownership in the valley. It is a regime different from the rest of the state, created by court order and made possible by the Valley's controlled hydrology. More than 1,100 irrigation rights total about 1.6 million acre-feet of water; municipal and domestic rights total about 245,000 acre-feet.

Because the diversion points along the river are higher than the water level itself, nearly all irrigation water drawn from the Rio Grande must be pumped. The 1969 adjudication and the subsequent amendments authorized by the state restrict the installation of pumps along the river, and all of the pumps are required to have gauges accurate to within 5 percent. The meters are read and records sent to the watermaster's office within five to seven days of each authorized diversion. Any withdrawal must have the prior approval of the watermaster. If the diverter has enough water credits for the requested amount, the request is debited to the account, and the watermaster authorizes the IBWC to release that much water.

Municipal and agricultural users are treated differently in the allocation of new water. At the beginning of the calendar year, each municipal water rights holder's account is replenished to its full amount. No leftover water is rolled over to the new year. If a city runs out of water before December 31, it must buy water from another municipal water right holder or find some other supply.

Agricultural users generally get to carry over their remaining storage balances indefinitely, as long as their water accounts are not com-

Figure 5-5. Water accounting flowchart



Source: Texas Administrative Code, Sec. 303; personal correspondence from Cindy Martinez, Rio Grande Watermaster, July 22, 1999.

pletely idle.[18] Each month, total inflow available for irrigation is divided proportionally among irrigation water rights holders.

Figure 5-5 illustrates the accounting procedure. At the end of each month, the watermaster receives from the IBWC/CILA a statement of

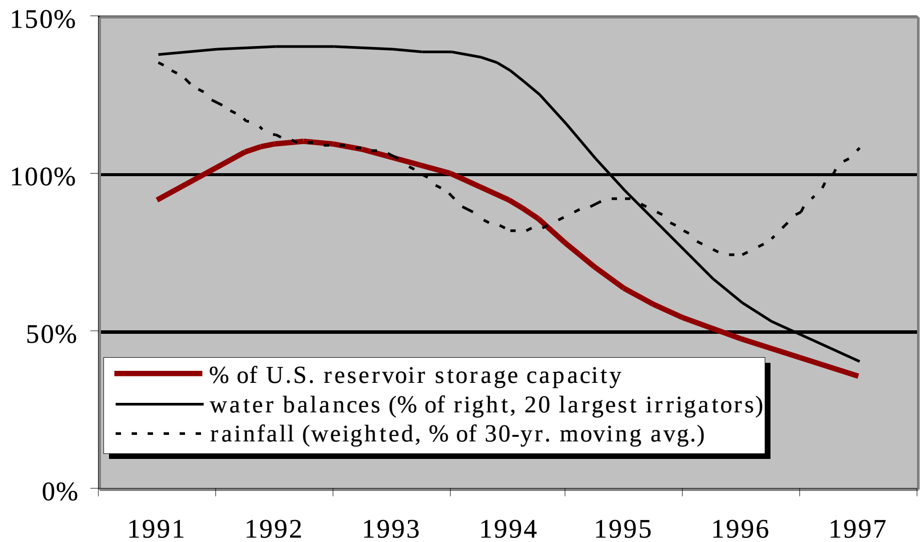
[18] If the water right holder does not put any water to use within a two-year period, the account is reduced to zero and no subsequent allocations are made until the water right holder advises the watermaster that irrigation will resume. An account may also be reduced to zero if the water right holders fails to pay the watermaster's annual assessment. At no time can an account exceed 141 percent of what is authorized by the water right. Personal correspondence from Cindy Martinez, Rio Grande Watermaster, July 22, 1999.

how much U.S. water is in Falcon and Amistad reservoirs. From this total is deducted a fixed amount of dead storage — the amount of water at the bottom of the reservoir that is too low to be released from the dams and is therefore permanently inaccessible. In addition, the Watermaster keeps a certain amount in reserve to cover normal water management requirements, such as transportation losses and other seepage. Then the reserve for municipal use is set aside; this was originally 60,000 acre-feet, but with urban growth and the conversion of some irrigation rights to municipal rights, the current municipal reserve is 225,000 acre-feet.

What remains after these deductions is irrigation water, some of which is leftover storage that has not yet been used, and some of which is new inflow. At this point, the watermaster then adds up the current water balances for all irrigators, and then subtracts this total from the remaining volume. If the amount left over is at least 50,000 acre-feet, it is considered new inflow for the month and allocated among all irrigation right holders on a basis proportional to the size of their authorized water rights. (If the monthly balance is less, it is carried over to the following months until the 50,000 acre-foot threshold is reached.)

Monthly allocations of new water and diversions of stored water are credited to or debited from the water balance for each account. These water balances not only give individual users precise knowledge of how much water they may reliably use in the foreseeable future, it shows water planners how much of a drought hedge they have. Figure 5-6 shows how the aggregate water account balances changed from 1990 to 1996, a time which includes the end of one drought, followed by three very wet years, and then by another severe drought from 1994 to 1996.

Figure 5-6. U.S. water reserves in the Lower and Middle Rio Grande



Note: Balance for any water right holder cannot exceed 141% of the authorized water right.

Source: International Boundary and Water Commission, electronic file of storage levels at Amistad and Falcon Reservoirs provided by Ken Rakestraw; National Weather Service, National Climatic Data Center, "Monthly Surface Data" database TD-3220 (Washington: U.S. Department of Commerce, 1999), tables for McAllen, Brownsville, Harlingen, Rio Grande City.; Rio Grande Watermaster's Office, year-end reports of water balances by all active water right holders, 1990-96.

Of all the 1.9 million acre-feet of irrigation rights in the Valley, 85 percent (or 1.6 million acre-feet) are held by irrigation districts. Another 13 percent (250,173 acre-feet) are in private hands, with the remainder held by federal, state, or municipal governments.

The water market

The stability afforded by the adjudication and by the activities of the watermaster has enabled a water market to evolve and flourish. For the most part, water trading in the middle and lower Rio Grande involves two kinds of transactions whose markets are essentially independent of one another: permanent sales of water rights, and short-term contracts under which the lessor retains the permanent right in full.[19] Permanent water right purchases are most often from irrigators to municipalities and are a function of urban growth and the city's water conservation policies. Most leases are between irrigators and are affected by drought. Recall the above-mentioned differences in the way municipal and irrigation water is allocated: the amount of water available to a municipal right holder is always the same on January 1 of each year regardless of reservoir storage and inflow, while irrigation rights are constantly adjusted according to availability.

Certainty of quantity, a controlled hydrology, and risk reduction make these two markets possible. In fact, the short-term market (so-called "bought-water" contracts) reduces agricultural risk even further by providing an alternative source of water during time of shortage. The one major administrative limitation on water marketing is that bought-water contracts must be for the same use. This prohibits irrigators from leasing water to cities, because such an exchange would involve changing the use of the water from agricultural to municipal. An irrigation

19 There are also a number of long-term contracts between municipal water suppliers and cities. Many of these suppliers are irrigation districts that have permanently converted a portion of their water rights from agricultural to municipal use.

right holder may *permanently* sell all or part of the right to a city, subject to approval by the TNRCC. In such permanent between-use sales, the volume of the right is adjusted once it is converted from irrigation to municipal use. An acre-foot of Class A irrigation converts to 0.5 acre-feet of municipal water rights, while the Class B conversion factor is 0.4.[20]

By far the most aggressive purchaser of permanent irrigation rights has been the City of Laredo, in the middle Rio Grande. Strategic necessity has guided Laredo's water acquisition policy; because it is in the middle reach of the Rio Grande and not in the lower valley, it was not a party to the original litigation or the adjudication process that took place from 1969 to 1971. In fact, Laredo had no water rights of its own prior to 1983, when it began purchasing permanent rights from other cities and irrigation rights holders.

In the early 1990s the Laredo city council authorized its water managers to buy permanent water rights at a converted municipal equivalent of $720 per acre-foot. The city acquired about 6,600 acre-feet of permanent irrigation rights, mostly from Class B irrigators on the other side of Falcon Reservoir in Hidalgo and Cameron counties, and in time the state agreed to convert these to municipal water rights of smaller amounts. By the end of 1997, Laredo had just more than 43,000 acre-feet of municipal water rights, more than any other city in the middle and lower reach.

Most cities have not been as aggressive as Laredo, Eagle Pass, or Brownsville have been in acquiring their own municipal water rights. About half of all municipal rights in the middle and lower reaches of the

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[20] Texas Administrative Code, Sec. 303.43.

Rio Grande are still held by irrigation districts, which contract with cities to provide municipal water supplies.[21]

Bought-water contracts were especially important during the drought of 1994-97. Stored water reached a low point during the summer of 1996, when the U.S. share of water in the two reservoirs troughed at about 800,000 acre-feet — less than 20 percent of Texas' full conservation storage capacity in the reservoirs. During the preceding months, however, a number of allocation mechanisms intervened to shift the burden gradually to irrigators and to protect municipal supplies. Holders of irrigation and mining water rights received no new allocations at the beginning of the year, forcing them to either draw down on their previous stored water supplies or purchase water from others. The total stored water held by irrigators in the Valley and the Middle Rio Grande fell from just over 1.7 million acre-feet to about 1 million acre-feet during the 1995 calendar year, and then to an estimated 300,000 acre-feet by the summer of 1996. This enabled the watermaster to ensure the mandated municipal reserve level of 225,000 acre-feet, and to maintain an operating reserve of 150,000 acre-feet in Falcon and Amistad reservoirs combined.

With no new water allotments coming from the watermaster, irrigators could only turn to each other for new water supplies. About 120,000 acre-feet of water changed hands under contract as irrigators drew down

[21] The Watermaster's rules of operation require that each district's irrigation and municipal water be recorded separately. Intermingling of water from municipal and irrigation accounts, even if held by the same water rights holder, is strictly prohibited. Only permanent changes in use are allowed, and such changes require an amendment to the underlying water rights. A number of the largest irrigation districts have converted a portion of their irrigation rights to municipal water rights in order to satisfy the needs of the cities and towns they supply.

their water balances in 1995 and 1996. Water contracts for irrigation are usually one year in duration; for municipal users, contracts extend to the end of the calendar year. Although each contract must be approved by the watermaster, there are in fact very few market-distorting restrictions on purchases between willing buyers and willing sellers in the process, except that the type of use be the same. The parties are required to report the contract price to the watermaster, but there are no restrictions on the price.[22] The Watermaster's main role is to verify the seller's water balance to make sure enough is in the account to satisfy the contract.

Figure 5-7 shows how active the contract water market has been since 1986, both by volume and by number of contracts. The 1989-90 peak represents about 2 percent of water authorized under irrigation rights; the 1995 peak about 5 percent. The largest-volume transactions during the drought took place relatively early, from the last quarter of 1994 up through the last quarter of 1995. By contrast, the greatest number of contracts occurred from the second quarter of 1995 through the third quarter of 1996, indicating that the market became more frenzied as the drought wore on.

Average prices (shown in Figure 5-8) have been increasing along an annual trend line of about $1.70 per acre-foot per year. Volume makes a difference in the selling price: each 1,000 acre-feet of transaction volume tends to reduce the price by about $1.15 per acre-foot.[23] Table 5-3

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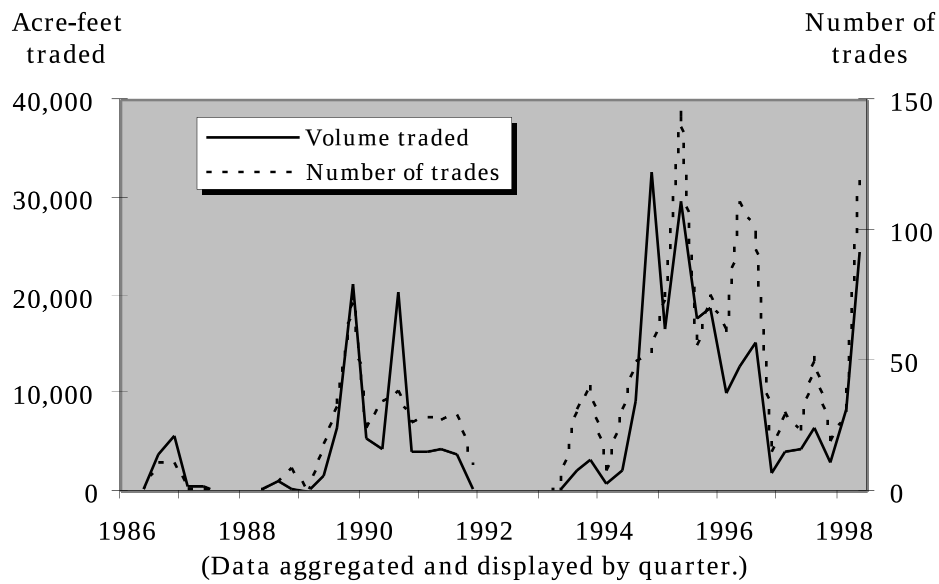
22 Texas Administrative Code, Sec. 303.53(a).

23 The 95 percent confidence interval of the trend parameter is $0.76 and $1.19 per year; and of the volume variable $0.24 and $2.07 per 1,000 acre-feet of water involved in a transaction.

Figure 5-7. Profile of water trading in the Rio Grande Valley



Source: Rio Grande Watermaster's Office, daily records of authorized water contracts, 1986-1997.

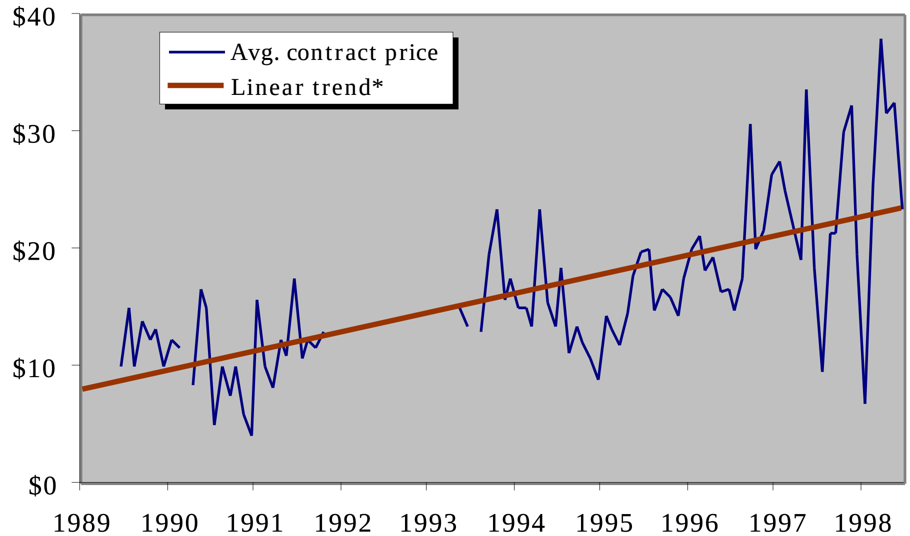
describes some of the dynamics evident in the bought-water contract market during the 1994-96 drought.

There are few obvious trends in the contract market once one looks past the aggregated data. For instance, the sellers with the largest number contracts were not the largest water rights holders, nor were they consistently the holders with the largest water balances. Moreover, of the top ten sellers in 1996, only six were selling water in the most active year, 1995, and only three were selling in 1994.

Conclusions

As a study of water marketing, the Lower Rio Grande Valley and the middle basin are about as ideal as can be found anywhere. The circum-

Figure 5-8. Average prices for bought-water contracts (by quarter)



*R^2 for simple linear trend is 0.45.

stances afforded by the watermaster almost completely fit the conditions described in the theoretical literature for a stable, limited-distortion market. There is only one economic distortion of any significance: the prohibition against lease contracts that involve changing the kind of use to which the water is applied. But so far, there has been plenty of bargaining room within the irrigation and municipal sectors separately.

The reason the area is such an ideal water market study area is that it is stable in the crucial points outlined in the last chapter. Not only is ownership of a right stable and largely beyond challenge, but the right is unambiguously quantifiable; all right holders know exactly how much water they control. The state — in this case, the watermaster — upholds rules of procedure that are open to all, and basic information about the market is available to all.

Table 5-3. Highlights of spot market for irrigation water, 1994-96

Period	Activity	Average price
4th quarter 1994	Market was narrow, focussed. Volume of water that traded hands was high, but the number of trades was low.	$12
2nd quarter 1995	Market was broad and active. Both volume of water and number of trades was high.	$20
3rd quarter 1995	Market was lethargic. Trades fell both in number and in total water volume.	$15
2nd-3rd quarters 1996	Market was active again. Volume traded and number of trades increased. Sharp price rise.	$15 to $23
4th quarter 1996	Market was exhausted. Volume and number of trades plummeted to pre-drought levels as water balances diminished.	$25

Water rights in the lower and middle Rio Grande are stable because of the exhaustive, comprehensive adjudication that swept away a system of water rights that was unworkable. By rejecting the precedent both of the riparian system and of prior appropriation, the court was able to fashion a new regime that was suited to the circumstances of the area. The adjudication dissolved the ambiguities and contradictions in prior law that stymied water management and, not coincidentally, rendered water marketing impossible.

Just as water marketing cannot be considered in isolation from its legal environment, neither can its results or its attributes be studied without taking into account prior agricultural practices and the dynamics of the farm sector. The trades shown in Figure 5-7 and Figure 5-8 all began and ended with some sort of agricultural objective, conditioned at least in part by previous history of irrigation practices. The next chapter will add that piece of the picture.

Chapter 6: Agricultural water use in the Lower Rio Grande Valley

The ultimate aim of modern water conservation policy is to use less water to do more things. So to see whether a policy has succeeded as a water conservation strategy, the first place to look is total water consumption and area-wide patterns: has water use indeed gone down? The political appeal of water marketing is that it uses the incentive of profit to encourage voluntary conservation by farmers, who may then sell what they save to cities and other users. Given that about 85 percent of the surface water used along the Rio Grande in Texas is for irrigation, the potential gains for the region's growing urban population are substantial.[1] But if the total amount of water applied to irrigation does not go down, then the question of shifting residual water to cities or to anywhere else is moot. There *is* no saved water to transfer to the municipal sector.

The purpose of this chapter is to examine the overall patterns of water use in the Lower Rio Grande Valley. What happens *between* water users will be examined in the next chapters, but for now, it is important to find out exactly what broad outcomes needs to be explained. If the economic efficiency of a water market is supposed to promote conservation,

1 Texas Water Development Board, *Water for Texas* (Austin, Texas: 1997), p. 3-181.

is there any empirical suggestion that irrigation has indeed been used more sparingly throughout the Valley as a whole since the regime permitting water marketing was created?

The critical time of interest begins in 1971. That is when the 1969 court decision was finally administered by the Texas Water Rights Commission, and when the watermaster became an agency of the state rather than an agent of the court. Only after that point were rights indisputable, clearly quantified, and monitored — all conditions of stability that are prerequisite to a regional water market. A second key juncture was in 1986, when water marketing — selling a quantity of water to another user while retaining the permanent rights — was formally institutionalized by the promulgation of administrative rules. Once these rules were in place, water trading took place at higher volumes and among more parties.

Two things will be accomplished in the exploratory analysis of this chapter: a description of current and historical water use, and clarification of the questions to be taken up in the next chapter with a more rigorous analysis. The Valley's agricultural sector is dynamic, and almost from its inception has been responding to technological change. The adjudication and more recent trade-driven population growth have affected agriculture, and to understand these changes one must first take careful stock of how water has been used during the time water marketing has been an option.

The indicator for conservation used throughout this study is water intensity: How many acre-feet of irrigation are applied per acre of farmland? If, as many theories predict, a viable market promotes water-saving practices among irrigators, then the first and most important question to ask is whether or not water intensity is indeed falling. The data presented in this chapter suggest that on the whole, applied water per acre is not decreasing; if anything, water intensity under the water marketing system has *increased*. This does not necessarily mean that economic theories are wrong, but it does demonstrate clearly that a naive application of such a framework does not fit the facts.

The Texas Department of Agriculture defines the Lower Rio Grande Valley as comprising Cameron, Hidalgo, Starr, and Willacy counties. About 375,000 acres — roughly one-third of the Valley's total cropland — are irrigated during a normal year. The largest share is in Hidalgo County (about three-fifths), with most of the remainder in Cameron County (about one-third). Soil conditions and terrain make productive irrigation difficult in Starr County, while in Willacy County the constraint is lack of direct access to the river.[2] Starr and Willacy counties together account for only one-twentieth of acreage actually irrigated. These between-county proportions have remained fairly constant throughout the past three decades.

According to the terms of the adjudication, a total of 690,000 acres are legally entitled to irrigation.[3] In practical terms, this figure is little more than an accounting device used by the courts and the Texas Water Rights Commission (TNRCC's predecessor agency in 1971) in determining the relative volume of the adjudicated water rights, as described in the previous chapter. The amount of water included in each irrigation

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2 Willacy County is the only county in the Valley that does not front the river and is technically outside the Rio Grande drainage basin.

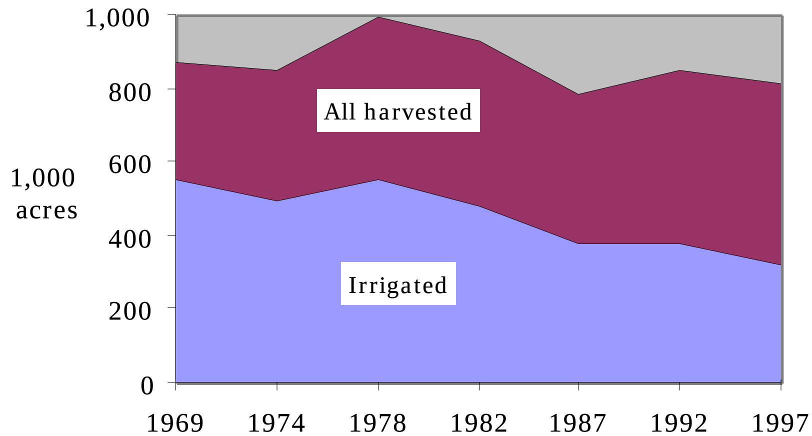
3 Texas Natural Resource Conservation Commission, Texas water rights database, 1997.

right was determined by the amount of irrigable land held by the claimant, multiplied by 2.5 feet for class A rights, and 1.47 feet for class B rights.[4] In the case of irrigation districts, acreage was determined by the area covered by the district. In the case of private rights holders, it was the farmland that historically had been irrigated by the holder at the time of the adjudication. Thus even though it is used as an accounting device, the authorized acreage specified in a water right may be taken as a reasonably good indicator of farmland that *can* be irrigated, even though much less actually is irrigated during any given year. This is especially true for irrigation districts. Land owners contiguous to an irrigation district who do not wish to irrigate will usually opt to exclude their property from the district in order to avoid being taxed by the district. This tends to minimize any land within a district that is in fact not irrigable.

Most municipalities in the Valley are almost entirely surrounded by irrigation districts. When urban growth absorbs farmland and the acreage is zoned for something other than agricultural use, the land is no longer irrigable. Many irrigation districts also supply water to municipalities, however, so when a city they serve takes over some of the farmland they used to supply with irrigation, the district petitions the TNRCC to convert that portion of its water right from agricultural to domestic use. This reduces the acreage authorized for irrigation under the water right, with the severed amount either shifted to the district's municipal water right or sold to the city as a permanent right. In the conversion, an acre-foot of a Class A irrigation right becomes 0.5 acre-

[4] Land area (in acres) times depth of irrigation (in feet) defines volume in acre-feet.

Figure 6-1. Harvested and irrigated acres in the Rio Grande Valley



Source: U.S. Census Bureau, *Census of Agriculture* (Washington: 1969, 1974, 1978, 1982, 1987, and 1992); U.S. Department of Agriculture, *Census of Agriculture* (Washington: 1997).

feet of municipal rights, while an acre-foot of Class B becomes 0.4 acre-feet of municipal rights.

The reduction of irrigable acreage has in fact been rather slow, happening at an annual rate of only 0.1 percent since the original certificates of adjudication were issued in 1971.[5] During that same time, however, land actually irrigated dwindled at a much faster rate of 1.6 percent annually.[6] Figure 6-1 shows that the 322,000 acres being irri-

5 Based on a sample of 19 irrigation districts representing 77 percent of all authorized irrigation. This urbanization trend is revealed in the water rights amendments approved since 1971 by the TNRCC and its predecessor agencies.

6 U.S. Census Bureau, *Census of Agriculture* (Washington: 1969, 1974, 1978, 1982, 1987, and 1992); U.S. Department of Agriculture, *Census of Agriculture* (Washington: 1997) Average annual rate of change between census periods.

Table 6-1. Number of farms in the Rio Grande Valley, 1969-97

	1969	1974	1978	1982	1987	1992	1997	Annual trend
Harvesting farms	5,927	4,265	4,095	3,280	2,759	2,246	1,954	*-3.5%*
Irrigated	4,649	3,217	3,581	2,770	2,175	1,724	1,566	*-3.2%*
Not irrigated	1,278	1,048	514	510	584	522	388	*-3.5%*

Source: U.S. Census Bureau, *Census of Agriculture* (Washington: 1969, 1974, 1978, 1982, 1987, and 1992); U.S. Department of Agriculture, *Census of Agriculture* (Washington: 1997).

gated in the Valley in 1997 compares with more than 549,000 irrigated acres in 1969.

Table 6-1 shows that number of irrigated farms has fallen at twice the rate of irrigated acres, indicating that time is taking its greatest toll on small farmers. In addition, the farms that are dropping out over time tend to be the ones not irrigating. Mid-sized and large farms acquire many of these closures, resulting in a gradually increasing number of farms larger than 500 acres.

The remainder of this chapter rounds out the general picture just sketched of irrigation in the Lower Rio Grande Valley. First, data on water use per acre, or water intensity, will be examined. Then building on inferences drawn regarding irrigation intensity system-wide, the analysis will look at cropping patterns. Correlating the clearly discernible changes in crop acreage with changes in water intensity will suggest features of a model for water market behavior that will be explained in the next chapter.

Changes in water intensity

Water intensity for irrigation in the Valley is low compared to the farm areas of the Gulf Coast and eastern Texas. On a per-acre basis, the Valley's agricultural sector uses about one-quarter of the water used in the Lower Colorado River Basin, which relies on surface water to irrigate its principal crop, rice. But even if water intensity is less in the Rio Grande Valley than elsewhere in the state, the more important question for this inquiry is whether there has been a clear trend towards less water intensity since the region's water market accelerated in the mid-1980s.

No reliable data set maintained by any agency matches irrigation with crop acreage by farm or by individual water right holder. Nor are any time-series data kept on the acreage actually irrigated under a water right. What is available are data on water diversions by right holder, irrigable acreage by right holder, and crop acreage by county.

The most useful time-series measure of irrigation intensity that can be constructed from the available data is water diverted per acre of irrigable land for the largest water users. In this case, the largest water right holders are irrigation districts, ten of which account for about 60 percent of all irrigation rights in the region by volume.[7] Continuous and

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7 The group includes Cameron County Irrigation District No. 2, Cameron County Irrigation District No. 6, Delta Lakes Irrigation District, Donna Irrigation District, Harlingen Irrigation District, Hidalgo Irrigation District No. 1, Hidalgo Irrigation District No. 2, Hidalgo Irrigation District No. 6, Hidalgo and Cameron Counties Irrigation District No. 9, and La Feria Irrigation District. Annual diversion data provided on hard copy by the Rio Grande Watermaster's Office.

reliable water use data exist for these 10 districts beginning in 1978. Irrigable acreage for each is represented by the water right itself, which specifies the amount of acreage covered. This includes all land that can be irrigated within a district, regardless of how it is actually used during any given season. A reduction in water use per acre under this measure could represent conservation through improved irrigation efficiency or through simple non-use of irrigation, in the form of dry-farming or fallowing.

Table 6-2 describes the trend in irrigation intensity for these districts. The model providing these results combines information cross-sectionally and by time. The dependent variable, feet of irrigation, is defined as the amount of water an irrigation district takes from the river per acre of irrigable land (acre-feet per acre) each year. Annual diversion data were obtained from the Rio Grande Watermaster, and land data taken from the districts' water rights as amended over the 21-year period. Twenty-one yearly observations for ten districts yield a data set comprising 210 observations.

Irrigation was then regressed against four system-wide variables: rainfall, an annual trend variable, a dummy variable indicating the time of formal water trading, and an interaction variable to reflect how the trend differed during the market period. Annual rainfall was calculated by weighting each month's recorded precipitation according to the month's relative importance to agriculture, as described in Equation 3-1 on page 61. The value for the dummy variable *market* was tied to the year following the promulgation of formal procedures for the region's water market, with 1 designating observations for 1987 or later.

Table 6-2. Trends in irrigation intensity for 10 major irrigation districts, 1987-98

Model: Irrigation[a] = Intercept + Rain + Trend + Market + Trend × Market +

$$\sum_{i=1}^{9} ID_i + \sum_{i=1}^{9} ID_i \times Trend$$

N=210 (21 years, 10 irrigation districts)
Adjusted R^2 of model: 0.41

System variables	Coefficient	T-statistic
Intercept	**2.37**	**10.46**
Rain[c]	**(0.71)**	**(5.39)**
Market[d]	**(0.43)**	**(2.34)**
Trend[e]	**(0.06)**	**(2.85)**
Trend x Market	**0.07**	**3.52**

Boldface type indicates variables significant at the 95 percent level or higher.

District variables[b]	Coefficient	T-statistic
ID_1	0.41	1.66
ID_1 × Trend	(0.01)	(0.46)
ID_2	**0.57**	**2.34**
ID_2 × Trend	(0.03)	(1.46)
ID_3	**0.80**	**3.24**
ID_3 × Trend	**(0.05)**	**(2.42)**
ID_4	0.15	0.61
ID_4 × Trend	(0.00)	(0.12)
ID_5	**0.97**	**3.95**
ID_5 × Trend	**(0.05)**	**(2.39)**
ID_6	**0.98**	**3.99**
ID_6 × Trend	**(0.06)**	**(2.88)**
ID_7	0.38	1.57
ID_7 × Trend	**(0.05)**	**(2.64)**
ID_8	0.09	0.37
ID_8 × Trend	(0.00)	(0.13)
ID_9	(0.01)	(0.05)
ID_9 × Trend	(0.01)	(0.56)

[a] Feet of irrigation withdrawn during the year by an irrigation district. Calculated by dividing the district's irrigation withdrawals as recorded by the Rio Grande Watermaster (in acre-feet) by the amount of irrigable acreage in the district as shown by the district's water right.

[b] ID_i is a dummy variable that is 1 if the observation is for irrigation district *i*, and 0 otherwise.

[c] Feet of precipitation per year, with each month's total weighted according to the method detailed in Chapter 7.

[d] Dummy variable indicating period of formal water contract market; 1 if observation is for 1987 or later, 0 otherwise.

[e] Annual index, with 1 designating the year 1978.

The model also included district-specific dummy variables to allow for significant individual deviations from the system-wide trends. Initially, three sets of interaction variables were included along with the simple indicator ID_i: $ID_i \times trend$, $ID_i \times market$, and $ID_i \times market \times trend$. (The index *i* designates a unique irrigation district.) These interaction variables were included to detect significant between-district variations in trends overall, differences in initial conditions at the time the market started, and differences in trends during the water marketing period. None of the individual variables in the $ID_i \times market$ set nor in the $ID_i \times market \times trend$ set was significant, suggesting that no individual district reacted to the water market any differently than the others did. These two interaction variable sets were therefore omitted from the model, and with only slight consequences. The overall adjusted R^2 was virtually unscathed, falling from .421 to .416, while the explanatory power of the remaining variables was greatly enhanced. On the other hand, when *market* and $market \times trend$ were dropped from the model also (that is, when all market-coincident effects were excluded), the explanatory power of the overall model dropped as the adjusted R^2 fell to .38.

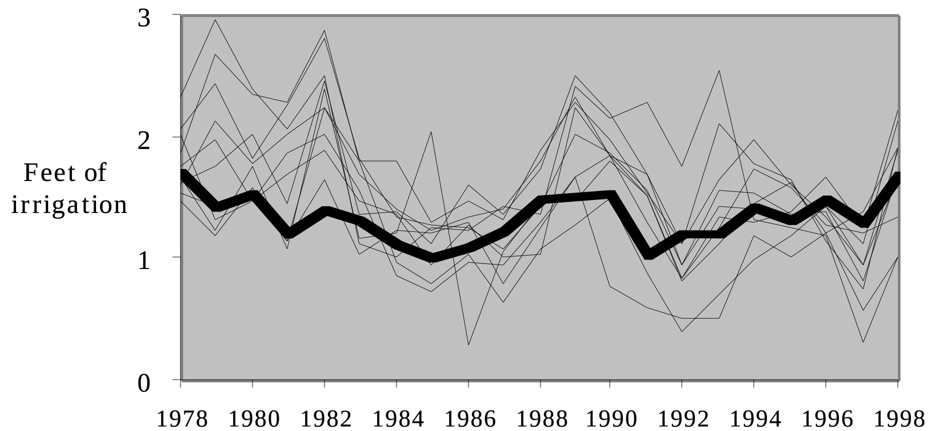
To test for sensitivity, the model was run three times using different assumed starting points for the water market period: the year prior to the promulgation of formal rules (1985), the year the rules were effected (1986), and the year afterwards (1987). The run for 1987 yielded the highest adjusted R^2 statistic (.42, compared with .41 for 1985 and 1986), suggesting that the effect of the institutional change was lagged by a year. This may be explained intuitively by the time required by farmers and their representatives to learn how the new rules for water trading worked. Although the run using 1985 as the transition point had an adjusted R^2 similar to that of the 1986 run, the trend variables were not statistically significant.

The intercept term carries a particularly interesting insight. It suggests that these ten districts, which make up the lion's share of all preferred (Class A) irrigation rights as defined by the court in 1969, were actually using *less* water than the court assumed they would require when the final decree was entered. The court fixed Class A irrigation rights at 2.5 feet (acre-feet of water per acre to be irrigated), but the intercept in this regression model suggests that in 1977, these districts were irrigating at a rate of only 2.37 feet *before* taking rainfall into account. (For 1977, the variable *trend* would be zero, as would *market*.) The parameter for the binary *market* indicates a conservation gain by 1987, with predicted irrigation in the complete absence of rain down to 2 feet.[8] From 1987 onward, however, the predicted irrigation intensity increases at a net rate of .01 feet per year (the combined parameter values of *trend* and *trend* × *market*). Figure 6-2 graphically compares the predicted trend line with the actual irrigation levels of the districts included in the analysis.

Up to the time formal rules for water marketing were instituted, the conservation picture seemed to be improving in the Lower Rio Grande Valley. This is seen in the fact that the coefficient for *trend* is significant and negative. But the prior trend towards greater conservation was offset by a statistically significant shift in the other direction after 1987,

8 For *market* to be 1, *trend* must be at least 10 because the market began in year 10. So the predicted system-wide irrigation level exclusive of rain in 1986 would be the intercept, plus the parameter for *market*, plus 10 times the parameter for *trend*, plus 10 times the parameter for *trend* × *market*.

Figure 6-2. Actual and predicted irrigation intensity by 10 major irrigation districts



Thin lines represent actual values for the 10 irrigation districts included in the analysis. Heavy line is the trend predicted by the regression model described in Table 6-2, given actual rainfall levels. Source for irrigation used by districts: Rio Grande Watermaster's Office, annual water use reports for irrigation account holders, McAllen, Texas, 1978-98. Source for districts' irrigable acreage: District water rights and amendments, TNRCC water rights database, Austin, Texas, 1999.

as shown by the interaction variable *trend* × *market*. The positive slope of this coefficient clearly shows that these districts on the whole began to use more water per acre of irrigable land once the market was formally institutionalized and trading began in larger numbers. Of course, the statistical relationship is insufficient to establish causality; we cannot tell from the numbers alone whether farmers started irrigating more *because* of water marketing. But we may be fairly sure that the water market did not cause additional conservation, because the conservation that had been taking place disappeared.

The variable sets ID_i and $ID_i \times trend$ show the manner in which individual districts deviated from the group pattern. Four of the districts started the period with an irrigation intensity demonstrably greater than the norm — from half a foot to a foot higher. But three of these four — the districts indexed 3, 5, and 6 in Table 6-2 — were progressing towards water conservation twice as fast as the group norm, a pace that was enough to keep them from backsliding after 1986. One other district was also progressing at a significantly faster rate.

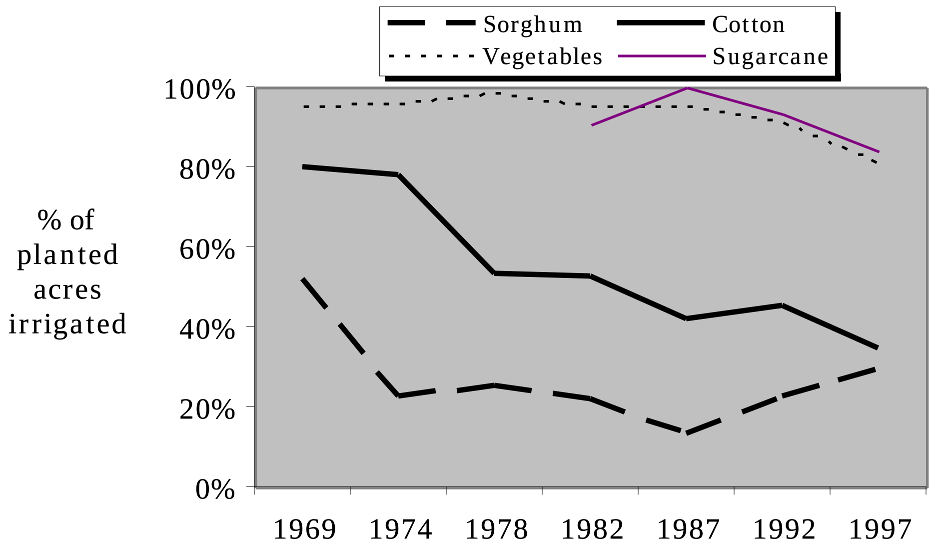
To adequately explore why the general conservation trend may have stopped — and to see whether the water market plausibly had anything to do with it — it will be helpful to take a more comprehensive look at how crop mix in the Valley has changed over the years.

Crop mix on irrigated land, 1970 to present

Changes in water intensity don't happen in isolation. Farmers use more or less water per acre because they are growing crops with different water requirements, or because they are irrigating differently. This section looks at data on cropping patterns in the Rio Grande Valley to see what farmers are doing differently, and why. Data come from the Department of Agriculture, which keeps annual data by county, and from the five-year Census of Agriculture.

Figure 6-3 gives some insights into how irrigation intensity as modeled in Table 6-2 may have changed. Recall that water per irrigable acre (as opposed to acres actually irrigated) can change due to increased technological efficiency or to greater non-use of irrigation. Data from the Census of Agriculture point to the latter explanation. An increasing amount of acreage planted in the Valley's two largest crops — cotton and sorghum — was being dry farmed up to the time the water market began to gain momentum. This strongly suggests that the conservation taking

Figure 6-3. Proportion of planted acreage that is irrigated

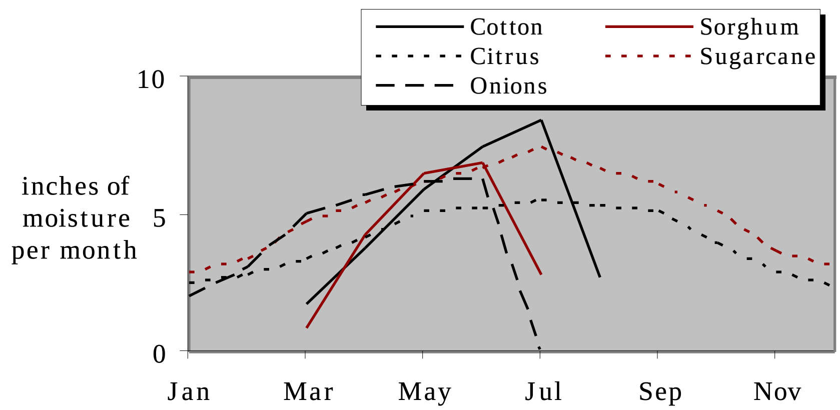


Source: U.S. Census Bureau, *Census of Agriculture* (Washington: 1969, 1974, 1978, 1982, 1987, and 1992); U.S. Department of Agriculture, *Census of Agriculture* (Washington: 1997).

place up to the mid-1980s was due to dry farming, and not necessarily to the installation of water-saving irrigation technologies. The trend towards more dry-farmed cotton and sorghum bottomed out when the water market became formalized.

Increased dry-farming freed up irrigation for other uses. The data clearly show the dynamics of how agriculture in the Valley is becoming more water intensive. Proportionately more of the area's principal crops are being dry farmed, while cultivation of water-intensive cash crops such as sugarcane is increasing. Water is migrating from sorghum and cotton to sugarcane and to a lesser extent, vegetable crops such as onions.

Figure 6-4. Crop water requirements, Lower Rio Grande Valley



Source: Calculated for the Lower Rio Grande Valley using procedures detailed in John Borrelli, Clifford B. Fedler, and James M. Gregory, *Mean Crop Consumptive Use and Free-Water Evaporation for Texas* (Austin, Texas: Texas Water Development Board, 1998)

Evapotranspiration, or ET, is often used as a relative measure of a crop's water intensity. (A more detailed discussion of evapotranspiration will be taken up in Chapter 7.) Figure 6-4 shows the monthly ET indices for the four major crops in the Lower Rio Grande Valley. Cotton — whether irrigated or dry-farmed — has an annual ET of about 2.5 feet, which not coincidentally is approximately the same value as the coefficient derived by the special watermaster in 1967 and accepted by the court in 1969 to determine how much water a bona fide Class A irrigator was entitled to.

Notice that all the water demand for cotton and sorghum occurs from March to August. Citrus, while not needing as much water as either cotton or sorghum during the peak months, has year-round water requirements. So on an annual basis, citrus requires about 4 feet of water (5 if weed control isn't practiced), compared to cotton's 2.5 and sorghum's 1.7. Sugarcane, which also requires water year-round, needs 5.1 feet annually. Spring onions, with an annual ET of 2.4, have a water demand that is shorter but more intense than any crop except cotton.

The water demand patterns shown in Figure 6-4 illustrate why irrigation demand is so high in June. Sorghum and onions are at their peak water demand, while cotton's ET, though not at its peak, is nevertheless higher than that of any other crop.

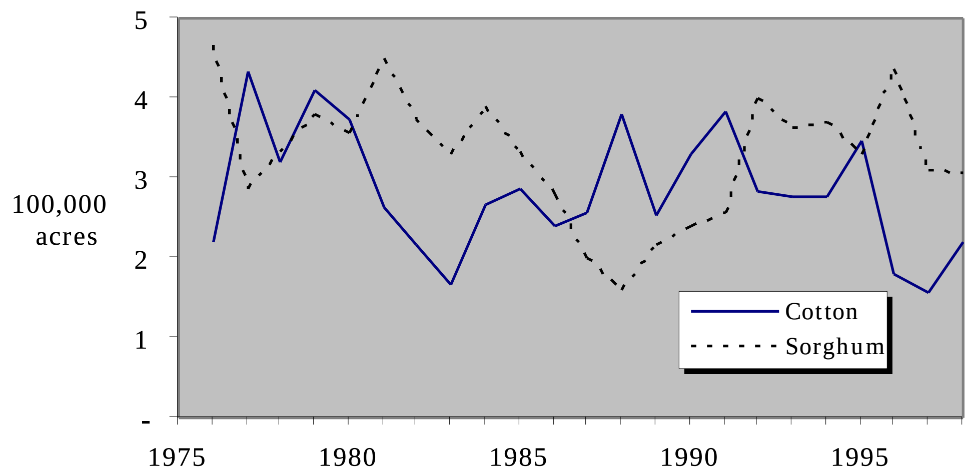
Sorghum and cotton

Sorghum and cotton are the valley's two largest crops in terms of acreage and production. Figure 6-5 shows the acreage planted in the two crops since 1972. Cotton and sorghum tend to run countercyclical to each other, with a mean combined planted area of about 710,000 acres.

Before the adjudication and the firm establishment of water rights, about half of the valley's sorghum crop and four-fifths of its cotton crop were irrigated. By 1974, just three years after the certificates of adjudication were issued, irrigated sorghum had fallen to about one-quarter, with the downward trend continuing at a rate of about 1.2 percent annually. Irrigated cotton stayed at its 1969 level, but then dropped to about half of planted acreage in 1978 and then continued to fall by about 3 percent annually.

Figure 6-6 and Figure 6-7 illustrate the relative return on investment for cotton and sorghum in the Valley. Both tend to be small-profit,

Figure 6-5. Lower Rio Grande Valley acreage in sorghum and cotton



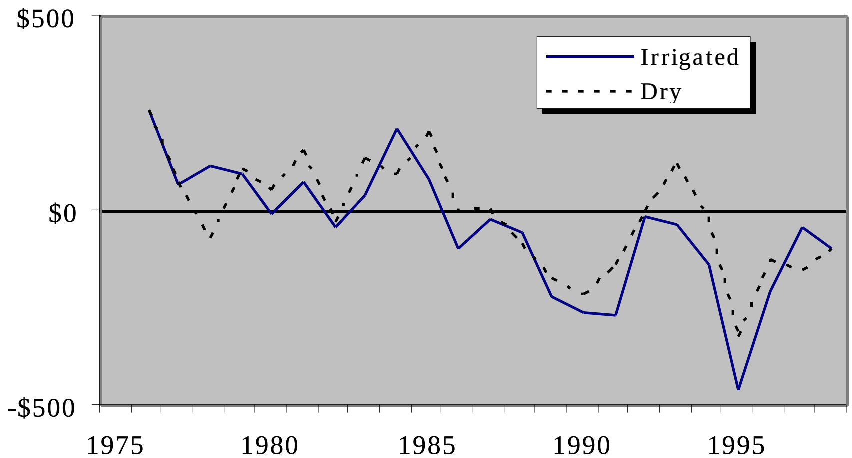
Source: National Agricultural Statistics Service, "Crop County Data" database (Washington: U.S. Department of Agriculture, 1999), tables for cotton and sorghum, 1972-98.

small-loss, low-cost crops that require less capital (as well as less water) than citrus or sugarcane.

Price fluctuations have hit cotton and sorghum farmers hard since the mid-1980s. The losses both crops experienced during the drought of the late 1990s have been due to poor prices rather than to poor yield. Cotton farmers were hammered by drought related losses in 1998, but what set them up for it was a slump in prices. Farmers in the Valley show a strong tendency to irrigate a smaller proportion of their cotton crops as the price of cotton goes down.[9] So when prices fell below their 20-year, inflation-adjusted average of 82 cents per pound to 65 cents,

9 The coefficient of correlation between percentage of planted cotton acreage irrigated and the inflation-adjusted price of cotton from 1976 to 1998 is 0.69.

Figure 6-6. Average return per acre, cotton

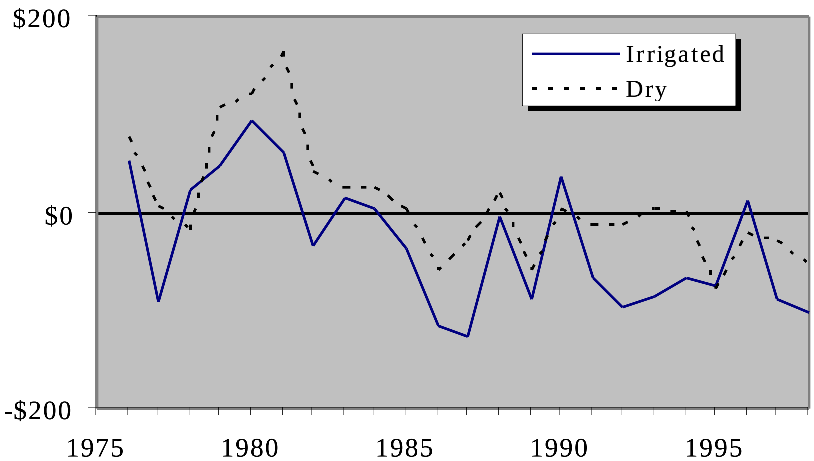


Calculated by multiplying yield by crop price (in 1998 dollars), and subtracting 1998 per-acre production costs. Prices exclude government subsidies. Sources: National Agricultural Statistics Service, "Crop County Data" database (Washington: U.S. Department of Agriculture, 1999); NASS, "Prices Received by Farmers for Field Crops" database (Washington: USDA, 1999); Texas Agricultural Extension Service, "Projected Costs and Returns per Acre, South Texas District, Cotton" (Weslaco, Texas, 1998).

cotton farmers cut costs by planting dryland crops rather than irrigated crops. This additional exposure left them highly vulnerable to drought, which hit with severity in 1998.

Even though irrigated crops have suffered more losses than dry-farmed crops, yields have tended to be more stable for irrigated crops. For sorghum, an average irrigated crop produces almost 50 percent more yield per acre, and with half the variance, when compared with the average dryland crop. The contrast is less pronounced for cotton, however.

Figure 6-7. Average return per acre, sorghum



Calculated by multiplying yield by crop price (in 1998 dollars), and subtracting 1998 per-acre production costs. Prices exclude government subsidies. Sources: National Agricultural Statistics Service, "Crop County Data" database (Washington: U.S. Department of Agriculture, 1999); NASS, "Prices Received by Farmers for Field Crops" database (Washington: USDA, 1999); Texas Agricultural Extension Service, "Projected Costs and Returns per Acre, South Texas District, Sorghum" (Weslaco, Texas, 1998).

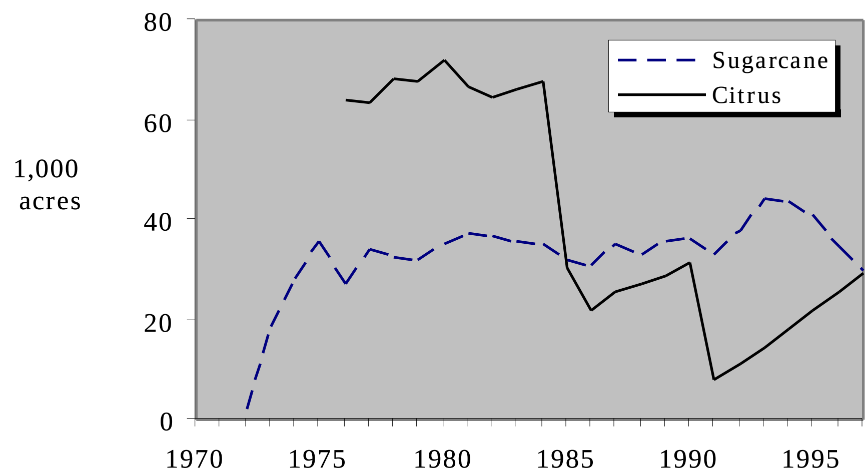
An average irrigated crop has a 29 percent higher yield than the average dryland crop, while variance of yield is 92 percent of dry crop.[10]

Citrus

Citrus, for which the Valley is famous, is water-intensive because trees need irrigation year-round. But the irrigation conserved from dry farming sorghum and cotton is not going to more orchards. Citrus is actually diminishing in importance, while sugarcane is increasing.

[10] Yield averages and variances are taken for the time period 1976 to 1998. Cotton yields for 1995 are excluded, as an unusually severe insect infestation dramatically reduced yield for both irrigated and dryland cotton.

Figure 6-8. Lower Rio Grande Valley acreage in citrus and sugarcane



Source: National Agricultural Statistics Service, "Crop County Data" database (Washington: U.S. Department of Agriculture, 1999), tables for citrus and sugarcane, 1972-98.

Figure 6-8 shows how cultivation of these two cash crops has fluctuated. The freeze of 1984 knocked out many of the bearing citrus trees, and the Valley has never since recovered to its pre-1984 level.

Citrus trees have a longer growing cycle than field crops or even sugarcane. It takes two years after planting for a tree to bear its first crop. From the third through the seventh years, the young trees' yield is not enough to offset all production costs. Only mature trees (eight years and older) bear the rich yield that makes citrus profit margins high. Table 6-3 shows the expected profits and losses over time. Consequently, a planting decision is not made on the basis of expected annual profits, but on the basis of a revenue stream over a number of years.

Table 6-3. Estimated profit stream from grapefruit trees

Time period	Expected net per acre per year
Year 1	$1,838 loss
Year 2	$690 loss
Years 3-7	$241 loss
Years 7-25	$856 profit
Net present value from planting (with 6% discount rate)	$2,908 profit

Source: Texas Agricultural Extension Service, "Projected Costs and Returns per Acre, South Texas District, Grapefruit" (Weslaco, Texas, 1998).

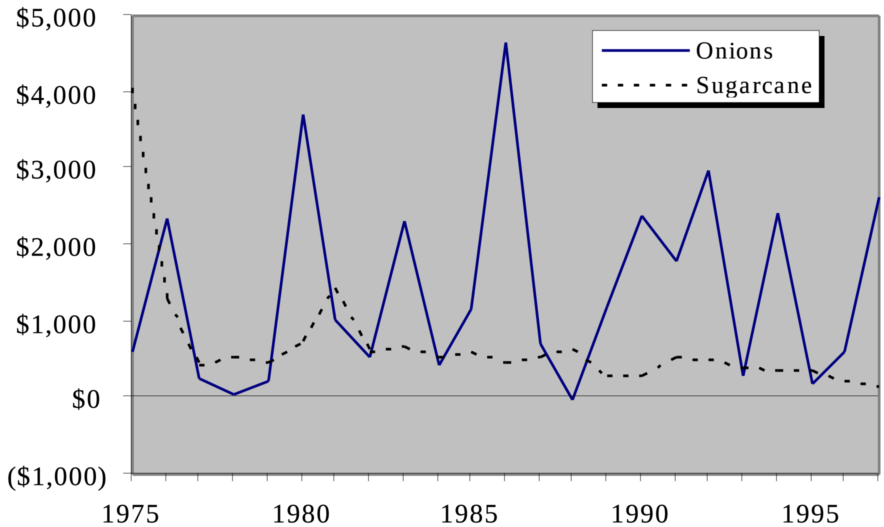
In recent years, the real threat to citrus profitability has not been the risk of drought during the summer, but the risk of a killing freeze during the winter. Two such freezes during the 1980s twice set the Valley's citrus farmers back to year 1, which accounts for the significant drop in orchard acreage between the 1970s and the 1990s.

Sugarcane

Sugarcane plantings increased from almost nothing before 1972 to almost 40,000 acres in 1975, and then continued increasing steadily up to the early 1990s. Sugarcane has a normal cultivation cycle of two or three years: that is, one planting will yield two or three years of harvests. The second- and third-year harvests, called "ratoon" crops because they grow back from the plants' root system, have lower yields than a first-year planting crop, but the operating costs are much lower as well.

Not only do sugarcane and citrus consume a lot of water in irrigation, they do so over a period years. This contrasts with cotton and sorghum, which are one-year crop and which allow easy shifts in crops from one

Figure 6-9. Average return per acre, sugarcane and onions

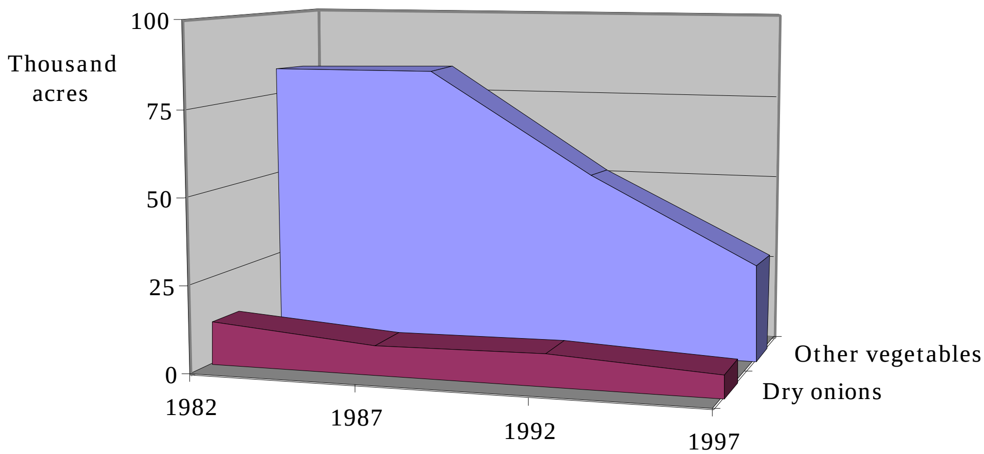


Calculated by multiplying yield by crop price (in 1998 dollars), and subtracting 1998 per-acre production costs. Prices exclude government subsidies. Sources: National Agricultural Statistics Service, "Crop County Data" database (Washington: U.S. Department of Agriculture, 1999); NASS, "Prices Received by Farmers for Field Crops" database (Washington: USDA, 1999); Texas Agricultural Extension Service, "Projected Costs and Returns per Acre, South Texas District," tables for sugarcane and onions (Weslaco, Texas, 1998).

year to the next. Production costs for sugarcane are normally near $770 per acre for newly planted crops and $470 per acre for ratoon crops (in 1998 dollars), with hired labor being the most variable component.

Figure 6-9 shows why sugarcane is increasing in importance in the Rio Grande Valley. Unlike cotton and sorghum, both of which are bedeviled by low prices, sugarcane is almost always a profitable crop. Even after excluding the effects of price spikes which bumped sugarcane profitability abnormally high, sugarcane growers normally realize a return of $300 to $600 per acre, with very little variance.

Figure 6-10. Harvested irrigated acreage for vegetables



Source: U.S. Census Bureau, *Census of Agriculture* (Washington: 1982, 1987, and 1992); U.S. Department of Agriculture, *Census of Agriculture* (Washington: 1997).

Onions and other vegetables

Census data illustrated in Figure 6-10 show that the acreage devoted to vegetables in the Valley has fallen drastically since 1987. The greatest declines have taken place in the cultivation of cabbages, lettuce, cantaloupe and honeydew melons. The data also show that while land in vegetables is declining, the amount of *irrigated* land in vegetables is declining at an even faster rate. As shown in Figure 6-3 earlier in this chapter, about 95 percent of all vegetable acreage was irrigated up to 1987. By 1997, that percentage had fallen to about 82 percent.

Onions, on the other hand, have remained fairly stable. Spring onions grew to account for 18 percent of all vegetable acreage in 1997, compared with 9 percent a decade earlier. A larger portion of this crop is irrigated in comparison to other vegetables; by 1997, 88 percent of onion acreage was still irrigated.

Onions need about as much water as cotton on an annual basis (see Figure 6-4), but they need it over a shorter span of time, making it more water-intensive. More significantly, the economic stakes are much greater for onions than for cotton. Both revenues and operating costs are higher, so there is a far greater penalty for not getting adequate water to the crop. The average return on onions has been about $1,464 per acre (using historical yields for the Rio Grande Valley, 1998 production costs, and statewide historical prices adjusted for inflation). That is far more than the average return on even sugarcane, although not as lucrative as the net present value of a citrus orchard's expected profit stream.

Even though onions are highly profitable on average, they are also a big gamble. Unlike sugar prices (which enjoy a high degree of governmental support within the U.S. domestic market and are shielded from foreign competition by import tariffs), onion prices are volatile. Consequently, the variance of profit as realized by onion farmers in the Rio Grande Valley is about 1,200 times the average profit. By comparison, the variance on sugarcane's smaller average profit of $512 per acre is much lower: only 139 times the average.

Conclusion

The trends outlined in this chapter — increasing water intensity, increasing use of dry farming for cotton and sorghum, more sugarcane crops, and a declining number of irrigated small farms — constitute a gradual shift in agricultural practices in the Valley. During the years immediately following the adjudication, no major reallocation of irrigation was necessary to sustain this transition. Private water rights holders could change their crops and stay within their entitlements, while irrigation districts had plenty of water to meet the marginal increase in customer demand.

By the late 1980s, these trends had evolved to the point at which some reallocation was necessary. A few purchases and leases took place before then, but it wasn't until the 1988-90 drought that a critical mass of buyers and sellers formed. Irrigation rights were leased as many farmers switched to dryland sorghum and cotton. During this time, sugarcane planting continued to increase, while citrus growers recovered from the disastrous killing freeze of the 1984-85 winter.

The abundant rainfall of 1991 to 1993 allowed all water rights holders to replenish their irrigation stock to their maximum allowed levels, and the water market vanished. Then during the drought of 1994-96, the water market returned with a vengeance. The long-term changes in the agricultural sector had reached a point at which major water reallocations among irrigators were necessary.

In sum, a model of water marketing in the Lower Rio Grande Valley has to take into account a number of observed facts. First, irrigated acreage is dwindling. This is happening despite the fact that the absorption of agricultural land by urbanization has been rather slow. The amount of land that can be irrigated and is entitled to irrigation has stayed rather even. Only the amount of acreage actually irrigated is diminishing.

Second, dry farming is increasing. This is a logical consequent of the fact that acreage is dwindling. This shift is facilitated by the fact that the

Valley's two major crops — sorghum and cotton — can be made an unirrigated crop.

Third, irrigation intensity is increasing. This is not due to any increase in irrigation, but to less acreage and a smaller number of farms being irrigated.

Finally, sugarcane plantings increased into the mid-1990s. Clearly, the increase in sugarcane is at least partly offsetting the decrease in citrus, which is about as water intensive.

The next chapter will draw on previous theoretical literature to construct a plausible model of water marketing behavior in the Lower Rio Grande Valley. It will go beyond the simple models developed so far in the literature on water marketing, and will attempt to show how economic pressures affecting a farmer's crop decisions change under market and non-market scenarios.

Chapter 7: Special inputs to the model

Before explicating the model and its constraints, it will be helpful to discuss in mathematical detail three of the key assumptions that make the simulation in Chapter 8 work. Two of these assumptions appear in the model as simple coefficients. The other forms the basis for estimating farmers' aversion to risk. Developing the concepts in this chapter will allow us to focus on the model itself in the next chapter.

Two numerical assumptions are integral to the optimization model described in the next chapter:

- An inch of rain is equivalent to 0.58 inches of irrigation.
- The first half of a crop's monthly water requirement carries 75 percent of the economic weight; the last quarter of the monthly water requirement carries only 6 percent of the economic weight.

This chapter will also describe why and how evapotranspiration is used to estimate crop water demand, and how the mean-variance method is used to account for farmer aversion to risk. A related analytical tool mentioned in Chapter 3 — weighted annual rainfall — will also be explained in conjunction with the discussion on the relationship of rain to irrigation.

The concepts detailed here will then be used without background explanation in the next chapter.

Rainfall and irrigation

In order to adequately capture how farmers respond to hydrological conditions, a model needs to take into account the fact that farmers cut back on irrigation when it rains. Chapter 3 introduced a way by which annual rainfall could be adjusted so that the resulting measure more closely reflected the effect of precipitation on agriculture. The regression analysis used to construct the system of weights also serves to establish an important empirical relationship: the amount of irrigation that is replaced by an inch of rain.

A rain-to-irrigation ratio specific to the Rio Grande Valley can be determined by ordinary least-squares regression. The dependent variable is feet of irrigation — that is, acre-feet of irrigation applied per acre of irrigated land. Land irrigated in the Valley each year is approximated by adding acres planted in the following crops: irrigated cotton, irrigated sorghum, sugarcane, and citrus. The sum also includes half of all acreage planted in vegetables. Taking a portion of total vegetable acreage compensates for the fact that some vegetable crops are not irrigated, and for the fact that some acreage is double-planted with different seasonal crops throughout the year. (To illustrate, if the same acre is used to grow onions in the spring and cabbage in the fall, it will show up in the yearly statistical bulletin as *two* acres — one acre of onions and one acre of cabbage.) Crop data are taken from the Texas Agricultural Statistics Service.[1]

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1 Texas Agricultural Statistics Service, *Texas Agricultural Statistics Bulletin*, annual editions for 1989 through 1998 (Austin, Texas: various years).

The independent variable of concern is feet of precipitation as measured by the National Weather Service at stations in McAllen, Brownsville, Harlingen, and Rio Grande City. For convenience of analysis, monthly data for all four stations are averaged and taken as representative of rainfall for the entire valley.

Along with rain are binary variables representing 11 months of the year. These “dummy” variables are added to capture any statistically significant seasonal effect. Because a model with dummy variables for all 12 months would be fully specified (and thus useless), the analysis includes two versions of the model: one that excludes November from the collection of monthly dummy variables, and one that excludes December.

The results of the regressions are shown in Table 7-1. Because both November and December are low-irrigation months, their parameters are not significantly different from zero. With these two months used as the swapping-out variables, the results for the remaining variables therefore show little difference between the two models. The averages of all statistically significant variables are shown in the right-most column.

The coefficient on the variable *rain* indicates that a 1-inch difference in rainfall correlates with a 0.58-inch countervailing change in the amount of irrigation diverted from the Rio Grande. The 95-percent confidence interval ranges from 0.43 to 0.73, comfortably distant from zero and narrow enough to lend credence to the parameter estimate.

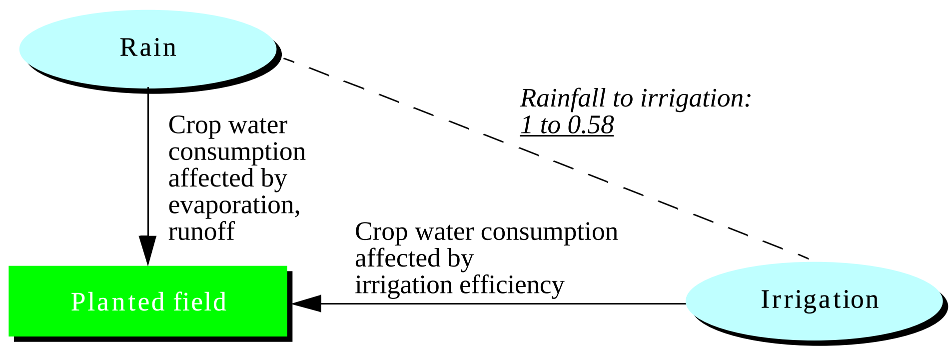
Why would rain be any different from irrigation as far as a crop is concerned? The three main reasons are evaporation, runoff, and irrigation efficiency. While the 1-to-0.58 ratio describes the mathematical

Table 7-1. Regression results: irrigation as a function of rain

Dependent variable: Feet of irrigation applied to all irrigated land. Observations: 120 (monthly, from January 1989 to December 1998)							
	Model 1: December excluded, Adjusted R^2: 0.53			Model 2: November excluded, Adjusted R^2: 0.53			*Average significant coefficient*
	Coefficient	*T statistic*	*P-value*	*Coefficient*	*T statistic*	*P-value*	
Intercept	0.17	4.23	0.00	0.17	4.31	0.00	0.17
Ft. rain	-0.58	-7.57	0.00	-0.58	-7.57	0.00	-0.58
Jan	0.12	2.21	0.03	0.12	2.12	0.04	0.12
Feb	0.07	1.31	0.19	0.07	1.22	0.23	-
Mar	0.12	2.11	0.04	0.11	2.02	0.05	0.11
Apr	0.28	5.09	0.00	0.28	5.02	0.00	0.28
May	0.35	6.39	0.00	0.35	6.32	0.00	0.35
Jun	0.37	6.63	0.00	0.36	6.57	0.00	0.37
Jul	0.20	3.62	0.00	0.20	3.53	0.00	0.20
Aug	0.22	3.87	0.00	0.21	3.80	0.00	0.21
Sep	0.18	3.09	0.00	0.18	3.04	0.00	0.18
Oct	0.20	3.42	0.00	0.19	3.37	0.00	0.19
Nov	0.00	0.08	0.93				-
Dec				(0.00)	(0.08)	0.93	-

relationship between rainfall and irrigation, the relationships that really matter to farmers involve the field where the crops have been planted. The rain-to-irrigation ratio is really a function of the amount of rain that evaporates after it lands on the field, the amount of rainwater that runs off the field without being absorbed into the crop's root system, and the technological efficiency of the methods used to get irrigation

Figure 7-1. Water and land relationships in agriculture



from the river to the field. The three-way relationship between land, rain, and irrigation is depicted in Figure 7-1.

Figure 7-1 graphically suggests two things: that irrigation efficiency is a component of the rainfall-to-irrigation ratio, and that if the technological efficiency of irrigation were to change, so too would the rainfall-to-irrigation ratio. With more efficient irrigation, less water would need to be diverted from the river to accomplish the same work in the field, because less would be lost during transmission due to canal leaks and other factors. Consequently, rainfall would replace less irrigation, because less irrigation is required to do the same productive work.

This intuition is supported mathematically. Recall the discussion in Chapter 1 about water's marginal productivity with respect to crop yield. We saw in Equation 4 of that chapter that the optimal amount of irrigation was described by the equation

Eq. 7-1:

$$\frac{\alpha}{2\beta^2} - \frac{rain}{\varphi} - \frac{\omega}{2p\beta\varphi^2}$$

The second of this equation's three components describes the amount of irrigation offset by rainfall, with φ the coefficient of irrigation efficiency. The variable *rain*, however, does not necessarily refer to the amount of measurable precipitation that actually falls on the field. Precisely speaking, it represents the "true" or underlying relationship between rain and irrigation independent of irrigation efficiency. In other words, it is what the relationship would be if irrigation were perfectly efficient and φ were equal to 1.

If nothing else were involved and φ were equal to 1, then rainfall would offset irrigation 1-to-1. But something else *is* involved: usually, some rain runs off the field and is therefore not absorbed into the crop's root system. Because runoff (by definition) does not stay long enough to replace irrigation, the overall irrigation equivalence of measurable precipitation is reduced as a natural course of events, independent of irrigation efficiency.

The underlying or "true" relationship of rainfall to irrigation, apart from irrigation efficiency, will be designated as ζ. This permits recasting the rain component of Equation 7-1 as

Eq. 7-2:

$$\frac{\zeta}{\varphi}\text{actual precipitation}$$

The regression analysis, however, indicated that the complex coefficient comprising ζ and φ is equal to 0.58 for the Rio Grande Valley. For analytical purposes, φ is assumed to be 50 percent for the Rio Grande

Valley. While the true efficiency may be different, this assumption will suffice to test for the economic effects of changes in irrigation efficiency. A 50 percent efficiency is reasonable for furrow irrigation, the most common practice in the region.[2] Anywhere from 5 to 45 percent of diverted water may be lost due to seepage (depending on whether the canal is lined), while the field efficiency of furrow irrigation is 55 to 70 percent.

Under the assumption that φ is equal to 50 percent, then by simple mathematics the value of ζ would be 0.58 times 0.5, or 0.29. More generally, the rain-to-irrigation ratio for the Rio Grande Valley is 0.29 divided by the rate of irrigation efficiency, a ratio that gets smaller as irrigation efficiency increases.

The result is a number that represents the relationship of rainfall to irrigation — 0.58 — and a formula for getting there based on the assumed technological efficiency of irrigation.

Weighting annual rainfall

The regression shown in Table 7-1 also serves another useful function: the adjustment of annual precipitation data. Many of the analyses throughout this study rely on annual crop data which have no meaningful monthly equivalents. Putting annual rainfall into the picture thus requires placing more importance on rain that comes when crops need it, and less importance on rain that falls off-season.

An agriculturally weighted substitute for annual rainfall is:

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2 Frits van der Leeden, *The Water Encyclopedia* (Chelsea, Mich.: Lewis Publishers, 1990), pp. 380, 382.

Table 7-2. Weights for monthly precipitation

January:	0.32	July:	0.54
February:	0	August:	0.58
March:	0.31	September:	0.48
April:	0.77	October:	0.53
May:	0.96	November:	0
June:	1.00	December:	0

Eq. 7-3: $$\text{weighted annual precipitation} = \sum_{t=1}^{12} \text{weight}_t \times \text{monthly precipitation}_t$$

The 12 weights range from zero to 1, with 1 the weight assigned to the month during which the most irrigation occurs independent of rainfall, and zero assigned to months with no statistically significant need for irrigation.

Table 7-1 shows that the largest irrigation coefficient is for June, while the coefficients for February, November, and December are not statistically significant. Therefore a weight of 1 is assigned to June, and zero to February, November, and December. Weights for the remaining months are determined by dividing their coefficients by that of June. Table 7-2 shows the complete list of calculated weights.

Evapotranspiration

The previous discussion dealt with two of the three major factors affecting the rain-to-irrigation relationship: irrigation efficiency and runoff. The third — evaporation — will be examined here in conjunction with evapotranspiration.

As the term implies, *evapotranspiration* involves *evaporation* and *transpiration*: water that is taken from the ground by the air and by the plant.[3] Normal evaporation is thus incorporated into the measure of a crop's ideal water requirement.

Local conditions — particularly humidity, wind, temperature, and soil quality — impose a certain degree of evaporation regardless of plant transpiration. So by combining natural evaporation with transpiration into the single measure, hydrologists and agronomists can describe how much water needs to be delivered to a crop's root system in a way that takes into account the inevitable evaporation that is, essentially, Mother Nature's tariff. Evaporation losses at the root system are exclusive of transmission losses, which can be controlled by the technology used in delivering water to the root system.

It is assumed here that a crop's ideal yield is related to the crop's ET. But "related to ET" is not the same as "determined by ET." The amount of the yield actually realized by a farmer will vary according to how densely the crop is planted, how much fertilizer is applied, and other factors besides water. ET does differ according to whether the crop is irrigated or dry-cropped (as will be explained below), but because the main analytical concern here is with farmers' irrigation decisions, ET for dry cotton and dry sorghum do not enter into the present picture.

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3 See, for example, the definition given under the topic "hydrologic sciences," *Encyclopedia Britannica Online*, <http://search.eb.com/bol/topic?eu=108984&sctn=6> [Accessed 30 August 1999].

What ET describes is how much water needs to reach the root system in the soil so that ideal plant growth occurs and ideal yield — whatever it may be given all other conditions — is achieved.

ET is measured in inches or feet, as is precipitation. If cotton has an annual ET of 2.5 feet, the amount of water required to cultivate one acre of cotton would be 2.5 acre-feet (net of any conveyance losses). Because climate and soil conditions vary, ET for the same crop differs from place to place and must be calculated independently for the areas being studied. Daily ET can be calculated, but estimating by month seldom harms analytical accuracy.[4]

ET has been calculated for the major crops in the Rio Grande Valley following the methodology detailed by Borrelli, Fedler, and Gregory.[5] The first step is to identify the start and end of a crop's local growing season. The period is divided into four stages: the initial period after planting, growth of the plant's above-ground canopy, the mid-season development of the plant at full canopy, and maturation. At the end of the maturation stage, the plant has produced as much as it can for the season and is ready for harvest.

The next step is to determine the crop's basal coefficient curve, K_{cb}. This curve, which is estimated in a piecewise manner, represents the water that passes from the soil at different points in the crop's growth cycle. The initial value of K_{cb}, which is assumed to hold up to the start of the canopy-development stage, is taken from an extensive compilation of

4 John Borrelli, Clifford B. Fedler, and James M. Gregory, *Mean Crop Consumptive Use and Free-Water Evaporation for Texas* (Austin, Texas: Texas Water Development Board, 1998), p. 17.

5 *Ibid*.

such values calculated by the U.S. Soil and Conservation Service. The value of K_{cb} at the beginning of the mid-season stage and at the end of maturation is then taken from SCS tables and adjusted for local humidity and wind.[6] The average value of the K_{cb} curve is then estimated for each month of the crop season. The estimated K_{cb} curve and month averages for cotton in the Rio Grande Valley are shown in Figure 7-2.

A crop's monthly ET is then calculated by multiplying K_{cb} by the ET of a reference crop, a grass with a year-round growth cycle. The ET for grass reference crops in near McAllen and Brownsville are shown in Figure 7-3. If a crop's K_{cb} for the month is less than 1, its monthly ET further takes into account a wetting factor derived from soil characteristics and the average number of wetting events for the month:

Eq. 7-4: $$ET_{crop} = ET_0 \times K_{cb} + ET_0\,(1 - K_{cb}) \times WF$$

for instances when K_{cb} is less than 1 but greater than zero, where ET_{crop} is the monthly evapotranspiration for the crop of interest, ET_0 is the evapotranspiration of the grass reference crop, and *WF* is a wetness factor that takes into account rain and irrigation. A month's wetness factor is based on the average number of days in which more than 0.1 inches of rain falls, plus the typical number of irrigations times 0.5.[7] (The calculations used here assume four irrigation events per month.)

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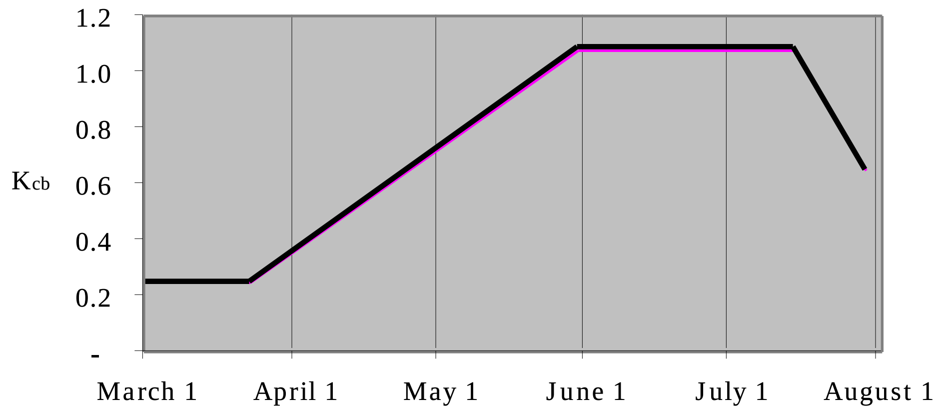
6 U.S. Soil and Conservation Service, "Irrigation Water Requirements," *Part 623 National Engineering Handbook* (Washington: U.S. Department of Agriculture, 1993), tables reprinted in Borrelli *et al.*

7 The factor 0.5 varies according to the type of irrigation methods used. The number used here is the one most commonly used for furrow irrigation. Borrelli *et al.*, p. 32.

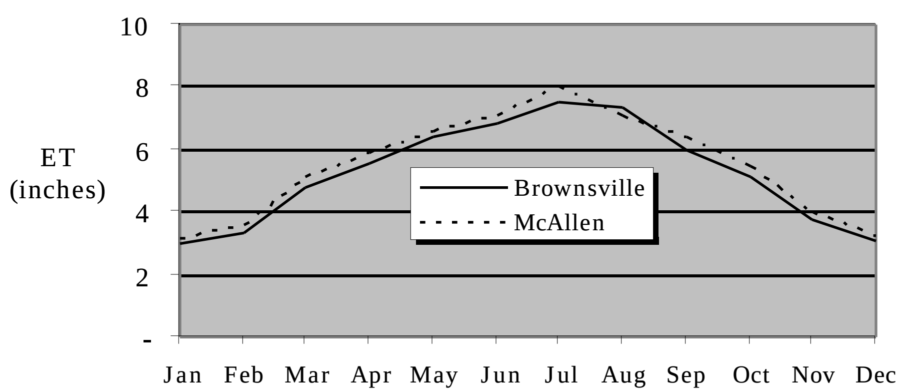
Figure 7-2. Basal coefficient curve (K_{cb}) for cotton in Hidalgo County



Month averages: 0.26 0.54 0.91 1.09 0.97

Calculated following John Borrelli, Clifford B. Fedler, and James M. Gregory, *Mean Crop Consumptive Use and Free-Water Evaporation for Texas* (Austin, Texas: Texas Water Development Board, 1998).

Figure 7-3. ET for grass reference crops in the Rio Grande Valley



From John Borrelli, Clifford B. Fedler, and James M. Gregory, *Mean Crop Consumptive Use and Free-Water Evaporation for Texas* (Austin, Texas: Texas Water Development Board, 1998).

Borrelli *et al.* provide a table of wetness factor values corresponding to different soils and frequency of water events.

The January ET calculations for onions, for example, is

Eq. 7-5: $$ET_{onions} = ET_0 K_{cb} + ET_0 (1 - K_{cb}) \times f\left(\text{rain days} + \frac{\text{irrigation events}}{2}\right)$$

$$= 3.13 \times 0.38 + 3.13 \times (1 - 0.38) \times 0.547$$

$$= 2.25$$

where ET_0 is the ET of the grass reference crop, K_{cb} is the basal coefficient for Hidalgo County onions in January, *rain days* is the average number of days in January with more than 0.1 inch of rainfall, and *irrigation events* is the assumed number of times irrigation is applied during a typical January. (The number 0.547 comes from the wetness factor table provided by Borrelli *et al.*, taking 6.25 wet events per month on soil of clay loam quality.)

A complete enumeration of the ET values used in this simulation may be found in Table 7-3. Values in the table have been converted to feet, so that the numbers can more readily be used in computations involving acre-feet of water.

Approximating water-to-yield curves

Recall from Chapter 1 that the water-to-yield relationship is described generally by a quadratic function of the form

Eq. 7-6: $$\text{yield} = \alpha \text{ water} - \beta \text{ water}^2$$

Table 7-3. Calculated ET (in feet) for major Rio Grande Valley crops

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Citrus	0.21	0.23	0.28	0.34	0.43	0.44	0.46	0.44	0.43	0.33	0.24	0.20
Cotton (C)			0.14	0.29	0.48	0.61	0.68	0.23				
Cotton (H)			0.16	0.33	0.50	0.64	0.72	0.23				
Onions	0.17	0.26	0.42	0.48	0.52	0.53						
Sorghum (C)			0.07	0.33	0.53	0.56	0.23					
Sorghum (H			0.08	0.37	0.55	0.58	0.24					
Sugarcane	0.25	0.28	0.39	0.45	0.52	0.56	0.62	0.56	0.51	0.43	0.31	0.26

Cotton and sorghum ET for Cameron County (C) and Hidalgo County (H) are taken as calculated by Borrelli *et al*. (p. 81). ET values for citrus, onions, and sugarcane are calculated in accordance with Borrelli *et al*.

To determine the amount of water necessary to obtain the best yield, it is necessary to find the first derivative of Equation 7-6, set it equal to zero in order to find the optimum, and then solve for water.

Eq. 7-7:

$$\frac{\partial \text{yield}}{\partial \text{water}} = \alpha - 2\beta \text{water}$$

$$0 = \alpha - 2\beta \text{water}$$

$$2\beta \text{water} = \alpha$$

$$\text{water} = \frac{\alpha}{2\beta} = 0.5 \ \frac{\alpha}{\beta}$$

This represents the volume of water necessary to obtain the crop's best yield. Applying less or more would reduce the yield obtained from the crop. A mathematical representation of best yield is found by taking the optimal value for water shown in Equation 7-7 and put it in the original water-to-yield relationship.

Eq. 7-8:

$$\text{yield} = \alpha\left(0.5\frac{\alpha}{\beta}\right) - \beta\left(0.5\frac{\alpha}{\beta}\right)^2$$

$$= 0.5\frac{\alpha^2}{\beta} - 0.25\frac{\alpha^2}{\beta} \qquad = 0.25\frac{\alpha^2}{\beta}$$

The result of Equation 7-8 represents best yield, which is obtained by supplying the amount of water represented in Equation 7-7. At this point, both yield and the amount of water needed to obtain it are still abstractions (α and β are yet undefined), but this will not prove to be a problem, as will soon be seen.

How yield responds when the crop gets 75 percent of its optimal water may be estimated by recalculating Equation 7-8 with the reduced value. The first step is to adjust the amount of water represented in Equation 7-7:

Eq. 7-9:

$$\text{optimal water} \times 75\% = 0.5\frac{\alpha}{\beta} \times 0.75 = 0.375\frac{\alpha}{\beta}$$

Applying this amount of water would result in the following yield:

Eq. 7-10:

$$\text{yield} = \alpha\left(0.375\frac{\alpha}{\beta}\right) - \beta\left(0.375\frac{\alpha}{\beta}\right)^2$$

$$= 0.375\frac{\alpha^2}{\beta} - 0.141\frac{\alpha^2}{\beta} \qquad = 0.234\frac{\alpha^2}{\beta}$$

The result obtained from Equation 7-10 may now be expressed as a percentage of best yield.

$$\textbf{Eq. 7-11:}\quad \frac{\text{yield with 75\% of optimal water}}{\text{best yield}} = \frac{0.234\,\frac{\alpha^2}{\beta}}{0.25\,\frac{\alpha^2}{\beta}} = \frac{0.234}{0.25} = 0.94$$

In other words, if a crop receives 75 percent of its optimal water, it will still produce around 94 percent of its best-possible yield (assuming all other factors are held constant). Notice that α and β — as well as the problem of abstraction — have disappeared from the picture at this point. A perfectly tangible ET value, taken as the optimal water requirement, may thus be used to approximate what will happen to yield if 75 percent of that amount is applied.

To complete the piecewise approximation of the water-to-yield relationship, Equation 7-6 is run again assuming half of the crop's ideal water requirement:

$$\textbf{Eq. 7-12:}\quad \text{optimal water} \times 50\% = 0.5\,\frac{\alpha}{\beta} \times 0.5 = 0.25\frac{\alpha}{\beta}$$

$$\textbf{Eq. 7-13:}\quad \text{yield} = \alpha\left(0.25\,\frac{\alpha}{\beta}\right) - \beta\left(0.25\,\frac{\alpha}{\beta}\right)^2$$

$$= 0.25\,\frac{\alpha^2}{\beta} - 0.0625\,\frac{\alpha^2}{\beta} \qquad = 0.1875\,\frac{\alpha^2}{\beta}$$

$$\textbf{Eq. 7-14:}\quad \frac{\text{yield with 50\% of optimal water}}{\text{best yield}} = \frac{0.1875\,\frac{\alpha^2}{\beta}}{0.25\,\frac{\alpha^2}{\beta}} = \frac{0.1875}{0.25} = 0.75$$

In plain language, Equation 7-11 says that a farmer can obtain 94 percent of a crop's best yield by applying 75 percent of the crop's full water requirement; Equation 7-14 says that if the crop gets half of its optimal water needs, a farmer can realistically expect to obtain 75 percent of best yield. Both of these relationships are contingent on all other factors remaining the same. Because the crop-specific parameters α and β drop out entirely, these proportions are reasonable for practically any crop to the extent the general yield equation holds.

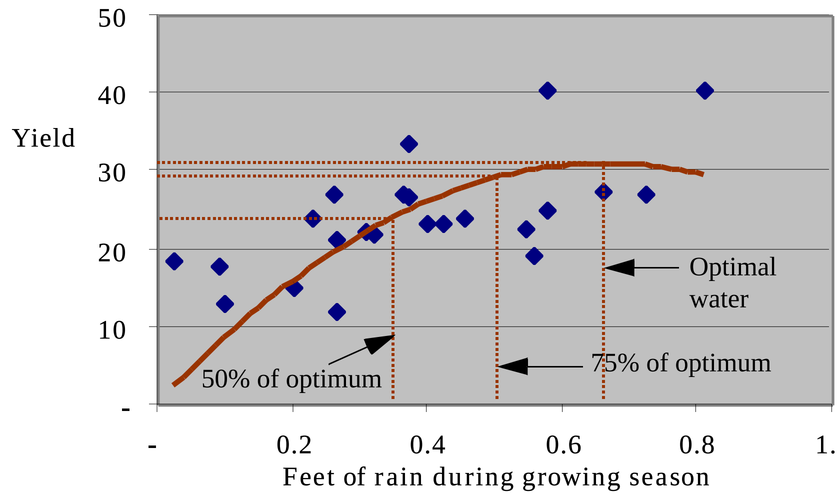
To see how this works graphically, consider historical yields for dry-farmed sorghum in Hidalgo County. Figure 7-4 is a scatter plot of yield and weighted annual rainfall from 1976 to 1998, excluding the two highest-yield and the two lowest-yield observations. The estimated trend line peaks at an optimum of 15.28 inches of rain, with an estimated best-yield of 25 cwt per acre. It may also be seen that if rain falls to 75 percent of the optimum, or 11.5 inches, yield tends to drop by only 1.5 cwt per acre.

(Recall that the estimates described in this section assume that all other factors affecting yield are held constant. The variance seen in the historical data reflects real-world changes in other factors besides rainfall.)

On the basis of these equations — backed up intuitively by trends teased out of historical yields — it is reasonable to break a crop's water demand into three consecutive segments:

- The first 50 percent of full water demand, which ensures the crop's viability and contributes to 75 percent of potential yield;
- The next 25 percent of full water demand, which ensures the crop's regular yield (94 percent of best potential yield); and

Figure 7-4. Water-to-yield curve for dry sorghum in Hidalgo County, 1976-98



Curve was estimated by regression from seasonal rainfall and historical yields for unirrigated sorghum in Hidalgo County from 1976-97, using the zero-intercept quadratic model $y = \alpha \text{ rain} - \beta \text{ rain}^2$.

- The last 25 percent of full water demand, which ensures the crop's best yield under all other circumstances.

Measuring risk-aversion

The last aspect of the model needing special explanation has to do with the method of taking into account farmers' aversion to risk. Although there are models of how risk aversion varies between farmers, they tend to be complex; moreover, between-farmer differences in risk aversion have little to do with the goal of this investigation. The aim here is more general and is concerned with macro-level responses: Are farmers risk-averse as a group, and if so, to what extent does the fact of their risk aversion affect cropping patterns?

The method used here to estimate risk aversion is mean-variance analysis. This method is described generally in Chapter 2; here, we will detail its use in this model.

Mean-variance analysis, as the name suggests, approximates risk by looking at how much a target outcome tends to wander from its average. If two crop alternatives both have an average profit margin of, say, $20 per acre, the crop that tends to vary by just a few dollars is preferable to the one gyrates widely around that same average. The first crop will still be a money-maker if its worst years are only $5 or $10 below average. On the other hand, if it is not unusual for the latter crop's profit margin to vary from the average by $50 or more, a bad season could mean a net loss.

Most farmers would rather ensure against loss than gamble on a windfall profit. This risk-averse tendency is approximated by treating variance as a penalty on average profit margins — the higher the variance, the greater the penalty on the average. When faced with many crop options, a farmer trades off between high expected profits (reflected by the highest means) and low risk (reflected by lowest variances).

In this simulation, acres planted in high-risk (i.e. high-variance) crops detract from the value of each year's objective function to a greater degree than do crops with low variance. A crop's risk penalty is also quadratic, making the penalty heavier as more acres are devoted to the crop. In effect, the simulation looks for the point at which devoting another acre to the crop adds more uncertainty than profit.

Let us first define **A** as a vector comprising the number of acres a_i planted in each possible crop choice *i*. We also define σ^2 as the variance-covariance matrix of per-acre profit over a period of time. The relative uncertainty associated with any given array of values for A may be described by the equation

Eq. 7-15: $$\text{risk} = \mathbf{A}\sigma^2\mathbf{A}'$$

which after expanding the matrix notation and considering a total of *N* crop alternatives becomes:

Eq. 7-16: $$\text{risk} = \begin{bmatrix} a_1 \\ a_2 \\ \\ a_N \end{bmatrix} \times \begin{bmatrix} \sigma_1^2 & \text{cov}_{2,1} & \text{cov}_{N,1} \\ \text{cov}_{1,2} & \sigma_2^2 & \text{cov}_{N,2} \\ \\ \text{cov}_{N,1} & \text{cov}_{N,2} & \sigma_N^2 \end{bmatrix} \times \begin{bmatrix} a_1 & a_2 & & a_N \end{bmatrix}$$

or when multiplied out:

Eq. 7-17: $$\text{risk} = \begin{bmatrix} a_1^2\sigma_1^2 & a_2a_1\text{cov}_{2,1} & a_Na_1\text{cov}_{N,1} \\ a_1a_2\text{cov}_{1,2} & a_2^2\sigma_2^2 & a_Na_2\text{cov}_{N,2} \\ \\ a_1a_N\text{cov}_{1,N} & a_2a_N\text{cov}_{2,N} & a_N^2\sigma_N^2 \end{bmatrix}$$

Summing all the elements in the matrix of Equation 7-17 gives the collective uncertainty of profit facing a farmer once the available acreage has been allotted to each crop *i*, with the variances and covariances acting as weights on the decision variables.

In a mathematical programming model, a higher value for the risk matrix hurts the value of the objective function, so the aim is to make the risk components as small as possible. Choices with a high variance of profit add to risk and detract from overall benefit. But pairs of crops with negative covariances help the objective function; choosing such crops in tandem tends to spread the risk over alternatives whose changes in profitability tend to offset each other, making the whole crop portfolio more stable.

The covariance matrices — separate ones for Cameron and Hidalgo counties — are shown in Table 7-4. The matrices are based on the estimated profit margin for each crop in each county from 1976 to 1998. Margins are calculated by a simple formula: price (real dollars per unit) at each harvest times countywide yield (units per acre) for each year, minus total production costs (dollars per acre) as estimated for 1998 by the Texas Agricultural Extension Service's regional office in Weslaco, Texas. In the simulation, risk for each county's crop decision is calculated separately, then the two results are added together.

To see how the covariance matrices work, consider Hidalgo County crop plantings in 1998 as an example: 29,200 acres of irrigated cotton, 5,700 acres of onions, 23,000 acres of irrigated sorghum, 15,000 acres of sugarcane[8], 32,600 acres of unirrigated cotton, and 102,400 acres of unirrigated sorghum. The uncertainty associated with mix of crops is found by multiplying the ordered array (and its transposed array) by the corresponding values in the covariance matrix. The result is a new

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[8] Numbers for onions and sugarcane represent harvested acres; data on planted acres are not available.

Table 7-4. Variances and covariances used in measuring crop risk

Cameron County	*cotton*	*onions*	*sorghum*	*sugarcane*	*dry cotton*	*dry sorghum*
cotton	**27,499**	5,872	5,362	2,744	21,427	6,170
onions	5,872	**1,667,041**	-34,080	50,728	9,584	-11,508
sorghum	5,362	-34,080	**5,320**	-2,684	3,985	4,055
sugarcane	2,744	50,728	-2,684	**18,756**	2,653	-846
dry cotton	21,427	9,584	3,985	2,653	**24,721**	6,042
dry sorghum	6,170	-11,508	4,055	-846	6,042	**4,249**
Hidalgo County	*cotton*	*onions*	*sorghum*	*sugarcane*	*dry cotton*	*dry sorghum*
cotton	**28,931**	-26,814	2,585	4,986	19,775	5,298
onions	-26,814	**1,667,041**	-30,646	54,756	4,999	4,239
sorghum	2,585	-30,646	**3,588**	-1,579	2,219	2,061
sugarcane	4,986	54,756	-1,579	**14,179**	6,183	686
dry cotton	19,775	4,999	2,219	6,183	**21,410**	4,924
dry sorghum	5,298	4,239	2,061	686	4,924	**3,457**

Boldface cells indicate crop profit variances

matrix of the same dimensions as the original covariance matrix. The diagonal of the new matrix consists of the original variances multiplied by the square of the number of acres planted in the corresponding crop. The off-diagonal cells are the original covariances, times the acres planted in the crops corresponding to the covariance.

The uncertainty measure is obtained by summing all the values contained in the new matrix. This results in a very large number: 2.72×10^{14}. (Scaling the result will be addressed in a moment.) If 3,000 acres intended for sugarcane were planted in onions instead, the value of the uncertainty matrix would increase to 3.38×10^{14}, due to the fact that 3,000 acres would be squared and multiplied by a bigger variance: that of onions. Regardless of how expected profit might change as a result of the shift, the portfolio of crops would become much riskier.

Now imagine the 3,000 acres divided equally among onions, irrigated cotton, and irrigated sorghum. Uncertainty still increases, but only to 2.92×10^{14}. If reallocating 3,000 acres among the three crops were to result in the same anticipated profit gain as planting all of it in onions, the three-crop option would dominate the onions-only option because it entails less uncertainty. This is due to the negative covariances between onions and cotton, and between onions and sorghum. It is also due to the fact that only one-third as many acres are being multiplied by onions' very large variance. Thus spreading the 3,000 acres among the three crops also spreads the risk.

When profit expectations and risk are combined into one utility function, the objective is to get the greatest returns with the least uncertainty. For this to happen, the number obtained from summing the two uncertainty matrices (one for Cameron County and one for Hidalgo County) must be scaled so that it is comparable to anticipated returns, which are expressed in familiar dollar terms. We designate λ as the constant by which the uncertainty measure is scaled.

Because risk aversion is intangible — and therefore fundamentally abstract — we must be guided by plausibility rather than precision in choosing a value for λ, testing our results for sensitivity to changes in λ as we go. For a scenario in which risk-aversion is absent in any fashion, λ is equal to zero and it doesn't matter how the uncertainty matrix resolves. This doesn't necessarily mean that farmers are neutral towards risk or that they are risk-takers; it means, rather, that risk aversion simply isn't part of the decision analysis.

A desirable upper limit on the value of λ would be one that allows the value of the uncertainty matrix to offset some of the expected profit without wiping it out altogether. Or to put it another way, a plausible λ would adjust the measure of risk to no more than what the value of the objective function would be if λ were zero. This suggests a straightforward procedure for estimating λ:

1. Run the simulation from 1993 to 1998 (under each market and conservation scenario) with λ set to zero.
2. Average the objective function values.
3. Calculate the uncertainty matrices using historical data on planting.
4. Calculate the values of λ necessary to make each year's risk measure equal to the average objective function value.
5. Take the average of each year's λ as the maximum λ to be used in the simulation.

The average objective function value for trial runs of the simulation without risk was approximately 67 million, which may be interpreted as the level of profit farmers collectively hope for based on their planting decisions, without taking risk into account. (By comparison, revenues from crop production in Cameron and Hidalgo counties were estimated by the Census of Agriculture at around $250 million for both the 1992 and 1997 census years.)

Crop data for 1992 through 1998 were then applied to the uncertainty matrices, with the results for the two counties added together. The resulting value for each year was then be put into a simple equation:

Eq. 7-18: (uncertainty matrix outcome) × λ = $67,000,000 or

$$\lambda = \frac{\$67{,}000{,}000}{\text{uncertainty matrix outcome}}$$

The average calculated λ value over all seven years was approximately 5×10^{-8}, which was taken as the maximum value for λ. To make sure the results of the simulation were robust to changes in λ, the derived average was halved (2.5×10^{-8})and used as an alternate value of λ.

Chapter 8: Simulation of irrigation demand

How is the agricultural sector likely to change if water marketing is allowed? Will farmers as a whole be better off economically? Will crop choices change? Will farmers be more or less likely to invest in water-saving irrigation systems? How will storage in the hydrological system be affected? These are some of the questions that lawmakers and water managers may consider when deciding whether to create institutions for a water market.

To approach these questions analytically and uncover some of the hidden economic influences, it is helpful to simulate the real-life decisions farmers face. For the purposes of this study, these decisions may be narrowed down to two: what to plant, and what to water. These two sequential decisions constitute the core of the mathematical optimization model used here to test the economic influence of a water market on conservation and economic benefits in the agricultural sector.

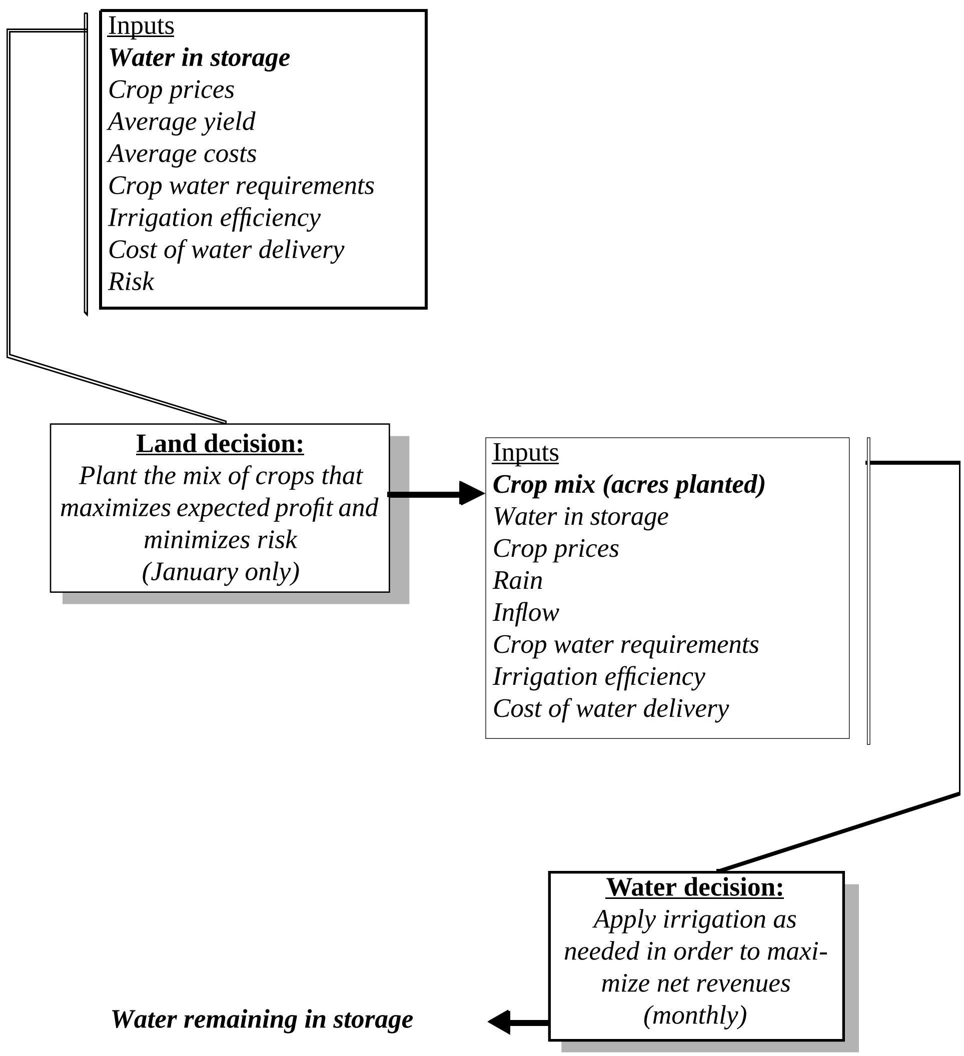
Planting and watering decisions are both sequential and dynamic. Once the planting decision has been made, the acres committed to irrigated crops become a factor in deciding how much irrigation is required over the ensuing months of the crops' growing seasons. The amount of stored water remaining at the end of the crop season is then one of the considerations going into the next season's planting decision. The less water available, the more likely a farmer is to plant dryland crops.

Some of the factors affecting each land decision and the consequent watering decisions are volatile. What is planted is often determined by current commodity prices more than water availability. The amount of irrigation required by whatever is planted will be determined by the crop's basic water requirements minus any rainfall that might moisten the soil. Figure 8-1 displays the various factors affecting the planting and watering decisions, and which are used in the simulation model.

By altering parts of the optimization model, it is possible to compare outcomes under different sets of rules and assumptions. Three possible changes are of concern here: the presence of a contract water market for irrigation, the use of water-conserving irrigation technologies, and how farmers respond to risk. A water market is treated as a binary condition (it's either permitted or it's not), while conservation effects are captured by a coefficient representing low irrigation efficiency and an alternative representing high efficiency.

By holding the objective functions and exogenous inputs identical across all runs of the simulation, one can look at how the objective function values and decision variables change over time under each of the different rule regimes. Especially important are the dual prices on the key land constraints. In an optimization problem involving bounded decision variables (such as the land variables here, as explained in detail below), changing the rules and inputs may cause no change in the amount of land planted in a particular crop if the simulated value is always pressing against an upper or lower bound. But the dual prices on such variables often do change; they measure the degree of economic pressure on farmers to plant more or less of a particular crop if a bound on that crop's acreage has been reached.

Figure 8-1. Schematic of planting and irrigation decision sequence



The most recent time series for which full data are available coincidentally spans an extremely wet period and an extremely dry period in the Valley. The simulation therefore takes 1992 as its point of initial conditions. During this year, all water accounts were at 100 percent of capacity, a fact that tremendously simplifies the task of finding appropriate initial conditions for the model. Actual data on inflow, rain, and commodity prices for the following five years are used for the simulation's exogenous volatile parameters. Outcomes simulated for 1996 through 1998 — in particular, total irrigation storage levels — offer comparisons to what in fact was the case during the severe drought conditions of that year.

Assumptions

Numerous assumptions have been made in order to make a simulation feasible and simpler. The most important of these is that irrigation is separable from all other water uses. The previous discussion of the Rio Grande watermaster's rules of operation for the Falcon-Amistad reservoir system shows that this is not only a realistic assumption, it is in fact how things are done in the area. Moreover, the prohibition against cross-use water leasing proves to be anything but a binding constraint with regard to modelling recent water use trends; even during drought, municipal users have always had water left over at the end of the calendar year (at which point their water accounts are replenished in full). Cities never would have bought water from irrigators even if it were permissible, because they've never been that desperate.

In short, this simulation doesn't model a physical water system, but a legal one. The water that flows into the pool of available irrigation follows a paper course as well as a watercourse, first as part of the U.S. apportionment as calculated by the IBWC/CILA, and then as a residual for Texas irrigators after other deductions have been made. Consequently, many of the variables that normally go into simulating a water basin (such as evaporation, seepage, and minimum instream flow) do not appear in this model, as they are already taken into account elsewhere in the watermaster's accounting procedures.

Data limitations force another major assumption: that farmers grouped by county have economic responses similar to those of individual farmers or farmers grouped by irrigation district. Aggregating by county is necessary because that is the smallest scale at which time-series data on water use can be matched with time-series data on farm production. Monthly data on irrigation diversions are available for each water right holder along the Rio Grande, but parallel data on what crops were irrigated by each water right holder do not exist in any usable time-series form. Compounding the problem is that fully 85 percent of the basin's total irrigation rights of 1,915,169 acre-feet are held by water districts, each of which sells to any number of individual farmers living within its boundaries.[1] Thus even the existing by-water-right diversion data are of limited use in telling how irrigation is used at a micro-level.

Two time series of crop data are available at the county level: detailed five-year data compiled by the Census of Agriculture, and annual data compiled by the National Agricultural Statistics Service of the U.S. Department of Agriculture. By aggregating all water rights by county and summing monthly diversions, it is possible to match a time-series data set for water diversions with one for the six crops that make up 90 percent of the region's output. So for analytical purposes, the area can be treated as comprising eight large farm areas: the counties along

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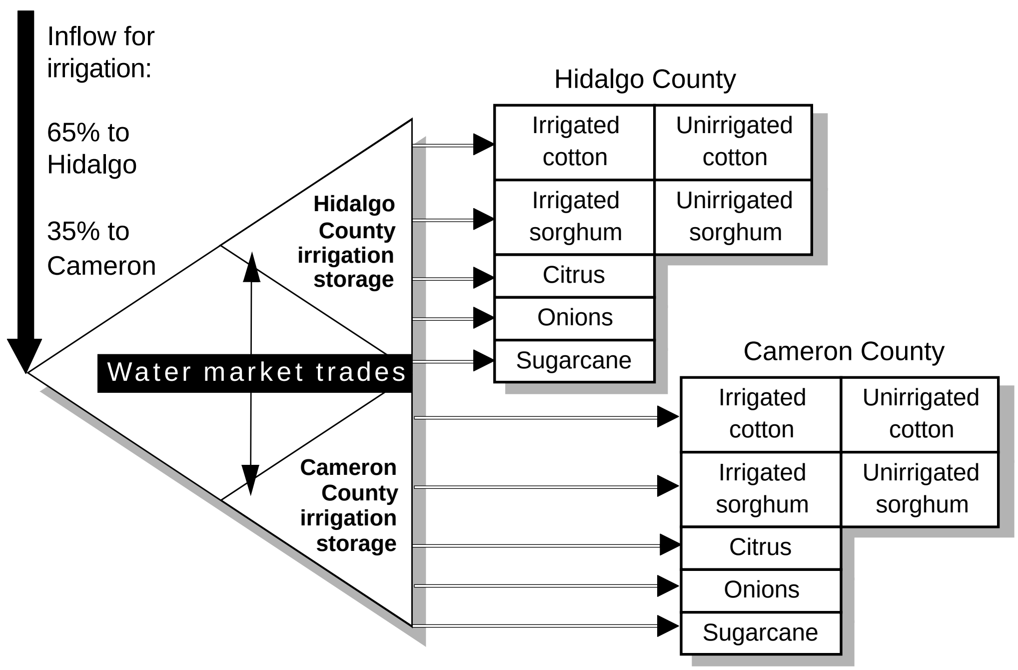
[1] Water rights database, electronic file, Texas Natural Resource Conservation Commission, 1999.

Figure 8-2. Schematic of Lower Rio Grande water use as simulated



the river downstream from Amistad International Reservoir. Two of these counties — Hidalgo and Cameron — dominate all the others in terms of irrigation use and farm output, so for all practical purposes the model can be collapsed into a textbook two-person economy so familiar to students of economics. Figure 8-2 shows what the simulation looks like spatially.

Aggregating data by county does less violence to the facts than one may suspect. By treating Hidalgo County as a single mega-farm with a single water entitlement, the assumption is that within the county, water is allocated on a purely economic basis without regard to within-county entitlements. But this is in fact what happens with the four-fifths of all irrigation entitlements that are controlled by irrigation districts. A typical individual farmer in Hidalgo County has no legal constraint on how much of his district's water he can use; he buys as much as he needs for what he has planted, and no more.

Formulating the first objective function: land

The objective function for the first part of the simulation combines profit-seeking with risk-aversion. The two farming units — Cameron County and Hidalgo County — will allocate available acreage among crops in a manner that, for each county, achieves the greatest expected profit with the least uncertainty. Table 8-1 shows how the objective function for the land decision is structured.

Maximizing the objective function for planting is subject to a number of constraints. First, the amount of land planted in each crop by each county cannot exceed its historical high or be less than its historical low. Second, each county's total planted acreage cannot be more than the land physically available (operationally, the historical high for total planted acreage in the county) nor can it be so small that it jeopardizes the county's on-going agricultural enterprise (taken as the historical low for total planted acreage). Third, irrigated crops are further limited by the amount of land accessible to irrigation (operationally, the historical high for acres planted in irrigated crops). Finally, if the expected 12-month water demand of the county's irrigated crops is more than what is contained in the county's water account in the reservoir system, the amount in excess of the water balance must be penalized. All these constraints are shown in Table 8-2.

Table 8-1. Objective function for the land decision

Objective function for each year T:

$$\max \sum_{i,\,j} \pi_{i,j,T} a_{i,j,T} - \lambda \mathbf{A}_{j,T} \sigma^2_j \mathbf{A'}_{j,T} - 20 \text{ water deficit}_{j,T}$$

Profit component	
$a_{i,j,T}$ (decision variables)	Number of acres planted in crop *i* by user *j* at the beginning of season *T*
$\pi_{i,j,T}$ (coefficients)	Expected profit margin per acre of crop *i* planted by user *j* based on crop prices at the start of season *T*
Risk component	
$\mathbf{A}_{j,T}$ (vector of decision variables)	A vector containing all values of decision variables $a_{i,j,T}$ for farming unit *j* during year *T*; $\mathbf{A'}_{j,T}$ is the vector's transpose
σ^2_j (matrix of coefficients)	The variance-covariance matrix of profit margins for all crops in vector $\mathbf{A}_{j,T}$
λ (scaling constant)	A constant to scale the outcome of multiplying $\mathbf{A}_{j,T}$, σ^2_j, and $\mathbf{A'}_{j,T}$
Speculative water penalty	
water $\text{deficit}_{j,T}$	The amount of water in excess of current storage required by *j* to irrigate all acres $a_{i,j,T}$; water that *j* does not presently hold but speculates will arrive (either as rainfall or river inflow) in time to satisfy crop water requirements during season *T*

How the first objective function is formed

The land formulation assumes that at the start of each year, a farming unit will plant the mix of crops that results in the greatest expected profit with the least uncertainty. Mathematically, the utility function $U_{j,T}$ for a typical farming unit *j* during any given year *T* is

Table 8-2. Constraints on the land decision

Constraint	Purpose
1: $LB_{i,j} \le a_{i,j,T} \le UB_{i,j}$	To place lower and upper bounds on each individual decision variable $a_{i,j,T}$; $LB_{i,j}$ is the least acreage planted in crop *i* by user *j* during any year from 1978 to 1998; $UB_{i,j}$ is the most
2: $LB_j \le \sum_i a_{i,j,T} \le UB_j$	To place upper and lower bounds on the total acres planted by user *j* during any year *T*; LB_j is the least acreage planted by user *j* during any year from 1978 to 1998; UB_j is the most
3: $\sum_{i=irr} a_{i,j,T} \le UB\ irrigated_j$	To limit the irrigated acres planted by user *j* during any year *T*; *UB* $irrigated_j$ is the greatest amount of acreage planted in irrigated crops by user *j* during any year from 1978 to 1998; includes only those crops *i* that are irrigated (*i=irr*)
4: $\sum_{i=irr} a_{i,j,T}\, ET_{i,j}\, \varphi^{-1} - water\ deficit_{j,T} \le reservoir\ storage_{j,T}$	To define $water\ deficit_{j,T}$ as the water user *j* expects to require for year *T* in excess of what is currently held in storage; water requirement for irrigated crop *i* is acreage planted ($a_{i,j,T}$) times annual evapotranspiration ($ET_{i,j}$) adjusted for technological efficiency of irrigation (φ^{-1})

Eq. 8-1: $$U_{j,T} = \sum_i a_{i,j,T}(yield_{i,j} \times price_{i,T} - cost_i) - \lambda \mathbf{A_{j,T}} \sigma^2_j \mathbf{A'_{j,T}}$$

where $a_{i,j,T}$ are the decision variables (acres planted in each crop *i* by farming unit *j* at the beginning of season *T*) and $\boldsymbol{A_{j,T}}$ is a vector comprising all $a_{i,j,T}$. In the profit component of the utility function, $yield_{i,j}$ is the average per-acre yield of crop *i* realized by *j* from 1978 to 1998, $price_{i,T}$ is the market price of crop *i* at the beginning of season *T*, and $cost_i$ is the average per-acre cost of production for crop *i*. (All prices and cost averages are adjusted for inflation.)

The objective function's per-acre profit coefficients $\pi_{i,j,T}$ proceed directly from U_{jT}. They are defined exogenously for each county *j* at the beginning of each season *T*, with the dynamic factor being current commodity prices:

Eq. 8-2: $$\pi_{i,j,T} = \text{yield}_{i,j} \bullet \text{price}_{i,T} - \text{cost}_{i,j}$$

For cotton and sorghum, yield averages are calculated for irrigated and unirrigated crops separately. It is assumed that, at the beginning of any given planting season, a farmer has in mind a crop's average yield irrespective of any unforeseen event that might uniquely affect yield for the coming year.

$Price_i$ is the market price of *i* at the time of planting, adjusted to 1998 dollars. For cotton and sorghum, the price variable includes direct government payments.[2] Even though the two largest crops — cotton and sorghum — are harvested during the third quarter of the year, prices used are those received by Texas farmers during the first quarter. This is because (a) there is a strong empirical correlation between first- and third-quarter prices for the same year, (b) many farmers in the Valley have their production under contract long before harvesting, and (c) the objective function seeks to capture *expectations* for profit rather than

2 Statewide subsidy rate is calculated by taking the total payments to Texas for the crop, and dividing by statewide production. This results in a payment-per-unit of production rate that is added to the price received by farmers. The sum is then adjusted for inflation.

actual profit, and the information contributing to a farmer's expectation is prices at planting.

The value $cost_i$ is the per-acre cost of cultivating i and is held constant over time and between counties. Cost information is taken from the annual regional survey of farmers conducted by Texas Agricultural Extension Agency's office in the Rio Grande Valley, and applying the 1998 figures to all years. With price data adjusted for inflation, the expected profit for all years is expressed as 1998-dollar equivalents.

In this simulation, grapefruit and oranges are not included as decision variables. Planting an orchard is not a decision made each year (it takes citrus trees up to seven years to mature), so a citrus farmer would not respond to the year-to-year factors being modeled here. The expected profit functions for citrus could have been modeled by calculating the net present value of future revenue streams, but the extra level of complexity would have added nothing to the model's intended purpose. Historical data described in the previous chapter show that a citrus farmer's land choice at the beginning of the year is affected by cataclysmic events (specifically, killing freezes that wipe out a crop) rather than by year-to-year changes in prices and water availability. Instead, the model simply takes the 1998 citrus acreages as constant values for all periods of the simulation. The total acreage involved is relatively small: about 12 percent of irrigated acreage, and 5 percent of all acreage.

Translating the risk component of Equation 8-1 into an objective function is more complex than the profit component. But its inclusion is important: It casts the objective function as a portfolio problem, an approach developed for investment analysis but which is often used in agricultural economics to capture the risk-spreading effect of crop diversity.[3]

This methodology was explained in detail in the previous chapter. Here, we further note that the matrix of terms obtained from multiplying vector $\boldsymbol{A}_{j,T}$, vector transpose $\boldsymbol{A'}_{j,T}$, and covariance matrix σ^2_j is quadratic. Each cell along the diagonal of the matrix contains a squared decision variable; each off-diagonal cell contains two decision variables multiplied by each other. Consequently, we must use quadratic programming rather than linear programming to optimize the land decision.[4]

The final component of the objective function exerts an effect only when water supplies are below the level needed to sustain the level of irrigation required by the decision variables. We may think of this water deficit as speculative water — a volume that the farmer expects to use over the coming season but does not yet have on hand. The speculation is that the water will arrive in the form of rainfall or additional inflow in time to meet some of the crop water demands.

The model penalizes rather than prohibits water deficits, because to constrain expected irrigation could jeopardize the simulation when supplies are low. As will be explained in the next section, the decision vari-

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3 See Peter J. Barry, ed., *Risk Management in Agriculture* (Ames, Iowa: Iowa State University Press, 1984) and John Eatwell, Murray Milgate, and Peter Newman, eds., *The New Palgrave: Finance* (New York: W.W. Norton & Co., 1989).

4 Here, we used the generalized reduced gradient (GRG2) algorithm developed by Leon Lasdon and Allan Waren, which is the engine used in major spreadsheet solver applications. It is possible, however, to algebraically construct a linear approximation of the uncertainty matrix so that this same analytical approach can be used in large-scale water basin simulation applications that use mixed-integer linear programming. This will be done in future research using the Oasis water modelling software developed by Water Resource Management Inc.

ables are all bounded. Even if all the irrigated crops are at their lower bounds, some amount of irrigation will still be required. If that lower-bound requirement is more than the water in storage, constraining expected irrigation to only the water on hand would lead the simulation down the path of infeasibility.

The water deficit penalty of $20 per acre-foot is based on the price at which irrigation was bought and sold during healthy market conditions in 1995 and 1996. ("Healthy" means a relatively large number of deals and a high total volume of water traded. See Table 5-3 in Chapter 5.) The penalty needs to be non-trivial, but not so onerous that it unfairly penalizes a farming unit forced (by other constraints) to speculate on future water. On the actual spot market for irrigation in 1995 and 1996, $20 per acre-foot was a typical price paid by buyers under what may be considered normal market conditions. Here, we interpret that price as the bet lost by farmers who gambled on having enough water, but were forced by circumstances to purchase additional supply. By setting the penalty at this level, a farming unit unable to cut its planting any further is permitted to speculate on water without bankrupting the objective function. And by setting the penalty at a price level revealed by the water market, we also allow for the possibility of dealing: A farmer may actually *choose* to take a deficit if there's a prospect that the additional profits might outweigh the risks.

It should be kept in mind, however, that although its magnitude is based on a market price, the penalty does not serve a market function in the simulation. The penalty remains in effect regardless of whether a water market exists or not. Rather, this penalty is understood to be the monetary answer to the question "How much is a farmer willing to bet that a certain amount of speculative water will arrive in time?"

How the constraints are formulated

Many factors other than water affect what a farmer decides to plant. Paid-off capital equipment, expertise, and other considerations limit the extent to which a farmer can switch from one crop to another. Rather than identifying these factors and attempting to model them explicitly, this model simply accepts these factors for what they are: constraints on crop switching. So for each crop included in the simulation, the feasible amount of planted acreage is bounded by the historical high and low for the period 1978 to 1998. These upper and lower bounds proxy all the intangible factors that limit the flexibility of planting decisions.

The decision variable bounds also serve another function crucial to the simulation. When a variable resolves to either its upper or lower bound, that bound becomes a binding constraint and it takes on a shadow price. The shadow price represents the degree to which the value of the objective function would improve if the binding constraint were relaxed by one acre. So while running the simulation under two different sets of operating rules may both show sugarcane planting at its bounded maximum, the difference between the shadow prices would show which scenario results in the greatest economic pressure to push the bound higher.

In addition to the bounds on individual crop plantings, there are also aggregate constraints based on the amount of land physically available. Constraint 2 represents the historical high and low values for total planted acreage from 1978 to 1998 in each county. All crops included in the simulation are governed by this constraint set.

Constraint 3 is similar to Constraint 2, except that it includes only cultivated land that is irrigated. Making land irrigable involves some capital investment that can be as simple as digging ditches or as technologically intensive as installing timed precision-application sprinklers. So while it is easy to decide not to irrigate land that has been prepared for irrigation, turning previously dry-farmed acreage into irrigable land is neither quick, easy, nor costless — hence the need to treat irrigated land separately. Only onions, sugarcane, irrigated cotton, and irrigated sorghum are affected by this constraint set.

The main function of Constraint 4 is to define the water deficit that appears in the objective function; it links the decision variables (acres planted in each crop) to the water deficit penalty. Each crop has a certain water requirement, and the technology used to deliver its irrigation has a certain efficiency. Evapotranspiration levels (ET) divided by irrigation efficiencies (φ) multiplied by the corresponding decision variables show the greatest amount of irrigation a farmer is likely to need during the ensuing year. This calculated amount — minus any water deficit — cannot exceed the volume of irrigation water in storage at the time of the planting decision.

In short, the first optimization calls for farming units to select at the beginning of each year the crop mix that promises the greatest profit with the least uncertainty, subject to upper and lower bounds on individual crops, total irrigated land, and total cultivated land and subject to the availability of water for irrigation.

Table 8-3. Objective function for the irrigation decision

Objective function for each month t:

$$\max \sum_{i,\,j,\,s} \text{weight}_{i,j,s,t}\ \text{delivery}_{i,j,s,t} - \text{buy}_{j,t}$$

$\text{delivery}_{i,j,1,t}$ (decision variables)	Acre-feet of irrigation delivered by farming unit *j* to demand segment *s* of crop *i* during month *t*. Each crop's monthly water demand is divided into three ordered segments: 1=viability, 2=ordinary yield, 3=best yield; water delivered to a higher segment is contingent on full satisfaction of lower segments.
$\text{weight}_{i,j,s,t}$ (coefficients)	Revenue per acre-foot of water used minus per-acre-foot irrigation costs, weighted and distributed across all three segments of a crop's water demand
$\text{buy}_{j,t}$ (decision variable)	The amount of irrigation purchased by farming unit *j* from another farming unit during month *t*. Assumed transaction cost (the coefficient on the decision variable) is $1 per acre-foot

Formulating the second objective function: irrigation

Once land is allocated among the various crop choices at the beginning of the year, it must be decide each month how much irrigation to apply. Acres planted — decision variables in the previous formulation — become inputs to the monthly irrigation decision.

The objective function for the water decision aims to maximize revenues net of irrigation costs while minimizing water purchases. Revenue potential is a function of irrigation applied throughout a crop's growing cycle. Table 8-3 outlines the objective function for the monthly watering decisions.

This objective is subject to a number of constraints. First, the economic weight of irrigation delivered to crop *i* by farming unit *j* during

Table 8-4. Constraints on the irrigation decision

Constraint	Purpose
5: $0 \le \text{delivery}_{i,j,s,t} \le \text{demand}_{i,j,s,t}$	Upper bounds on irrigation delivered for demand segment *s* of crop *i* by farming unit *j* during month *t*. The segments are ordered so that segment 2 receives no water until segment 1 has been completely satisfied, and 3 gets nothing until the previous two have been satisfied
6: $\text{sell}_{\text{Cameron},t} - \text{buy}_{\text{Hidalgo},t} = 0$ $\text{sell}_{\text{Hidalgo},t} - \text{buy}_{\text{Cameron},t} = 0$	An accounting identity to permit the buying and selling of irrigation between the two farming units modelled in the simulation.
7: $\sum_{i,s} \text{delivery}_{i,j,s,t} + \text{sell}_{j,t} - \text{buy}_{j,t}$ $\le \text{inflow}_{j,t} + \text{reservoir storage}_{j,t}$	To limit deliveries of water to all crops *i* by *j* during month *t* — net of selling and buying — to no more than what is available from inflow allocated to *j* during *t* and from *j*'s existing storage.
8: $\text{reservoir storage}_{j,t} + \text{inflow}_{j,t} -$ $\sum_{i,s} \text{delivery}_{i,j,s,t} + \text{buy}_{j,t} - \text{sell}_{j,t} - \text{spill}_{j,t}$ $= \text{reservoir storage}_{j,t+1}$	To update farming unit *j*'s reservoir storage balance at the end of month *t* after delivering water to crops *i*. The value $spill_{j,t}$ is the amount of water that must be released by *j* at the end of *t* without use when the ending balance would otherwise exceed *j*'s storage capacity
9: $0 \le \text{reservoir storage}_{j,t+1} \le \text{capacity}_j$	To ensure that water held in storage by farming unit *j* during month *t* is non-negative and does not exceed *j*'s storage capacity
For t>1, 10: $\text{demand}_{i,j,1,t-1}\,\text{bin}_{i,j,s,t} - \text{delivery}_{i,j,1,t-1} \le 0$ $\text{demand}_{i,j,s,t}\,\text{bin}_{i,j,s,t} - \text{delivery}_{i,j,s,t} \le 0$	To ensure that dead crops won't be irrigated; equivalent to the if-then statement, "If in any month a crop is denied the water it needs for basic viability, then apply no more water to it for the rest of the season," with binary variable $bin_{i,j,s,t}$ forcing $delivery_{i,j,s,t}$ to be zero if during the previous month delivery was less than that required to satisfy segment 1

month *t* must diminish as more water is applied, becoming zero when the crop's monthly water requirement is fully satisfied. Second, purchases and sales must be linked in a market framework. Third, what is delivered to all crops in any given month cannot be more than the water available (reservoir storage plus new inflows, net of any purchases or sales). Finally, there must be continuity in the system over time so that water use during month *t* defines a beginning balance for month *t+1*. These constraints are shown in Table 8-4.

How the second objective function is formed

The intermediate goal of a farming enterprise once the crop has been planted is to maximize net revenue. The focus is on revenue rather than profit because many costs are already sunk once the crop begins to grow. Moreover, harvest costs are not likely to vary tremendously regardless of the realized yield. Once an irrigated crop is planted, it embodies a maximum revenue potential that is realized by applying the ideal amount of water (holding all other factors constant). If less than the ideal amount of water is applied, yield per acre goes down — and so too does revenue.

It also matters when the water is applied. Cotton requires more water in April and May than it does in March or June, and scrimping on irrigation during the peak growing time cannot be offset by extra watering during the maturation cycle.

Let us define $\textit{water demand}_{i,j,t}$ as the amount of water (in acre-feet) required by a farming unit *j* during month *t* to grow what it has planted in crop *i* so that *i* achieves its best yield at harvest time. The value for $\textit{water demand}_{i,j,t}$ is exogenously determined each month by evapotranspiration requirements, acres planted, and irrigation efficiency. The formula is

Eq. 8-3: $$\text{acres}_{i,j,t} \bullet \text{ET}_{i,j,t} \bullet \varphi^{-1}_{i} = \text{water demand}_{i,j,t}$$

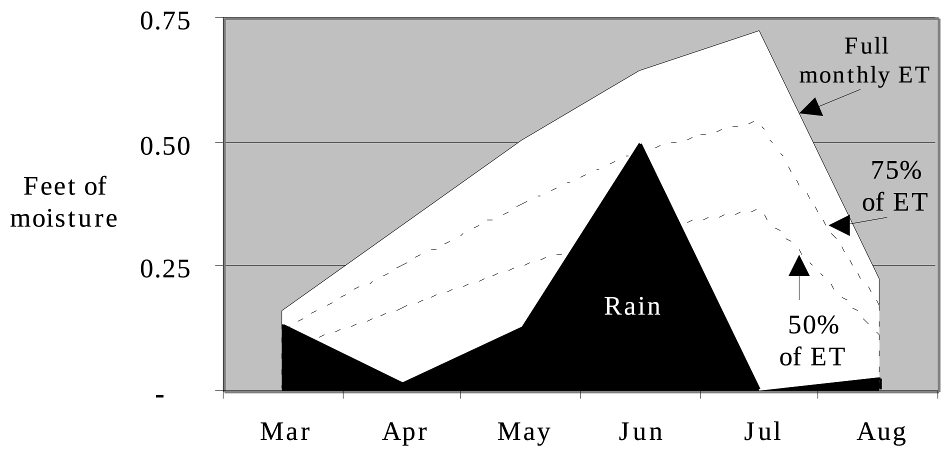
where $acres_{i,j,t}$ is the amount of land farming unit *j* has planted in crop *i* as of month *t*, $ET_{i,j,t}$ is crop *i*'s water requirement for month *t* (measured in feet), and φ_i^{-1} captures the irrigation efficiency associated with crop *i*.

Let us now define *irrigation demand*$_{i,j,t}$ as *water demand*$_{i,j,t}$ minus rain, or in other words, the amount of a crop's water demand not satisfied by rainfall. As detailed in the previous chapter, it is assumed that a foot of rainfall is equivalent to about .58 feet of applied irrigation, and that this number can be further broken down into .29 divided by the assumed overall level of irrigation efficiency, taken to be 50 percent. Rain excess of the crop's natural water demand is treated as runoff and disregarded, in which case irrigation demand becomes zero.

Figure 8-3 illustrates the difference between water demand and irrigation demand for cotton. The upper curve represents cotton's water requirement throughout its growing season, while the bottom curve represents rainfall adjusted by the coefficient 0.58. *Irrigation demand* would be the area between the two curves. In this example for 1993, *irrigation demand* was nearly the same for April, May, and June, even though cotton's normal *water demand* grows considerably.

To approximate the nonlinearity of the water-to-yield relationship, we first break demand into three consecutive segments *s*: irrigation delivery that is adequate to ensure the crop's survival and basic viability (segment 1), an additional amount of irrigation with which the crop

Figure 8-3. Example of monthly irrigation demand for cotton, 1993



Full monthly ET is cotton's evapotranspiration curve for Hidalgo County, and is divided into 75% and 50% segments. *Rain* is monthly precipitation recorded in McAllen by the National Weather Service in 1993, multiplied by a factor of 0.58 to adjust it to an irrigation equivalent. Cotton's demand for irrigation was the area between the two curves during any given month.

could thrive well enough to realize its ordinary yield (segment 2), and a final "topping off" amount that would result in the best yield possible (segment 3). Segment 1 comprises the first 50 percent of a crop's monthly ET, segment 2 the next 25 percent, and segment 3 the final 25 percent.

Monthly rainfall is applied to segment 1 first. If rainfall alone is enough to satisfy the crop's viability needs for that month, *irrigation* $demand_{i,j,1,t}$ equals zero and any rain beyond that which offsets the first demand segment is applied to the second demand segment. Otherwise, demand for the first segment is the difference between rain and 50 percent of the crop's total ET for the month.

The upper bounds for the each demand segment are defined as follows:

Eq. 8-4: $$\max\Big|_{0}^{\text{irrigation demand}_{i,j,t} - 0.5 \ \text{water demand}_{i,j,t}} = \text{demand}_{i,j,1,t}$$

Eq. 8-5: $$\max\Big|_{0}^{\min\big|_{0.25 \ \text{water demand}_{i,j,t}}^{\text{irrigation demand}_{i,j,t} - 0.25 \ \text{water demand}_{i,j,t}}} = \text{demand}_{i,j,2,t}$$

Eq. 8-6: $$\min\Big|_{0.25 \ \text{water demand}_{i,j,t}}^{\text{irrigation demand}_{i,j,t}} = \text{demand}_{i,j,3,t}$$

In words, $demand_{i,j,1,t}$ is what remains of irrigation demand (which, recall, is net of rain) after deducting what is to be given to the other two segments to fulfill. The more it rains, the smaller $demand_{i,j,1,t}$ becomes, up to the point at which $demand_{i,j,1,t}$ becomes zero.

Equation 8-5 says that $demand_{i,j,2,t}$ is what remains of irrigation demand after deducting what is to be given to the last segment to fulfill, but cannot exceed 25 percent of total water demand. If rain reduces irrigation demand to less than half of total water demand, then $demand_{i,j,2,t}$ gets smaller the more it rains, up to the point at which $demand_{i,j,2,t}$ becomes zero.

The last segment, $demand_{i,j,3,t}$,is simply irrigation demand (if rainfall completely offsets the other two segments), or 25 percent of water demand, whichever is smaller.

With irrigation demand broken into segments and with each segment defined, the next step is to weight each segment according to its estimated contribution to yield. Generally, the first segment (survival and viability) accounts for a disproportionately large share of yield, with the third segment increasing yield only slightly. We operationalize this general approach with the proportions explained in the previous chapter:

- Satisfying all of a crop's water demand results in the best yield obtainable,
- Satisfying 75 percent of a crop's water demand results in 94 percent of best yield, and
- Satisfying 50 percent of a crop's water demand — enough for survival and viability —results in 75 percent of best yield.

Let us now define the parameter $\rho_{i,j,t}$ as what farming unit *j* anticipates to be the harvest revenue generated by crop *i* per acre-foot of water consumed by the crop under optimal conditions, given commodity prices during month *t*. Specifically,

Eq. 8-7:

$$\frac{\text{yield}_{i,j} \quad \text{price}_{i,t}}{\text{annual ET}_{i,j}} = \rho_{i,j,t}$$

or

$$\frac{\frac{\text{units}}{\text{acre}} \quad \frac{\text{dollars}}{\text{unit}}}{\text{feet of water}} = \frac{\text{dollars}}{\text{acre-foot of water}}$$

where $yield_{i,j}$ is the average productivity of crop *i* per acre for farming unit *j*, $price_{i,t}$ is the current price of *i*, and $annual\ ET_{i,j}$ is the annual evapotranspiration of *i*. High-dollar crops score a large $\rho_{i,j,t}$, but so, too, do crops that use water sparingly.

We now use the proportions explained in the previous chapter to distribute $\rho_{i,j,t}$ across a crop's three demand segments. The weight for crop *i*'s viability demand (segment 1) becomes $0.75\rho_{i,j,t}$; for regular yield, $0.19\rho_{i,j,t}$; and for best yield, $0.06\rho_{i,j,t}$.

The resulting weights, $\rho_{i,j,s,t}$, prioritize water delivery among various crops so that those generating the most revenue per acre-foot of water get preference. Conceivably, meeting a high-profit crop's third-tier irrigation demand could command a greater weight than the ordinary or even the survival demand of a low-profit crop. The weight also transforms each decision variable — acre-feet of water delivered — into a dollar equivalent.

Constructing the demand weights in this way also has a very useful property: It orders the delivery of irrigation to each crop's three demand segments. Crop *i*'s viability demand segment will always command a greater weight than its normal-yield and best-yield segments, so it will always be satisfied first. Water for best yield will always be delivered last, because it carries the lowest weight.

One further adjustment must be made to $\rho_{i,j,s,t}$. Although sunk costs are assumed not enter into the irrigation decision, the cost of irrigation itself does. The simulation therefore poses the question: "Will the additional revenues a farmer gets from applying a certain amount of water be more than what it costs to apply that amount?" As $\rho_{i,j,s,t}$ is an expression of revenues per acre-foot of water, the weight is easily adjusted by subtracting the cost per acre-foot of delivering irrigation: $\rho_{i,j,s,t} - 13$.

Here, we assume that an acre-foot of irrigation costs about $13 to deliver. This is based on cotton and sorghum production costs for 1998 as estimated by the Texas Agricultural Extension Service, with the TAES's estimated per-acre cost of $28 adjusted by the two crops' per-acre water demand. (If an acre of a crop needs around 2.2 acre-feet of water — the average of annual ET for cotton and sorghum, as shown in the previous chapter — $28 per acre becomes $13 per acre-foot.) Including this adjustment for irrigation costs ensures that water will not be applied to a crop unless it is profitable to do so.

The second term of the objective function, $buy_{j,t}$, relates to water marketing and represents the amount of water purchased by farming unit j from another irrigation holder. By including it in the objective function in this manner, there is an implicit penalty of $1 for each acre-foot of water purchased. This minimizes the amount of water bought, preventing the simulation from spuriously allowing one party to hoard all irrigation supplies.

It is important to make clear, however, that the implicit coefficient on $buy_{j,t}$ ($1 per acre-foot) represents the estimated transaction costs of a market transfer, and not the price at which the trade actually takes place. A transaction cost differs from the exchange price in that it represents the efficiency loss involved in the trade — "nuisance" costs that do not contribute to the welfare of either the buyer or the seller. Legal expenses, time spent finding a seller, and agency processing all contribute to a deal's transaction costs.

In order for a rational trade to occur, the buyer must be willing to pay enough to overcome the transaction costs and to compensate the seller for doing without the water. But while transaction costs are included in the objective function, compensation to the seller is not. The reason for this comes from basic economic theory and from the nature of mathematical programming. The value to which the objective function resolves is a reflection of the net change in overall economic benefit to society. Money received by the seller represents a transfer of economic benefit from one party to another, however, and is not a net change in overall social benefit. The additional productivity that happens when the purchaser puts bought water to use does result in a net social gain, but this is captured by the $delivery_{i,j,s,t}$ variables and their weights.

How the constraints are formulated

Constraint 5 simply defines the demand segments to be satisfied in the objective function; the upper bounds $demand_{i,j,s,t}$ are calculated as explained previously.

Constraint 6 creates a water market by linking the storage supplies of both farming units. Aside from the common-sense budget identity (what the buyer buys must equal what the seller sells), this constraint provides a platform by which the marginal productivity of water can be compared between the two users. When supplies are less than demand, the available water can migrate towards the most productive uses while curtailing the least productive uses, even if it means moving water from one farming unit to another. Under no-market scenarios, the non-decision variables $sell_{j,t}$ are constrained to zero, which effectively prevents any exchange of stored irrigation.

Physical constraints are embodied in constraints 7, 8, and 9. The total amount of water delivered by farming unit j to its crops during any month t cannot be more than what is physically available at the time, either from storage, new inflow, or purchases of irrigation from other farming units (if allowed). If a water market is assumed, then irrigation deliveries net of trading must be within the bounds of what is on hand. Water activity during month t results in a reservoir storage balance for month $t+1$, subject to j's maximum storage capacity, that will be used by j in the next time period.

Testing for differences: 12 scenarios

The three factors that change throughout the scenarios to be compared are whether or not water marketing is permissible, whether or not there is widespread use of water-conserving irrigation technologies, and whether farmers are risk-averse or risk-neutral. These effects are controlled by adjusting parameters and by the inclusion of special variables.

If a water market does not exist, the variables $sell_{j,t}$ are constrained to zero in the irrigation optimization. For the land decision, each farming unit j's water deficit is determined by j's own water reserves if there is no market. If water trading is allowed, however, the market is assumed to act as a new potential supply of water, and each user's water deficit is calculated on the basis of combined storage. In other words, a deficit does not exist in a market if there is enough water available for purchase. For the irrigation decision, the variables $sell_{j,t}$ are unconstrained when a market exists.

The effects of water-conserving irrigation practices are captured by changing the exogenous parameter for irrigation efficiency, φ. As onions crops always require special irrigation, the efficiency coefficient for onions is assumed to be 0.6 for all runs. For the nonconservation runs for all other crops, it is assumed that the primary irrigation method is furrow, and φ is set at 0.5. For the conservation runs, φ is 0.6 for all crops. This allows (a) testing the results for sensitivity to assumptions about φ, and (b) estimating how overall benefits might change with a 20 percent improvement in irrigation efficiency.

Table 8-5. Parameters for the scenarios modelled

		Water market	**No water market**
Current irrigation efficiency system-wide	**Risk-agnostic**	*sell* unconstrained φ = .5 λ = 0	*sell* = 0 φ = . 5 λ = 0
	Somewhat risk-averse	*sell* unconstrained φ = .5 λ = 2.5×10^-8^	*sell* = 0 φ = .5 λ = 2.5×10^-8^
	Very risk-averse	*sell* unconstrained φ = .5 λ = 5×10^-8^	*sell* = 0 φ = .5 λ = 5×10^-8^
20% improvement in irrigation efficinecy system-wide	**Risk-agnostic**	*sell* unconstrained φ = .6 λ = 0	*sell* = 0 φ = .6 λ = 0
	Somewhat risk-averse	*sell* unconstrained φ = .6 λ = 2.5×10^-8^	*sell* = 0 φ = .6 λ = 2.5×10^-8^
	Very risk-averse	*sell* unconstrained φ = .6 λ = 5×10^-8^	*sell* = 0 φ = .6 λ = 5×10^-8^

Risk aversion is a factor only in the land decision. It is reflected in the parameter λ, which takes on a value of 0 if farmers are assumed to act in a manner completely agnostic to risk. To test the sensitivity of the model to risk assumptions, two values of λ are used in different scenarios: 5×10^{-8} and 2.5×10^{-8}.

The various runs of the simulation are summarized in Table 8-5. With these changes between the different scenarios, the comparisons will focus on differences in the objective function values, and more importantly, changes in the crop portfolio and in the shadow prices associated with the binding land constraints. The comparisons of greatest interest will be between each pair of market/no-market scenarios. This is what we will examine next.

Chapter 9: Results of the simulation

The theoretical assumption behind this study is that farmers regard a water market as an additional source of irrigation that, for those who can afford to pay, reduces the risk of water shortage. Farmers are risk-averse, and a water market changes their behavior because it reduces uncertainty, not because it is an additional source of income.

The behavior that this theory predicts is that the farm sector as a whole will use more water, not less. It will do so because high-profit, water-intensive crops will be a safer bet. Extra irrigation will be available, higher profit margins will make buying the water more economical, and therefore farmers will feel more secure planting the water-intensive crops.

Another predicted behavior is that with irrigation available for purchase on an as-needed basis, farmers will be less inclined to switch from irrigation methods with low water-efficiency (such as furrow or flood irrigation) to water-conserving alternatives. What is *not* predicted is the conventional-wisdom scenario: That farmers will irrigate more efficiently so that they can sell what they conserve.

These are the behaviors that the simulation described in the two preceeding chapters attempts to model. What farmers plant, how much water they use, how much profit they expect, whether they have an economic incentive to irrigate efficiently, and how these four things change under a water market are the insights to be extracted from the results.

The specific hypotheses to be tested are that when short-term leasing of irrigation entitlements is allowed:

- Farm profits are higher;
- Reservoir storage falls faster;
- There is less incentive to invest in efficient irrigation systems; and
- There is more incentive to plant high-profit, water-intensive crops.

The following sections of this chapter deal with each of these four hypotheses in turn. Each section begins with a restatement of the hypothesis and a description of what one would expect to see in the results of the simulation were the hypothesis true. The section will then describe the relevant results, comparing the expected outcomes to what was actually obtained.

The chapter concludes with a brief summary of how the well the study's theoretical framework — as conveyed by the four hypotheses — fared under the simulation. Detailed results for all twelve of the simulated scenarios are included in the Appendix.

Hypothesis: Under a water market, farm profits are higher

> *Expected result: Objective function values for the annual planting decisions would be consistently higher for the market scenarios than for the corresponding non-market scenarios.*

Under each scenario simulated, the land decision involves optimizing an objective function. The values to which these annual objective functions resolve indicates the expected net worth — anticipated revenues minus costs, based on current crop prices and adjusted for uncertainty — of what farmers throughout the region decide to plant for the ensuing year. Farmers plant what they believe will give them the maximum profit possible given the rules governing the scenario, exogenous factors (i.e. prices and rainfall), and current reservoir storage.

The year-to-year objective function values for each scenario's land decisions are shown in Figure 9-1. To test the above hypothesis, however, it is necessary to compare the trend lines shown in this figure. Specifically, the objective function values for each of the six scenarios in which irrigation purchases are prohibited are subtracted from the objective function values for the corresponding market scenario:

Eq. 9-1:

$$\text{obj}_{T,\lambda,\varphi,\text{ market}} - \text{obj}_{T,\lambda,\varphi,\text{ no market}} = \Delta\text{obj}_{T,\lambda,\varphi}$$

where $obj_{T,\lambda,\varphi,\,market}$ is the value of the planting decision's objective function for year T assuming a risk factor of λ (5×10^{-8}, 2.5×10^{-8}, or zero), a system-wide irrigation efficiency of φ (either 50 percent or 60 percent), and a water market; $obj_{T,\lambda,\varphi,\,no\ market}$ is the objective function value for the same year, same efficiency, and same risk assumptions when irrigation leases are prohibited; and $\Delta obj_{T,\lambda,\varphi}$ is the difference in objective function values due solely to the presence of a water market.

If a water market were to improve expected farm profits, one would look for $\Delta obj_{T,\lambda,\varphi}$ to be positive. That is, the market objective function values should be greater than their corresponding no-market objective function values.

As Figure 9-2 illustrates, this was indeed the case. Under no circumstance did a water market result in less overall benefits. Only at the

Figure 9-1. Objective function values for the land decision

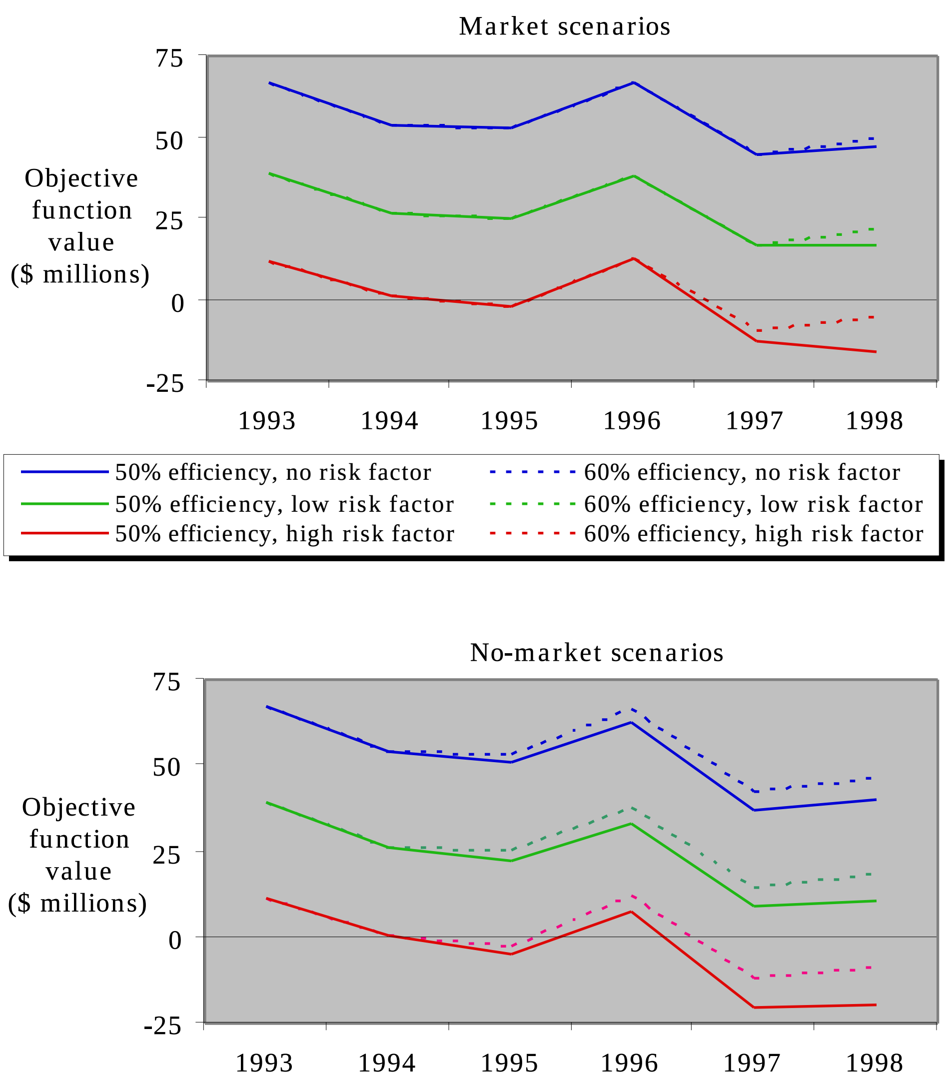
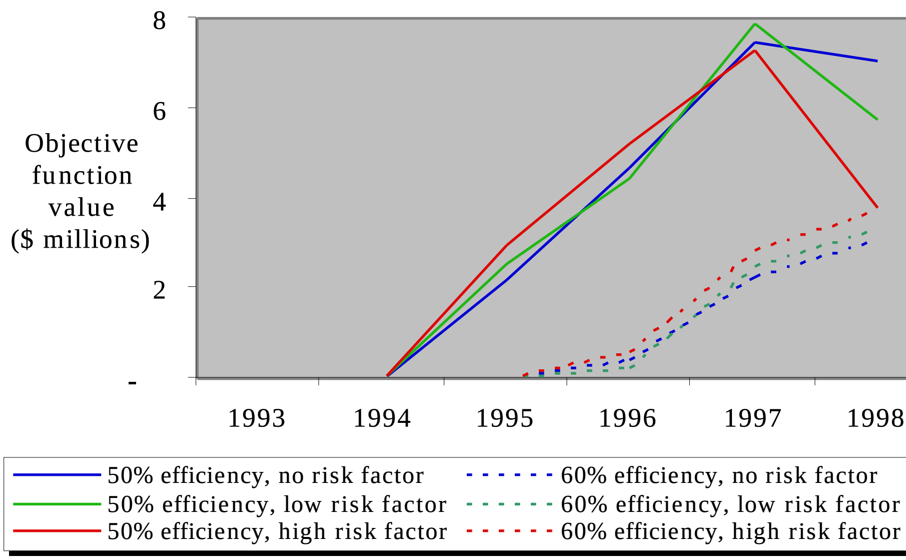


Figure 9-2. Differences between market and non-market scenarios in objective function values (land decision)



beginning — when water for irrigation was abundant — was there no difference between the market and no-market objective function values.

An especially interesting aspect of the results shown in Figure 9-2 is that a water market always helped boost expected profits more when a lower degree of irrigation efficiency was involved. In other words, less irrigation efficiency meant more economic benefit when moving to market-based water regime. In addition, a water market began enhancing the objective function values a year earlier in the scenarios assuming a lesser degree of water conservation.

A corollary to the above result is that there was no economic incentive to move towards greater irrigation efficiency under a water market.

The objective function values displayed in Figure 9-1 show the three risk scenarios moving somewhat parallel to one another for all market and irrigation efficiency scenarios. Under each of the runs assuming no water market, the objective function values are greater when irrigation is more efficient. Under the market scenarios, efficient irrigation brought additional economic benefit only during the worst year of the drought (1998).

Patterns in the land objective function values were robust to different assumptions about risk; in most cases, it mattered little whether the risk factor was high, low, or even zero. The only exception was in 1998, when severe reservoir shortages led to risk-sensitive results under the lower irrigation efficiency scenarios. The greater the risk factor, the less a market contributed to overall benefits when water supplies were critically low.

A final word of clarification is in order. The value of the planting decision's objective function is essentially a dollar value, but strictly speaking, it cannot be thought of as money in the bank. First, these values reflect *anticipated* profits over the ensuing year, not profits actually realized. Second, the values are more appropriately understood in the economic sense of *utility*; high potential profits are less useful as they grow in uncertainty. Thus we may think of the objective function value as how useful farmers perceive their cropping strategies to be, inclusive of both anticipated profit and risk.

Hypothesis: Under a water market, reservoir storage falls faster

> *Expected result: Predicted reservoir storage levels would be consistently lower for all market scenarios than for all corresponding non-market scenarios.*

The monthly irrigation decisions allocate water to all crops to extent that it is profitable to do so (i.e., the additional revenues are greater than the cost of irrigating). Once irrigation has been delivered for the month, the simulation then updates the water balance for each farm decision unit. The sum of all water balances for that month indicates the amount of water stored in the reservoir that is available for further irrigation.

Testing the above hypothesis is a straightforward matter of comparing storage levels between scenarios that differ only in whether or not water marketing is allowed:

Eq. 9-2: $$\text{storage}_{t,\lambda,\varphi,\text{ market}} - \text{storage}_{t,\lambda,\varphi,\text{ no market}} = \Delta\text{storage}_{t,\lambda,\varphi}$$

where $storage_{t,\lambda,\varphi,\ market}$ is the amount of water held by both Cameron and Hidalgo counties during month t when irrigation entitlements may be leased, $storage_{t,\lambda,\varphi,\ no\ market}$ is the amount when water marketing is not allowed, and $\Delta storage_{t,\lambda,\varphi}$ is the difference between the two. (Indices λ and φ are defined as in the previous section.)

If a water market were to result in more irrigation and lower reservoir levels, one would look for $\Delta storage_{t,\lambda,\varphi}$ to be negative. That is, there should be less water stored in the reservoirs when holders of irrigation rights are allowed to lease their entitlements to others.

Figure 9-3 shows the simulated irrigation storage levels under all twelve scenarios, grouped by assumed irrigation efficiency. (Actual storage levels are also included for comparison.) A visual examination of the data shows what one might expect: that storage levels are higher when irrigation efficiency is higher. In addition, the scenarios assuming 50 percent irrigation efficiency tend to cluster more closely around the actual storage levels than do the scenarios assuming a higher irrigation efficiency, suggesting that the lower assumption is a reasonable approximation of overall irrigation efficiency in the Lower Rio Grande Valley.

The differences described in Equation 9-2 are shown graphically in Figure 9-4. These results show that a water market always caused reservoir storage to drop faster. The differences were greater (and were apparent sooner) under the scenarios assuming lower irrigation efficiency. This suggests that not only do reservoir levels fall more under a water market, the draw-down is faster when farmers overall are not irrigating efficiently.

Under the assumption of 50 percent irrigation efficiency, the difference between market and non-market reservoir storage was insensitive to the magnitude of the risk factor used. This remained the case up to the summer of the final year, when critical water shortages seriously disturbed all of the scenarios. For 1998, the difference between the market and no-market scenarios was smallest when risk was excluded from the analysis, and greatest when a high risk factor was used.

A factor related to reservoir storage levels is “speculative water.” Recall from the previous chapter that speculative water is defined mathematically as the total water required to irrigate all crops at their chosen planted acreages in excess of water currently held in storage.

Figure 9-3. Predicted irrigation storage under the 12 scenarios

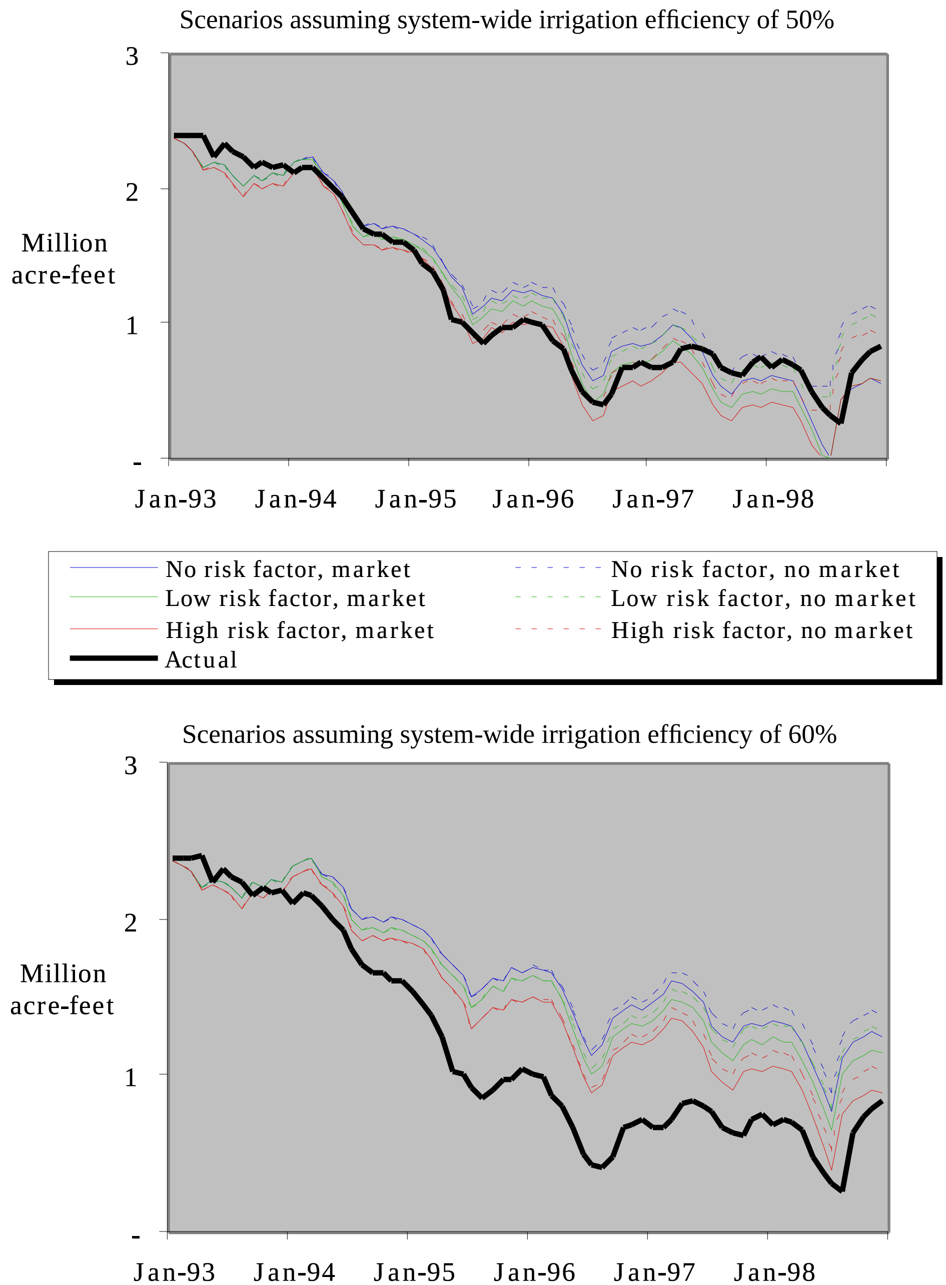
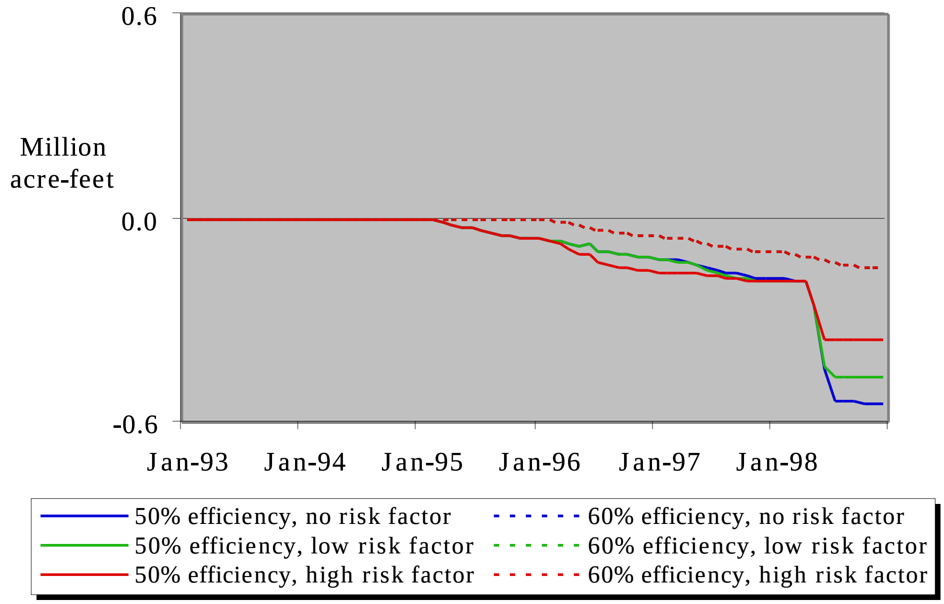


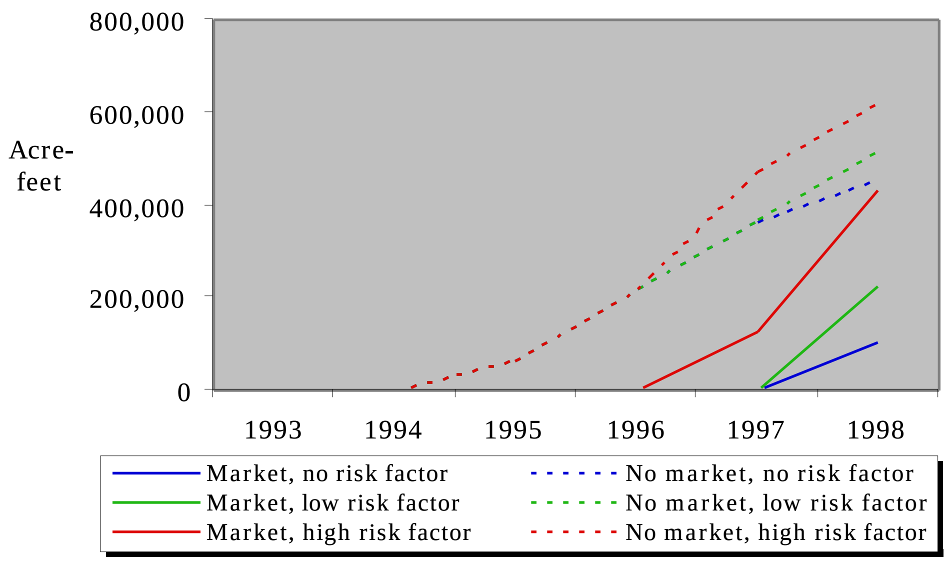
Figure 9-4. Differences in simulated storage levels between market and non-market scenarios



Market minus non-market storage levels for scenarios with same conservation and risk assumptions. Positive values indicate more storage under market scenario; negative values indicate more storage under non-market scenario.

Figure 9-5 shows the amounts of speculative water obtained under each scenario. The large difference between market and non-market scenarios, though eye-catching, is not the most important insight to be gleaned from this figure, however. (The absolute difference is due largely to the way the simulation is structured.) The surprising — and somewhat ironic — outcome is that taking risk into account actually increases the tendency to speculate on water under the market and no-market scenarios alike.

Figure 9-5. Speculative water under 50% irrigation efficiency



"Speculative water" is the total amount of water required to irrigate the selected crop portfolio minus the amount of water currently held in storage. When no water market exists, speculative water is computed on the basis of each user's own storage. When water marketing is allowed, it is computed on the basis of combined storage.

The irony (that risk aversion promotes more water speculation rather than less) may be explained by considering the variances for dry crops and for sugarcane. Dry crops, especially cotton, have a high variance of profitability that tends to drag the objective function value down as the risk factor λ is increased. This means a greater tendency to plant more irrigated crops. Among these irrigated crop choices, sugarcane has a high profit margin that is relatively stable. Sugarcane's low variance thus tends to attract economic activity more strongly when λ increases, complementing a commensurate flight from high-risk, low-profit dry crops. That the alternative, sugarcane, also requires much more water does not stop the risk-driven change in cropping patterns.

Hypothesis: Under a water market, there is less incentive to invest in efficient irrigation systems

> *Expected result: The increase in objective function values due to an increase in irrigation efficiency would be less under market scenarios than under non-market scenarios.*

Some of the results described in the previous sections suggest two mutually reinforcing trends that mitigate against conservation under a water marketing regime. One is that low irrigation efficiency adds to a market's tendency to draw down reservoir levels during drought. The other is that the expected benefits to be derived from irrigating efficiently vanish or are reduced under a water market. More irrigation is used under a water market, and there is less incentive to find better ways of irrigating.

This section takes a closer look at what the simulation says about irrigation efficiency. The conceptual approach taken here begins with the assumption that upgrading irrigation methods from the status quo to something more efficient tends to increase a farmer's net operating margin (harvest revenues minus operating costs, exclusive of capital costs). This increase may or may not be large enough to justify the additional capital cost of upgrading. The question raised by this section's hypothesis is whether a water market changes the operating margin so that an investment is harder to recoup.

The system-wide irrigation efficiency of 50 percent will be taken as the *status quo*, a convenience justified by the fact that simulated reservoir storage so closely follows actual storage in the six scenarios that use this efficiency rate. (See Figure 9-3.) The primary irrigation method used in the Lower Rio Grande Valley is furrow, with relatively little use of high-efficiency alternatives.

The economic incentive to switch from the *status quo* to something more efficient depends on the additional benefit to be gained. As was described earlier in this chapter, anticipated benefits are reflected in the land decision objective function values. If the objective function values for the high-conservation scenarios are greater than those of the *status quo* scenarios, then there will be an additional economic incentive to upgrade.

Testing the above hypothesis requires a two-stage comparison. The first question to be asked is, "Do overall benefits increase or decrease with conservation?" The second is, "Do conservation benefits change *differently* under a water market?" These questions may be answered by first taking the difference in objective function values between *status quo* and conservation scenarios, and then seeing how those six differences vary between market and no-market scenarios.

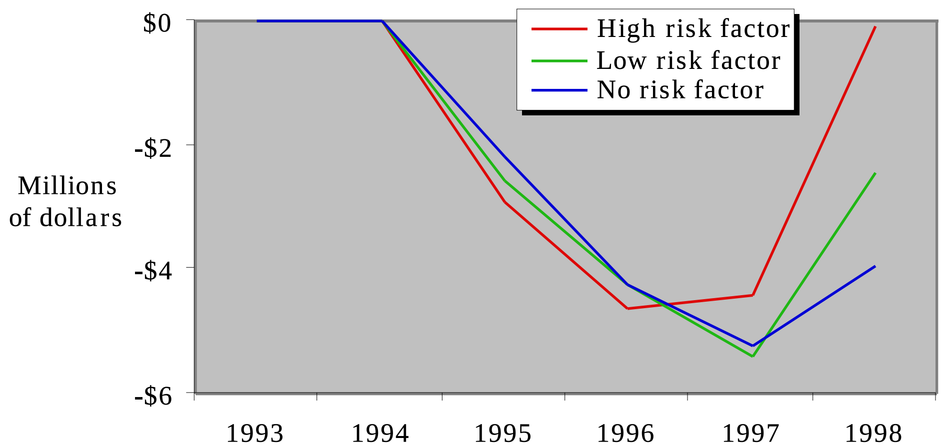
Eq. 9-3: $$\text{obj}_{T,\lambda,\,\varphi=60\%,\,\text{market}} - \text{obj}_{T,\lambda,\,\varphi=50\%,\,\text{market}} = \Delta\text{cons}_{T,\lambda,\,\text{market}}$$

Eq. 9-4: $$\text{obj}_{T,\lambda,\,\varphi=60\%,\,\text{no market}} - \text{obj}_{T,\lambda,\,\varphi=50\%,\,\text{no market}} = \Delta\text{cons}_{T,\lambda,\,\text{no market}}$$

Eq. 9-5: $$\Delta\text{cons}_{T,\lambda,\,\text{market}} - \Delta\text{cons}_{T,\lambda,\,\text{no market}} = \Delta\text{cons}_{T,\lambda}$$

where $obj_{T,\lambda,\,\varphi=60\%,\,market}$ and $obj_{T,\lambda,\,\varphi=50\%,\,market}$ designate objective function values for year T, risk factor λ, and a water market under, respectively, conservation and *status quo* scenarios; $\Delta cons_{T,\lambda,\,market}$ is the change in benefit due solely to moving from *status quo* efficiency to greater conserva-

Figure 9-6. How a water market affects benefits accruing from higher irrigation efficiency



Differences in objective function values as described in Equations 9-3 to 9-5.

tion. Equation 9-4 is the same thing for scenarios in which water trading is not allowed. In Equation 9-5, $\Delta cons_{T,\lambda}$ is how much a water market adds to or detracts from the change in objective function values.

The important attribute of $\Delta cons_{T,\lambda}$ is its sign. If negative, this value would suggest that a water market detracts from the economic incentive to upgrade irrigation technology; if positive, a market would add to it. Given the hypothesis of this section, the expectation is that $\Delta cons_{T,\lambda}$ would be negative.

Figure 9-6 shows that the indicator $\Delta cons_{T,\lambda}$ is never positive, and is negative to a greater degree as drought becomes more severe. What this suggests in plain language is that if investing in more efficient irrigation is not attractive to a farmer who can't buy extra water, it will be even less attractive to a farmer who can.

Of course, switching from low-efficiency to high-efficiency entails a capital cost that was not part of any scenario. Whether such a switch would be economical depends on the average cost of the investment (amortized over a period of time) versus the average savings in operating costs.

Amosson has estimated the net per-acre investment required for various kinds of sprinkler systems to be $220 to $240 per acre, and around $50 for surge systems.[1] Labor costs, how far water had to be pumped, and how often a crop had to be irrigated were the factors determining whether such investments made economic sense. Under assumptions of labor costs and lift requirements most closely resembling those of the Rio Grande Valley, switching to efficient irrigation methods was never profitable if the farmer continued to raise cotton, regardless of the kind of technology considered. For low-energy precision-application (LEPA) systems, investment costs were about $30 per acre more than the expected savings.

On the other hand, Amosson concludes that switching from furrow to LEPA could be profitable for crops with relatively higher water requirements. That conclusion is especially significant in the context of the present study because, as will be detailed in the next section, the water market in the Rio Grande Valley has tended to encourage more sugarcane cultivation. So while a market may discourage investment in efficient irrigation methods *ceteris paribus*, this negative effect may be

[1] Assuming coverage of 130 acres. Stephen H. Amosson, "An Economic Comparison of Alternative Irrigation Systems," presentation at the American Agricultural Economics Association annual meeting, Manhattan, Kansas, August 4-7, 1991.

somewhat offset if at the same time farmers are switching to more water-intensive crops.

Hypothesis: Under a water market, there is greater incentive to plant high-profit, water-intensive crops

> *Expected results: The reduced gradients for sugarcane would be higher under the market scenarios than under the non-market scenarios; for irrigated cotton and irrigated sorghum, the change in reduced gradient values due to a water market would be smaller than or opposite the change expected for sugarcane.*

If a quadratic programming (QP) model were a boiler, its reduced gradients would be the pressure gauges. Reduced gradients result when the QP optimization pushes a decision variable to its upper or lower bound. For example, if an iteration of the land decision were to place sugarcane acreage for Cameron County at its maximum, the reduced gradient for Cameron sugarcane would indicate how much the objective function would gain if one more acre of sugarcane could be planted. The higher the reduced gradient, the greater the economic pressure to plant more.

Conversely, a decision variable at its lower bound results in a reduced gradient with a negative sign. This may be regarded as how strongly the QP pushes to reduce the decision variable further than its lower constraint permits. If irrigated cotton in Hidalgo County were to resolve to its lower bound, the reduced gradient would show how much the objective function would improve if cotton planting could be reduced by one more acre. The lower the negative reduced gradient (that is, the larger its absolute value), the greater the economic pressure to plant less.

Based on this section's hypothesis, the expectation is that a water market would result in higher reduced gradients for high-profit crops that require a lot of water. In this case, the crop would be sugarcane. In the instances where the simulation places sugarcane acreage somewhere between the upper and lower bounds, the expectation is that more acres would be devoted to sugarcane under the market scenarios.

In addition, it would be expected that the reduced gradients for low-profit crops — here, irrigated cotton and irrigated sorghum — would increase under a water market to a much lesser extent than what would be expected for sugarcane, and may even decrease when a water market exists. Mathematically,

Eq. 9-6: $$GR_{T,\lambda,\varphi,\text{ market, crop}} - GR_{T,\lambda,\varphi,\text{ no market, crop}} = \Delta GR_{T,\lambda,\varphi,\text{ crop}}$$

Eq. 9-7: $$\Delta GR_{T,\lambda,\varphi,\text{ sugarcane}} > 0$$

Eq. 9-8: $$\Delta GR_{T,\lambda,\varphi,\text{ sugarcane}} > \Delta GR_{T,\lambda,\varphi,\text{ \{ irrigated cotton or irrigated sorghum \}}}$$

where Equation 9-6 defines the relevant relationship, and Equations 9-7 and 9-8 show the hypothesized relationships. $GR_{T,\lambda,\varphi,\, market,\, crop}$ is the reduced gradient associated with a particular crop, and $\Delta GR_{T,\lambda,\varphi,\, crop}$ is how the crop's reduced gradient differs from market to no-market scenarios for the same year, risk factor, and irrigation efficiency. (The index markers T, λ, and φ are defined as in the previous sections.)

Together, these expectations describe the mechanics by which a water market might cause reservoir levels to fall at a greater rate. The verification of both expectations would reflect a tendency to migrate from cotton and sorghum and towards sugarcane when water marketing is allowed. This would also account for the increase in overall economic benefits under a market.

There are no clear prior expectations for how onion acreage would be affected by a water market. Onions are a high-profit crop, but they require about the same amount of water as does cotton and much less than sugarcane needs. In addition, the profitability of onions is more price-sensitive than water-sensitive, and is highly erratic. There is no particular expectation for dry-farmed crops, except that its reduced gradients (and perhaps its predicted planted acreage) would be sensitive to different λ values.

The reduced gradients and acreage predictions for all scenarios are detailed in the Appendix. Generally, the results for sugarcane, irrigated cotton, and irrigated sorghum conformed with the expectations suggested by this section's hypothesis. This was especially so for Cameron County under *status quo* irrigation efficiency: Not only were the reduced gradients higher under the market scenarios, predicted acreage went to the upper bound under the market scenarios and to the lower bound under the no-market scenarios for the simulation years 1995-97. Under the improved irrigation efficiency scenarios, the same pattern was delayed a year.

The sugarcane trend was not as pronounced in Hidalgo County. In fact, during the final and driest year of the simulation, a water market actually caused planted acreage to retreat to its lower bound when farmers were assumed to be risk-agnostic and irrigating at *status quo* efficiency. When risk was part of the scenario, the opposite effect was seen earlier in the simulation: a market pulled sugarcane acreage *away* from the lower bound, a result that conforms to the hypothesis. For the scenarios assuming improved irrigation efficiency, a water market exerted no effect on the sugarcane results for Hidalgo County.

A market did not drive farmers further away from irrigated cotton and irrigated sorghum. In fact, the reduced gradients generally show a weakened push to plant less of these two crops under a water market. As predicted, however, the increase in reduced gradient values is not as pronounced as is the case for sugarcane. The interpretation: While the additional irrigation available under a water market relieves some pressure on all crops, most of that change is directed towards planting more sugarcane.

This is most readily apparent in Cameron County. Under status quo irrigation efficiency, a water market weakened the reduced gradients for irrigated cotton by about $100, and for irrigated sorghum by about $70. (The changes were about 10 percent smaller under the improved-irrigation scenarios.) A market added around $200 to Cameron sugarcane's reduced gradients, however. As mentioned previously, this shift in economic force was enough in some cases to move sugarcane planted acreage from its lower bound to its upper bound. Thus the main beneficiary of a water market clearly was sugarcane.

In Hidalgo County under *status quo* irrigation efficiency, a water market bumped up reduced gradients for irrigated cotton and irrigated sorghum by $40 to $90 for the risk scenarios. When λ was zero, a water market actually pushed farmers away from these two crops even harder; the reduced gradients were more strongly negative. By comparison, a market increased Hidalgo sugarcane's reduced gradients by $120 to $180 for the two risk scenarios, in both cases pulling planted acres away from the lower bound. For the risk-agnostic scenarios, however, a market pushed sugarcane planting to its lower bound during the year irrigation supplies ran out, which is opposite of what is predicted by the hypothesis.

Generally, risk assumptions affected the timing of the reduced gradient changes, but not their magnitude. While the results largely conformed to the hypothesis, the exceptions took place only under the risk-agnostic scenarios during the most severe drought year, and only in one county.

An interesting result outside the hypothesis' expectations was for unirrigated sorghum. This turned out to be the "slack" crop for both counties for all of the risk scenarios, in that it was never at an upper or lower bound at any time during the simulation. Two related explanations are possible. First, when a county's total land constraints demanded that more acres be planted, unirrigated sorghum tended to be the safest crop to add, due to its relatively low cost of production. Second, shifting irrigation from cotton or sorghum to sugarcane involves using the same volume of water on about half as much land. (See the evapotranspiration values in Table 7-3 on page 185.) This would require doing something with the other half of the land: either fallowing it, or dry farming it. Unirrigated sorghum is a low-cost option by which some additional income may be obtained, assuming prices do not drop so low that even a low-cost alternative would result in a loss.

One final point about interpreting the reduced gradient values must be made. Because these values arise from a quadratic programming model, they implicitly lie on a curve rather than a straight line. As a result, a reduced gradient value would converge to zero as the upper or lower bound were relaxed; it would not change at a constant rate. This contrasts with linear programming, in which a constraint's shadow price remains constant up to the point at which the constraint is no longer binding.

Conclusions

The results of the simulation largely conform to the hypotheses stated at the beginning of this chapter. The scenarios that included a water market showed

- More economic benefits accruing to the agricultural sector;
- Reservoir levels being drawn down faster;
- A weaker incentive to switch from furrow irrigation to methods that do a better job conserving water; and
- A general (if inconsistent) economic push towards planting more of a water-intensive crop.

Outcomes related to the first three hypotheses, which are expectations about *what* would happen, are for the most part robust to different assumptions about risk. Explaining *how* these effects come about, which the fourth hypothesis attempts to do, is sensitive to whether or not farmers' risk aversion is included in the simulation, however. While the low-risk-factor and high-risk-factor scenarios produced results for the fourth hypothesis that were theoretically consistent with the results for the first three, this was not the case for the scenarios in which risk aversion was omitted. During the last and most drought-stricken year of the simulation, some of the results ran counter to what was suggested for the first three hypotheses.

There was one other case in which a result was sensitive to risk: a water market's effect on reservoir storage when water-conserving irrigation methods are widespread. Refer again to Figure 9-4 on page 234, which shows lower reservoir storage under a water market *except when irrigation efficiency is high and risk aversion is low*. If taken at face value, this anomaly sounds a note of optimism about the conservation effects of short-term water leasing: a water market can indeed result in water saving if farmers are irrigating efficiently and if risk-aversion is less intense. The policy implications of this result will be discussed in the next chapter.

These empirical results are important because they are theoretically consistent, and because the theory that unifies them is different from many of the assumptions that are often implicit in other scholarly work about water marketing. The results here suggest an additional policy dimension to water marketing: that when left to itself, a water market will improve economic efficiency but will also discourage conservation.

On the other hand, some of the results suggest that the economic efficiency provided by a water market need not suffer if conservation can be encouraged in other ways. Figure 9-1 on page 228 suggests that risk-averse farmers will be no worse off — and during serious drought, could be slightly better off — under a water market if they are already irrigating efficiently. But as Figure 9-6 on page 238 shows, getting farmers to that higher level of conservation is more difficult under a market because the economic incentive to make such an investment is reduced; there is still a payoff for greater conservation under a water market, but it isn't as much.

The findings presented in this chapter suggest a parallel track of pro-conservation policies that would complement a water market's ability to increase economic benefits through voluntary redistribution of irrigation supplies. These recommendations will be discussed in the following chapter.

Chapter 10: Conclusions and Recommendations

By itself, the ability to buy and sell irrigation short-term will not bring about water conservation among farmers because a market tends to reduce the economic incentive to switch to more efficient irrigation methods. But if for other reasons farmers are using water-saving irrigation methods, a water market will leave farmers as a whole economically better off, especially if they are averse to risk.

This is the salient policy conclusion from research presented here. It does not necessarily contradict existing theoretical work on water marketing, but it does add a dimension that previous literature misses. Theory must unequivocally separate conservation and economic efficiency, because to conflate one with one the other obscures the danger posed by the rapid depletion of stored water during times of drought.

Chapters 1 and 2 offer a theoretical explanation of how a market could cause — or at least contribute to — a reduction in conservation activities and an increase in per-acre water consumption among irrigators. Unfortunately, real-world data seldom permit comparison of different "what if" scenarios with a sufficient degree of validity. But as this study shows, theory can be modelled and operationalized by way of a mathematical simulation. By using Occam's razor to craft a minimal set of regime rules and seeing how historical data perform under those rules, the simulation is able to model a number of “what if” scenarios that normally would be beyond the reach of the historical data alone. While the simulated cropping patterns may have little predictive value (too many other factors enter into a farmer's actual planting decision), these results have tremendous value as a comparison of how the economic forces underlying a farmer's planting decision will tend to change under different rules and assumptions.

The legal and historical analyses of Chapters 4 and 5 show another dimension of water marketing that has largely been overlooked in the literature: for a market to work, quantities must be known. Sellers must know exactly how much water they control, and buyers must be able to take delivery of exactly the amount for which they contract. This need is becoming increasingly evident as more areas attempt to fashion their own water markets. The water regime of the middle and lower Rio Grande makes such certainty possible, which constitutes a major difference from water law in the rest of Texas. Under the rule of prior appropriation governing the rest of the state’s surface water, a stable water market is problematic because the more severe the drought, the more uncertain are the quantities controlled by all but the most senior water right holders. The uncertainty increases exponentially in areas where groundwater is a viable option. Not only are quantities not fixed, water taken from one well can affect the quantity available from neighboring wells.

The data presented in Chapter 6 showed that from the time water marketing became permissible, conservation has actually gone a few steps backwards. A word of caution is in order, however: Though suggestive, data on per-acre water use prove nothing about causality. All that can be said with confidence is that higher per-acre water use, an increase in sugarcane plantings, and a water market were coincident. It raises, but does not empirically answer, the question of market causality.

The simulation presented in Chapters 7 and 8 goes beyond water market theory by constructing an empirical framework in which specific hypotheses may be tested — something that is hardly ever done in water marketing literature to date. It goes beyond anecdote because important parameters can be controlled and alternative outcomes evaluated, which the descriptive literature on the California water banks, for example, does not do. The simulation results detailed in Chapter 9 do not provide the causal link missing from the exploratory data analysis of Chapter 6, but they do establish an explanation of how such a link would work if a water market does indeed lead to more water-intensive agricultural practices. The economic drive to plant water-intensive sugarcane was unambiguously stronger when a water market existed, especially when irrigation efficiency was relatively low. Cotton and sorghum farmers were less inclined plant unirrigated crops when they could buy additional water. In the simulation, these tendencies caused reservoir levels to fall faster under all water marketing scenarios.

Another important inference to be drawn from the simulation is that risk matters. Farmers who are risk-averse make different planting decisions than would be predicted if risk were ignored. They tend to respond quicker to water shortage by reducing the acreage planted in water-intensive crops. If farmers are risk-averse, then the common theoretical rationale for water marketing (that upgrading irrigation will always dominate not upgrading if water marketing is allowed) becomes tenuous. If a water market also reduces risk, it will strongly increase the economic impetus to plant high-profit water-intensive crops such as sugarcane and onions.

Policy recommendations

The arguments and conclusions presented here have implications for how public waters are managed. Markets can be a useful and efficient tool for moving water to its best and highest use, as long as policy makers and water managers are careful not to expect results that a market simply isn't equipped to deliver. A market seeks the most efficient path to the highest profits; it is not concerned with ensuring the reservoir has water. Social values are aided by a market only if — and only to the extent — they are recast in terms of economic efficiency.

From the outset, the goal of this research has been to use the Lower Rio Grande Valley as a case study from which broader policy conclusions may be drawn. The following policy recommendations therefore have little to do with the Valley directly. Rather, they are intended for any region where policy makers are considering market-based water resource management.

The specific policy recommendations include:

Do not rely on a water market to make conservation happen.

Risk-averse farmers do not use less water when they have the option of bidding competitively for additional irrigation. They use more, and they put it to use more profitably. Thus, if averting water shortages by getting farmers to do more with less is the policy goal, a water market is the wrong policy tool. A market encourages farmers to do more *with more.*

This is not to imply that a water market is a bad policy tool. On the contrary, it is ideal for increasing economic benefits overall. But it is not the right tool for the job if the job is to achieve water conservation among farmers.

If considered across the agricultural sector, a market's anti-conservation effect is seen in its tendency to push the regional crop mix toward water-intensive crops. At the microeconomic level, conservation is retarded because upgrading from furrow irrigation to something more technologically efficient tends to result in less additional profit under a market regime, unless other measures are taken to reduce farmer uncertainty. If the uncertainty factor is reduced, then the disincentive will get smaller and it will be easier to encourage conversion to more efficient irrigation in a market setting.

Conservation can be encouraged alongside a water market. But whatever its form, promotion of conservation must be regarded as a separate activity from the water market.

Make irrigation upgrades easier to finance.

If the agricultural sector as a whole is to gain benefits from a water market, then part of those benefits should be used to make financing irrigation improvements more attractive economically. Either lengthening the term of a loan, reducing the interest rate, or doing both will reduce the monthly capital cost of installing a more water-efficient irrigation system. This would offset any effect the water market might have of making such an investment less economically desirable.

An example of such a program is the Texas Water Development Board's Agricultural Water Conservation Loan Program. This program makes use of institutional financial leverage to reduce the cost of financing new irrigation systems. First, the state lends money at a low interest rate to an irrigation district, river authority, or some other institution whose membership includes a large number of farmers. The institution then uses this capital to finance irrigation improvements by their farmers at a rate not more than 1 percentage point over the rate at which the institution received the funds from the state.

It may not be necessary to wait for state participation if the institution has a sound debt rating. Traditional agricultural lending institutions may feel confident enough to provide better terms on their own if it can be shown (through a simulation such as the one for this study, or through some other means) that a water market can increase overall farm profits sufficiently in their service areas.

Integrate a water market with the existing system of water accounting under the agency responsible for monitoring water use.

The Rio Grande water market has worked extremely well because of the institutional stability provided by the Rio Grande watermaster. The system of water accounting maintained by the watermaster since 1971 establishes in detail and with clarity how much water accrues under each water right and how much is put to use. Operating a water market involves many of the monitoring tasks the watermaster had already been doing.

This success suggests that a water market is best operated by an agency with a strong local presence that already measures the quantities of water used. It need not be a local entity such as a water conservation district, but it does need to have jurisdiction — either singly or in conjunction with other authorities cooperating in a water market — over the entire hydrological area. This includes aquifers as well as streams. Partial jurisdiction means incomplete intelligence about the market, and incomplete intelligence increases uncertainty and makes it more difficult for prospective buyers and sellers to place a value on water in a transaction.

Establish explicit rules that are easily learned by all parties.

The market for leased water rights in the Rio Grande Valley gained momentum almost immediately after rules were promulgated in 1986 that detailed how transactions were to occur and how they would be recorded. Most importantly, the rules added little in the way of transaction costs (fees, studies, or other expenses that do not contribute to the value of the deal for the parties involved). There is no negotiation over how a lease is executed; buyer and seller deal primarily over quantity, price, and timing of delivery.

It is the lack of complexity that makes the rules of the game widely known. In turn, widely known rules have open the door to many sellers and even more buyers, preventing monopoly or monopsony and enabling transaction prices to seek their equilibrium values.

The rules should go no further than what is required to establish confidence on the part of buyers and sellers that making a deal is safe. Transactions must be fair, and also must be perceived so. Rules must require the verification of the seller's water right, assure the adequacy of transport mechanisms, and properly credit and debit water accounts.

Delimit markets by sector or by type of use.

While much of the attention on water marketing has focussed on transfers of water from agriculture to cities, there are also efficiency gains to be obtained from same-use trading: farmers selling to other farmers. Where existing laws constrain the migration of water from one kind of use to another, like-use markets may be administratively easier to establish.

If it is politically infeasible to force all users to compete for all water supplies, a water marketing regime could instead define the boundaries of multiple markets as has been done in the Rio Grande Valley. Part of the Watermaster's job is to divide and quantify the amount of water available for each class of use to each water right holder. Within these sectoral bounds, however, right holders may buy and sell freely. This significantly eases any equity concerns that are bound to arise when water moves between a private user such as a farmer and a public user such as a municipality.

A sectoral approach to water marketing may also alleviate some of the political difficulty likely to arise in negotiations over interstate or international water markets. When Mexico sought to borrow water from Texas during the 1997 drought, the IBWC/CILA established procedures that, among other things, prohibited Mexico from using water borrowed from Texas to irrigate crops; water could be borrowed only for municipal use.[1] This illustrates how politically sensitive an international exchange of water can be, even under the duress of drought. However, if an inter-

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1 Jorge Garces, Office of the Governor of Texas, telephone conversation with the author, October 8, 1999.

national market is demarcated by sector, then there will be no danger of Mexican farmers competing with U.S. cities for Texas water. Mexican farmers would be dealing with Texas farmers (or irrigation districts) for water that would be used for irrigation regardless of the buyer's nationality. (Of course, there would remain other formidable obstacles to an international water market. These issues are beyond the scope of this investigation.)

Defining the bounds of multiple non-overlapping markets also gives the state more latitude in providing for important public purposes for which little or no income is generated. More often than not, these public-interest uses have to do with maintaining in-stream flow, estuaries, and recreation. If, for example, state water officials determine that the maintenance of estuaries requires a minimum flow, they may exclude such a volume from all other uses so that it remains in the streambed undiverted. The market competition for water will take place over the volume of water that is allowed for economic use; within those bounds, a free market will allocate supplies to their most economically efficient uses.

The prohibition against cross-use water trading in the lower Rio Grande basin, while not exactly according to Hoyle in terms of pure economic theory, has done nothing to suppress the robustness of the region's water market. This may be taken as a clue that market forces still can accomplish some degree of allocative efficiency within a clearly demarcated economic and hydrological space.

Sellers must know how much water they control

Within the boundaries of the defined market, the water rights regime should provide a mechanism for quantifying, verifying, and enforcing the volumes legally controlled by the water right holders. Saliba and Bush, along with others, emphasize how important it is to a water market for entitlements to be secure. It is additionally argued in Chapter 4 that knowing the quantity of one's entitlement is part and parcel of the stability of a water right. The less an entitlement is quantified, the more abstract and less saleable it is.

Quantification is most convenient and fungible when done through a system of water accounting as maintained by the Rio Grande Watermaster. But it is also possible to use time as a measure, similar to what was done under Spanish water law. Whatever the measure, it must be enforceable and verifiable.

Allow buyers and sellers to negotiate their own contracts

Once the bounds of a market have been defined, the only actors in any given deal should be the buyer and seller. At this point, the role of the state should be that of an accountant or a bank officer: to ensure that there are sufficient water "funds" to make good on the transaction negotiated by the parties to the deal, and to debit or credit water accounts accordingly.

It may be argued that the California Water Banks of 1991 and 1992 were not true water markets because buyers and sellers did not deal with one another directly. There was one buying price and one selling price; all purchases and sales were with the water bank; individuals could not buy from one another. The result was exactly what economic

Table 10-1. Purchases and sales in the California Water Banks

	1991	1992
Price received by sellers	$125	$50
Water sold to bank (acre-feet)	820,664	193,246
Price paid by buyers	$175	$72
Set-aside for water quality maintenance (acre-feet)	165,137	34,478
Water bought from bank (acre-feet)		
Municipal use	307,373	39,000
Irrigation	82,597	95,250
Total set-asides and consumptive purchases	555,107	168,728
Remaining water (acre-feet)	265,557[a]	24,518[b]
Value at price paid by bank	$33.2 million	$1.2 million

[a]Remaining balance purchased by State Water Project as per water bank rules.

[b]Purchased by Department of Fish and Game to support wildlife habitat.

Source: California Department of Water Resources, "The 1991 Drought Water Bank Program," paper published on the Internet [http://wwwswpao.water.ca.gov/other/wbank91.html], accessed Oct. 11, 1999; and CDWR, "The 1992 Drought Water Bank Program," paper published on the Internet [http://wwwswpao.water.ca.gov/other/wbank92.html], accessed Oct. 11, 1999. Additional calculations made by the author.

theory would have predicted: a tremendous deadweight loss and drain on the state treasury because the fixed prices were higher than what would have obtained in an open market. The distortions caused by state price-fixing deprived water purchasers of economic benefits they could have obtained with more water at a lower price. Buyers received a windfall at the state's expense because what they were paid was more than what the water was worth in terms of its marginal productivity. The use of excess water in 1992 to support wildlife habitat, while arguably a worthy policy goal, was in fiscal terms an interagency fund transfer. It did not give the state any additional money to offset the opportunity cost of buying the water.

The public loss incurred in the California experience underscores the need for the state to define the limits of a market, but to take a minimal role in managing what takes place within the bounds it sets.

Drought forecasting

Drought forecasting that includes economic as well as hydrological factors could significantly reduce the uncertainty felt by risk-averse farmers. This goes beyond most river basin models that do a good job of responding to climatological change but sometimes miss economic dynamics that could affect agricultural water demand.

Most drought forecast models are either economic or hydrological; few are both. What is apparent from this study, however, is that drought in an area such as the Rio Grande Valley is largely a socioeconomic phenomenon due to the tremendous demands of agriculture on available water supplies. Drought is a function of what is taken out of the water system, not just of what flows in. The simulation used here shows how both natural and economic factors can be taken into account dynamically, allowing forecasters to see how water supplies might change under different sets of rules applied to a variety of scenarios. A forecasting model needs to be able to test different rainfall and inflow patterns as well as changes in commodity prices.

Another reason for forecasting is that information is at least a partial antidote for uncertainty. If farmers know the range of probable outcomes from various drought scenarios, they will be better informed and possibly more interested in conservation.

For transboundary markets, ensure that the same transaction rules apply for all participating jurisdictions.

As suggested previously, a water market need not be limited by political boundaries. If continguous jurisdictions agree on the same transactions rules and have a system of water accounting capable of crediting and debiting water between any pair of legitimate buyers and sellers, then a water market can work if the political obstacles can be resolved to the satisfaction of all parties.

For states party to a transboundary contract water market, a reasonable strategy would be to ensure the market runs as smoothly as possible so that the gains in economic efficiency may be harnessed to support a parallel track of policies to promote water conservation. The above recommendations provide a starting point for crafting a set of rules in which (ideally) trading would leave the region as a whole better off without leaving anyone worse off.

Interstate compacts such as the one between Texas, New Mexico, and Colorado governing the Rio Grande can be amended such that water could be bought and sold across state lines (between users near El Paso, Texas, and users near Elephant Butte and Caballo reservoirs 100 miles away in New Mexico, for example). The details of such actions are closely scrutinized by all states in the compact to ensure that each one's interests are protected. This kind of painstaking rulemaking is necessary if an interstate water market is to operate transparently and without bias.

As difficult as the negotiations between jurisdictions may be, however, they must focus on institution-building. In other words, the agreement must authorize a mediating agency (possibly the U.S. Bureau of Reclamation, if its water projects are involved) to administer water market transactions according to the rules agreed upon by the parties to the interstate compact. To require that each lease be separately approved by the member jurisdictions would burden each deal with transaction costs that would suffocate a market.

(Long-term or permanent deals that happen only once are another matter, however. The recommendations offered here are intended only for temporary leases involving recognized water right holders who will presumably continue to hold their rights permanently.)

The foreign trade aspects of an international water market (one that includes Mexico's side of the Rio Grande Valley, for example) could be highly problematic, however. Even though a sector-limited water market could be made compliant with the general free-trade principle of national treatment, agriculture is a foreign trade area where a country's protectionist tendencies often run strongest. While transboundary water trading along the Rio Grande is a subject worth exploring, we abstract from the thorny trade issues here, setting them aside for later inquiry.

A final note

Regardless of its conservation effects — or lack thereof — a water market clearly accomplishes economic efficiency. The more economic benefits a market creates, the greater the flexibility society has in dealing with other policy objectives such as conservation. But it must be remembered that the market isn't going to save water. A market exists to be efficient and profitable; it does not contemplate goals such as long-term conservation. With the right policy mix, however, conservation and economic efficiency can complement each other on the public agenda.

Appendix

The following crop-by-crop analysis is based on the solutions to the land decisions, which come from 12 runs of the quadratic programming (QP) solver. Two elements of the QP output are used: the amount of acres planted in each crop at the beginning of the season (shown in Figure A-1), and the reduced gradients that result when acreage resolves to a crop's upper or lower bound (Table A-1).

Irrigated cotton

Depressed cotton prices throughout the period of the simulation kept planted acreage at the lower bounds in both counties for all scenarios. Multiplying average yields by these low prices produced per-acre revenue estimates that were less than per-acre costs. As a result, the profit coefficient on the decision variables for irrigated cotton acreage was negative — indicating a predicted overall *loss* on cotton crops. This established irrigated cotton as a crop to be avoided to the greatest degree allowed by the system constraints.

In Cameron County, there was a strong economic urge to avoid irrigated cotton. For the most part, the economic pressure was insensitive to irrigation efficiency, except for 1997 and 1988 when water shortages were severe. Greater irrigation efficiency eased the pressure to avoid cotton during these drought years.

A pairwise comparison of scenarios that differed only in the existence of a water market showed that Cameron County farmers have less of an economic urge to flee irrigated cotton if they can buy and sell water. Moreover, this effect began in 1995, rather early in the drought, and was fairly insensitive to assumptions about risk.

In Hidalgo County, which tends to have more available irrigation than Cameron County does, the economic pressure away from irrigated cotton was less sensitive to irrigation efficiency and the presence of a water market. A market did have an effect later on in the drought, as irrigation shortages began to encroach on Hidalgo County farmers' planting decisions. In addition, the effect showed up earlier as the assumed risk factor was increased. A market relieved the pressure away from irrigated cotton in 1996 when a high risk factor was assumed, and in 1997 with a low risk factor. There was an unusual result for 1998, however, which showed a market *adding* to the flight from cotton. This is probably due to the fact that by 1998, overall irrigation storage was severely depleted under the market scenario, while shortages for the same year under the no-market scenario were less severe.

The simulation supplied irrigated cotton with enough water for normal yield under all scenarios for 1993, 1994, and 1997 — that is, shorting only the increment needed to obtain best yield. For 1995 and 1996, cotton prices were high enough to justify irrigation in full. As water shortages deepened in 1998, however, Hidalgo County cotton crops did not receive enough irrigation under the 50 percent irrigation scenarios to satisfy their assumed viability requirements by mid-year. In Cameron County, enough irrigation was applied to keep the crops alive, but no more than that. On the other hand, both counties were able to irrigate for normal yield when system-wide efficiency was 60 percent.

What is most interesting about the deep-drought results is that a water market kept Hidalgo County's cotton crops alive for an additional month. The crops survived until July under the market scenarios, but the extra time was not enough to see the crop through to the August harvest.

Onions

Onion plantings in both counties demonstrated far more sensitivity to prices than to any other factor modeled. When prices were high in 1993 and 1995, the simulation planted as many acres in onions as were allowed in all scenarios, and across the board, there was a strong economic push to plant even more. When prices were low in 1994 and 1996, planted acreage was thrown to the lower bounds.

The reduced gradients show rather conclusively that a farmer's economic desire to plant more onions is affected by the way risk is treated. Ignoring risk results in a picture of farmer choice that seeks more strongly to follow a rate of return that, on average, is considerable. Adding risk to the decision picture tempers that economic urge.

As water becomes scarce, the ability to purchase additional water adds to the incentive to plant onions. Similarly, a water market reduced the economic tendency to flee from onions when prices dropped and plantings stayed at their lower bounds.

The economic currents driving onion plantings were largely insensitive to changes in irrigation efficiency, up to the year of severe water shortage in the final year of the simulation. This is hardly a surprise, given that onion farmers were assumed to be irrigating at a higher rate of efficiency for all scenarios. With the crop's own irrigation efficiency remaining at a constant 60 percent, any efficiency-related change in reduced gradients would reflect how onions' *relative* economic attractiveness changed as a result of the entire sector becoming more water-efficient.

The most striking efficiency-related change was for Cameron County during the severe water shortage of 1998. When everyone was irrigating more efficiently and a water market existed, there was a stronger economic desire to plant onions. This tendency was at least partly risk-related; the higher the risk factor used, the less intense was the desire to plant additional onions.

Onions were irrigated to their full water requirement for all years under all scenarios. The one exception occurred when water supplies were depleted in 1998 under the low-efficiency market scenarios. When the rest of the agricultural sector was irrigating at a 50 percent efficiency rate and there was no water market in place, water ran out during the onion season in both counties — at which point the crop was assumed to be either dead or severely stunted.[1] A water market put off the day of drought reckoning long enough for the onion crop to survive to harvest.

Irrigated sorghum

Moreso than any other crop choice, irrigated sorghum proved to be a haven from uncertainty, especially for Hidalgo County. The economic

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1 Even though the irrigation accounts were separate under the no-market scenarios, the simulated depletion during 1998

drive to plant and irrigate less sorghum was weakened considerably the more risk was added to the picture. In some cases, a high risk-adjustment factor actually reversed a tendency to plant as little sorghum as possible. These particular results provide strong evidence that risk matters when modeling crop choices.

Although a crop with very low returns, sorghum is also a very stable crop, as shown by its low variance in historical profit margins (see Table 7-4 on page 193). Thus sorghum's migration between upper and lower bounds was utterly unlike that of onions, which is sensitive to wide price fluctuations and relatively insensitive to the presence of a water market. Instead, sorghum moved in response to uncertainty connected with other more profitable crops.

The ability to buy and sell irrigation made a big difference in how the simulation treated irrigated sorghum, especially when water was in short supply. In Cameron County, whose share of inflow is about half the size of Hidalgo County's, a water market greatly reduced the economic desire to flee irrigated sorghum beginning very early in the drought. While this effect was evident in all scenarios with regard to Cameron County, in Hidalgo County it was seen only when irrigation efficiency was assumed to be low and risk was part of the analysis. When a high risk factor was used, a water market pushed sorghum planting to its upper bound for Hidalgo County in 1996; in 1997 using a low risk factor, a market reduced the impetus to avoid sorghum.

By and large, the simulation provided enough irrigation to sorghum crops to ensure normal yield, but rarely provided 100 percent of the crop's water demand. As with other crops, irrigated sorghum didn't survive the 1998 season when a 50 percent irrigation efficiency was assumed, as by mid-year the irrigation deficits prevented sorghum from getting enough water to ensure its basic viability. Water markets helped keep the sorghum crops alive one or two months longer in both counties when the risk factor was low or zero, but it was not enough to get the crop to harvest.

Sugarcane

Sugarcane is one of the most lucrative crops grown in the Rio Grande Valley, so it is hardly a surprise that plantings in both counties were at the upper bounds for the first two years of the simulation across the board. As the drought deepened, however, different stories emerged.

In Cameron County, the story was unambiguous: A water market delayed or prevented sugarcane plantings from being thrown to the lower bound, an effect that was insensitive to assumptions about risk or irrigation efficiency. From 1996 onwards into the deepest part of the drought, sugarcane went to its lower bound in every no-market scenario. The lower bounds were hit a year earlier when a lower irrigation efficiency was assumed. The push away from sugarcane was weakest when the risk factor was higher.

Water-rich Hidalgo County fled sugarcane much later than did Cameron County, and under assumptions of high irrigation efficiency, the lower bound was never reached at all. Under the low-efficiency scenarios, farmers turned away from sugarcane sooner as the assumed risk factor got higher. Here, the low-efficiency scenarios showed a "threshold" pattern: during a critical year (1996 for a high risk factor, 1997 for a low) plantings fell to the lower bound under the market scenarios, but not for the no-market scenarios. After the critical year, sugarcane acres planted under both market and no-market scenarios were at the lower bound and had the same reduced gradients.

Prices and costs were such that the simulation irrigated sugarcane sufficiently to assure normal yield, but never did it provide enough for best yield. The 1998 shortage hit Cameron County sugarcane in May, and Hidalgo County sugarcane a month later; in both cases, the ability to buy extra water over the course of the simulated period extended the life of that year's sugarcane crop by two months.

Dry crops

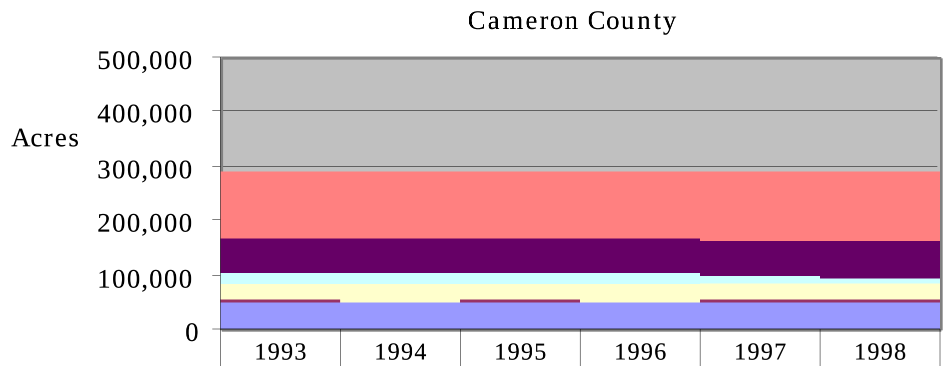
Dry-cropped sorghum proved to be the predominant slack crop for both counties; in most cases, planted acreage floated somewhere between the upper and lower bounds. When acreage did reach one of the bounds, the economic urge to carry the trend further was rather weak.

As one might expect, neither dry cotton nor dry sorghum was much affected by the presence of a water market. Nor were they affected by assumptions about system-wide irrigation efficiency. But risk did matter. The economic push to avoid planting dry cotton became stronger the more risk was factored into the analysis. This is because dry cotton, whose yield is largely dependent on rainfall, has a relatively high variance that pulled down the objective more as the risk factor got larger.

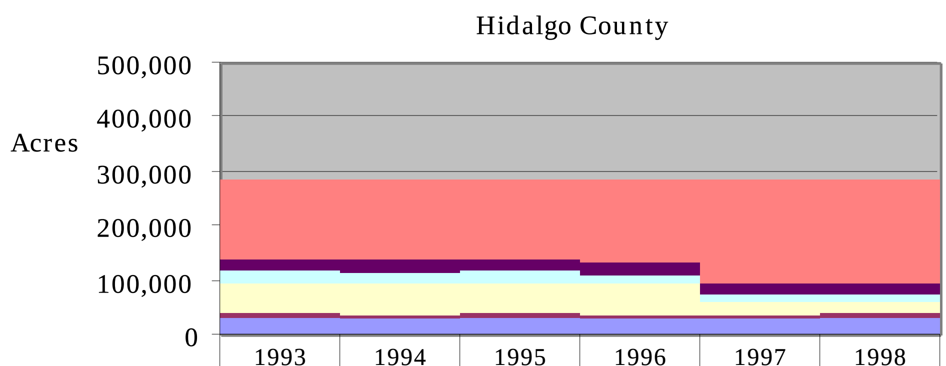
Dry sorghum's risk-related responses were in the same direction as that of dry cotton, but far less pronounced. Planting went to the upper bound occasionally only when uncertainty was ignored; otherwise, the number of acres planted drifted between the upper and lower bounds for all years in both counties.

Figure A-1. How the simulation allocated land

High risk factor, current irrigation efficiency, market



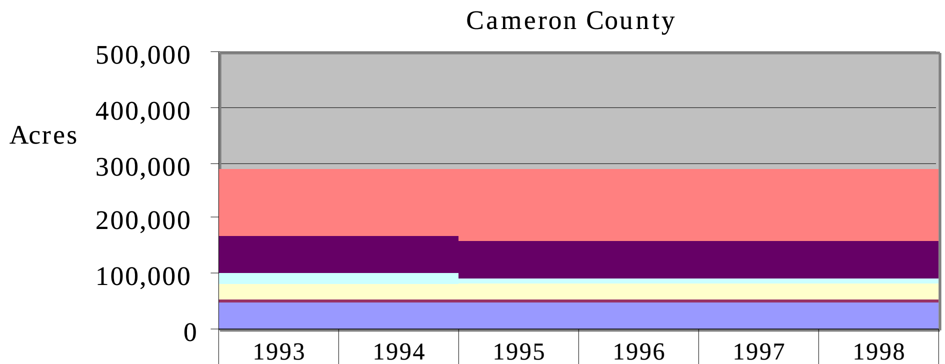
	1993	1994	1995	1996	1997	1998
Dry sorghum	121,670	122,770	121,670	122,770	126,933	130,670
Dry cotton	66,600	66,600	66,600	66,600	66,600	66,600
Sugarcane	19,800	19,800	19,800	19,800	14,537	10,800
Sorghum	30,700	30,700	30,700	30,700	30,700	30,700
Onions	2,000	900	2,000	900	2,000	2,000
Cotton	49,700	49,700	49,700	49,700	49,700	49,700



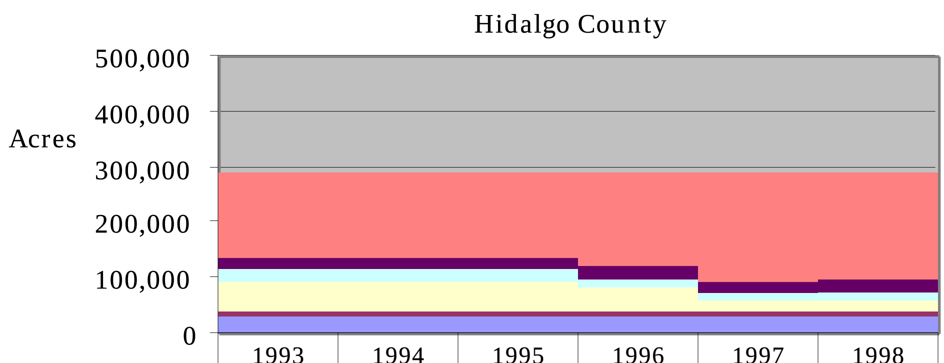
	1993	1994	1995	1996	1997	1998
Dry sorghum	149,260	151,060	149,382	156,209	192,760	190,960
Dry cotton	20,700	20,700	20,700	20,700	20,700	20,700
Sugarcane	23,000	23,000	23,000	17,851	15,000	15,000
Sorghum	54,700	54,700	54,700	54,700	21,000	21,000
Onions	9,300	7,500	9,178	7,500	7,500	9,300
Cotton	29,200	29,200	29,200	29,200	29,200	29,200

Figure A-1. (Cont.) How the simulation allocated land

High risk factor, current irrigation efficiency, no market



	1993	1994	1995	1996	1997	1998
Dry sorghum	121,670	122,770	130,670	131,770	130,670	130,670
Dry cotton	66,600	66,600	66,600	66,600	66,600	66,600
Sugarcane	19,800	19,800	10,800	10,800	10,800	10,800
Sorghum	30,700	30,700	30,700	30,700	30,700	30,700
Onions	2,000	900	2,000	900	2,000	2,000
Cotton	49,700	49,700	49,700	49,700	49,700	49,700

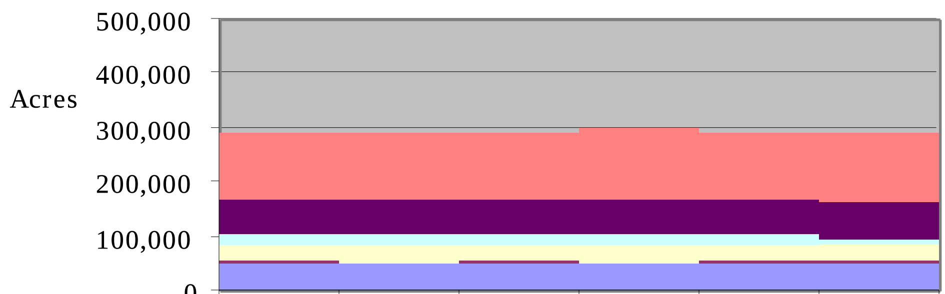


	1993	1994	1995	1996	1997	1998
Dry sorghum	149,260	151,060	149,382	167,255	192,760	190,960
Dry cotton	20,700	20,700	20,700	20,700	20,700	20,700
Sugarcane	23,000	23,000	23,000	15,000	15,000	15,000
Sorghum	54,700	54,700	54,700	46,505	21,000	21,000
Onions	9,300	7,500	9,178	7,500	7,500	9,300
Cotton	29,200	29,200	29,200	29,200	29,200	29,200

Figure A-1. (Cont.) How the simulation allocated land

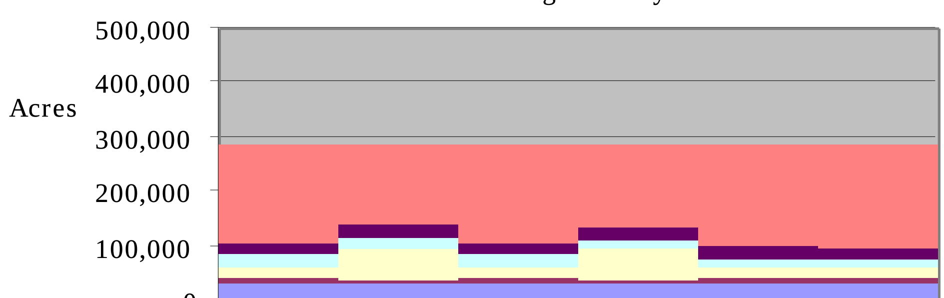
Low risk factor, current irrigation efficiency, market

Cameron County



	1993	1994	1995	1996	1997	1998
Dry sorghum	121,670	122,770	121,670	132,116	121,670	130,670
Dry cotton	66,600	66,600	66,600	66,600	66,600	66,600
Sugarcane	19,800	19,800	19,800	19,800	19,800	10,800
Sorghum	30,700	30,700	30,700	30,700	30,700	30,700
Onions	2,000	900	2,000	900	2,000	2,000
Cotton	49,700	49,700	49,700	49,700	49,700	49,700

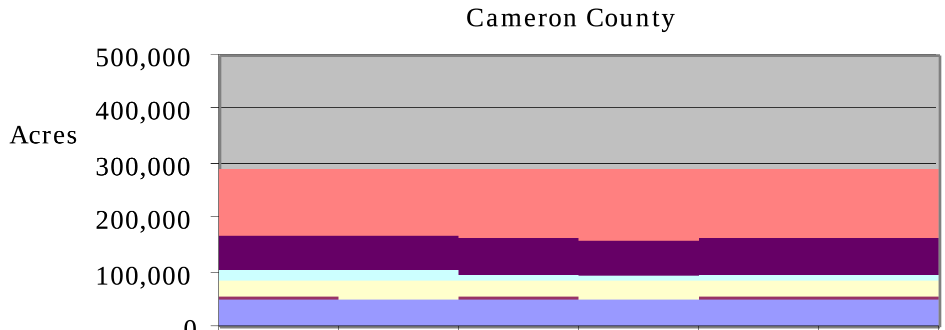
Hidalgo County



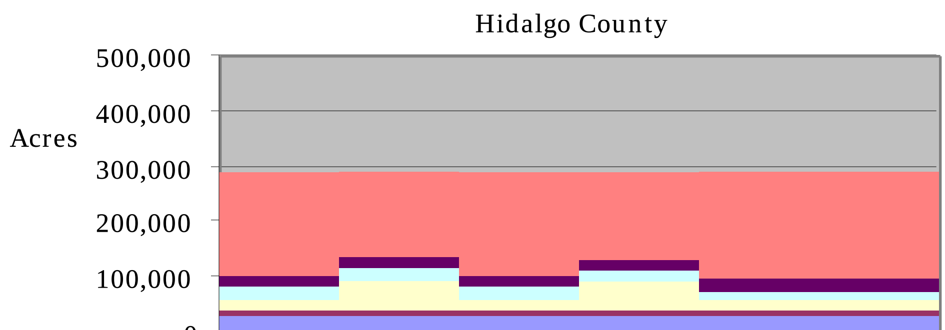
	1993	1994	1995	1996	1997	1998
Dry sorghum	182,960	151,060	182,960	155,914	189,852	190,960
Dry cotton	20,700	20,700	20,700	20,700	20,700	20,700
Sugarcane	23,000	23,000	23,000	18,146	16,444	15,000
Sorghum	21,000	54,700	21,000	54,700	21,000	21,000
Onions	9,300	7,500	9,300	7,500	8,964	9,300
Cotton	29,200	29,200	29,200	29,200	29,200	29,200

Figure A-1. (Cont.) How the simulation allocated land

Low risk factor, current irrigation efficiency, no market



	1993	1994	1995	1996	1997	1998
Dry sorghum	121,670	122,770	130,670	131,770	130,670	130,670
Dry cotton	66,600	66,600	66,600	66,600	66,600	66,600
Sugarcane	19,800	19,800	10,800	10,800	10,800	10,800
Sorghum	30,700	30,700	30,700	30,700	30,700	30,700
Onions	2,000	900	2,000	900	2,000	2,000
Cotton	49,700	49,700	49,700	49,700	49,700	49,700

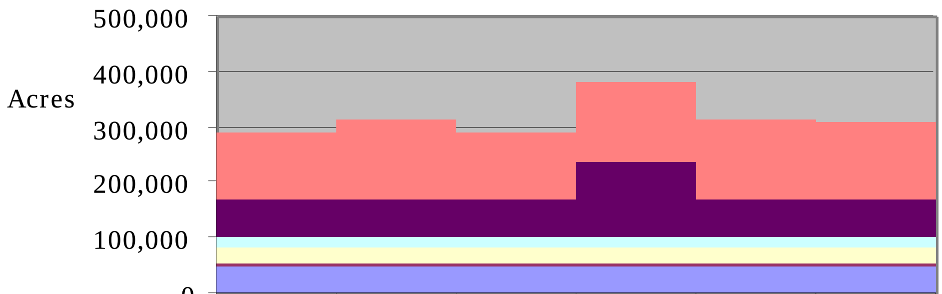


	1993	1994	1995	1996	1997	1998
Dry sorghum	182,960	151,060	182,960	155,914	192,094	190,960
Dry cotton	20,700	20,700	20,700	20,700	20,700	20,700
Sugarcane	23,000	23,000	23,000	18,146	15,000	15,000
Sorghum	21,000	54,700	21,000	54,700	21,000	21,000
Onions	9,300	7,500	9,300	7,500	8,166	9,300
Cotton	29,200	29,200	29,200	29,200	29,200	29,200

Figure A-1. (Cont.) How the simulation allocated land

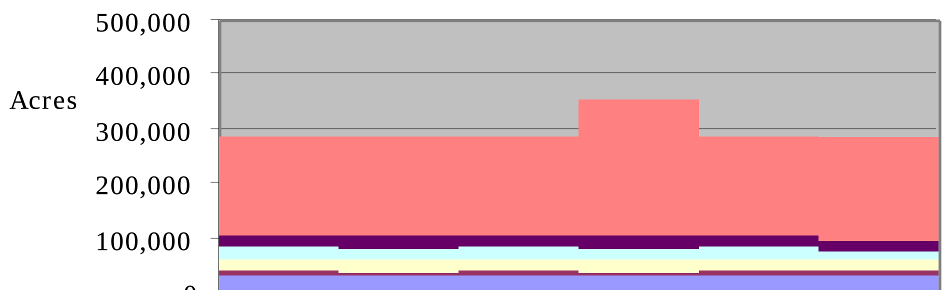
No risk factor, current irrigation efficiency, market

Cameron County



	1993	1994	1995	1996	1997	1998
Dry sorghum	121,670	143,300	121,670	143,300	143,300	143,300
Dry cotton	66,600	66,600	66,600	134,600	66,600	66,600
Sugarcane	19,800	19,800	19,800	19,800	19,800	17,379
Sorghum	30,700	30,700	30,700	30,700	30,700	30,700
Onions	2,000	900	2,000	900	2,000	2,000
Cotton	49,700	49,700	49,700	49,700	49,700	49,700

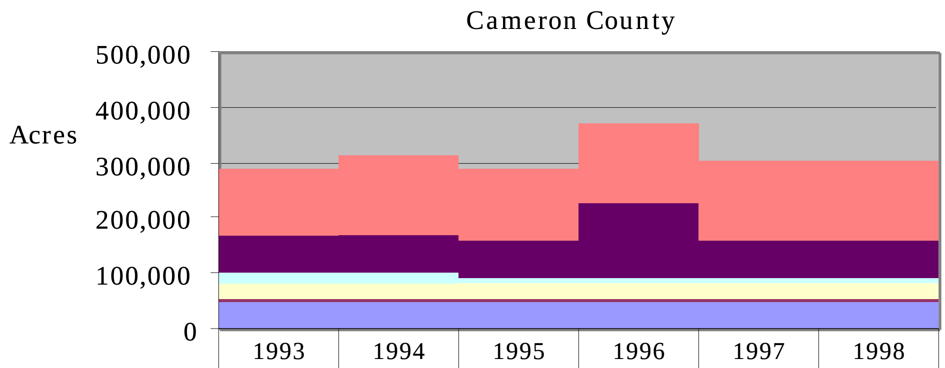
Hidalgo County



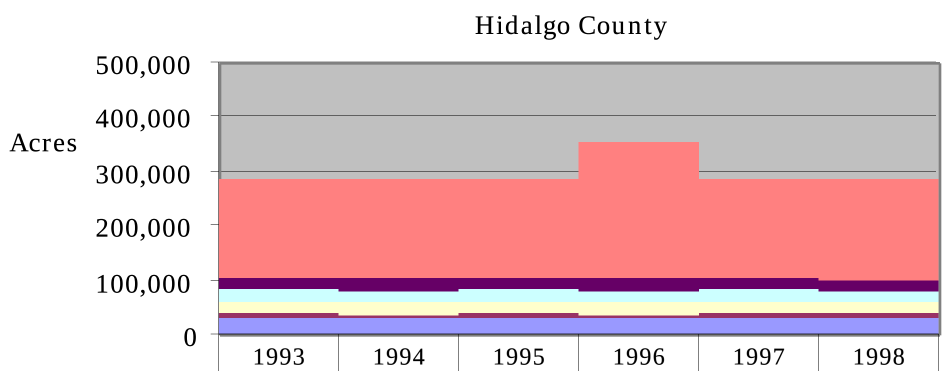
	1993	1994	1995	1996	1997	1998
Dry sorghum	182,960	184,760	182,960	250,400	182,960	190,960
Dry cotton	20,700	20,700	20,700	20,700	20,700	20,700
Sugarcane	23,000	23,000	23,000	23,000	23,000	15,000
Sorghum	21,000	21,000	21,000	21,000	21,000	21,000
Onions	9,300	7,500	9,300	7,500	9,300	9,300
Cotton	29,200	29,200	29,200	29,200	29,200	29,200

Figure A-1. (Cont.) How the simulation allocated land

No risk factor, current irrigation efficiency, no market



	1993	1994	1995	1996	1997	1998
Dry sorghum	121,670	143,300	130,670	143,300	143,300	143,300
Dry cotton	66,600	66,600	66,600	134,600	66,600	66,600
Sugarcane	19,800	19,800	10,800	10,800	10,800	10,800
Sorghum	30,700	30,700	30,700	30,700	30,700	30,700
Onions	2,000	900	2,000	900	2,000	2,000
Cotton	49,700	49,700	49,700	49,700	49,700	49,700

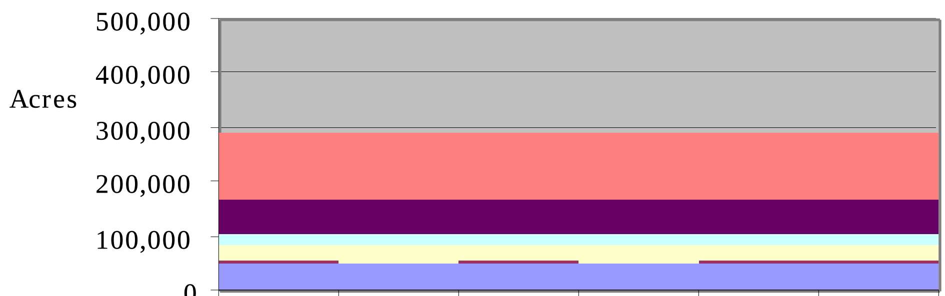


	1993	1994	1995	1996	1997	1998
Dry sorghum	182,960	184,760	182,960	250,400	182,960	188,732
Dry cotton	20,700	20,700	20,700	20,700	20,700	20,700
Sugarcane	23,000	23,000	23,000	23,000	23,000	17,228
Sorghum	21,000	21,000	21,000	21,000	21,000	21,000
Onions	9,300	7,500	9,300	7,500	9,300	9,300
Cotton	29,200	29,200	29,200	29,200	29,200	29,200

Figure A-1. (Cont.) How the simulation allocated land

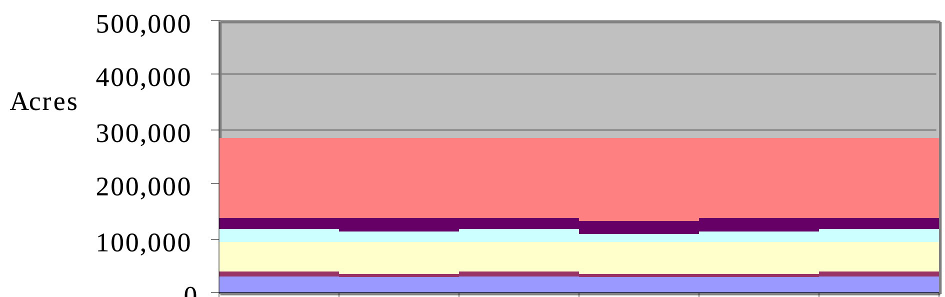
High risk factor, improved irrigation efficiency, market

Cameron County



	1993	1994	1995	1996	1997	1998
Dry sorghum	121,670	122,770	121,670	122,770	121,670	121,670
Dry cotton	66,600	66,600	66,600	66,600	66,600	66,600
Sugarcane	19,800	19,800	19,800	19,800	19,800	19,800
Sorghum	30,700	30,700	30,700	30,700	30,700	30,700
Onions	2,000	900	2,000	900	2,000	2,000
Cotton	49,700	49,700	49,700	49,700	49,700	49,700

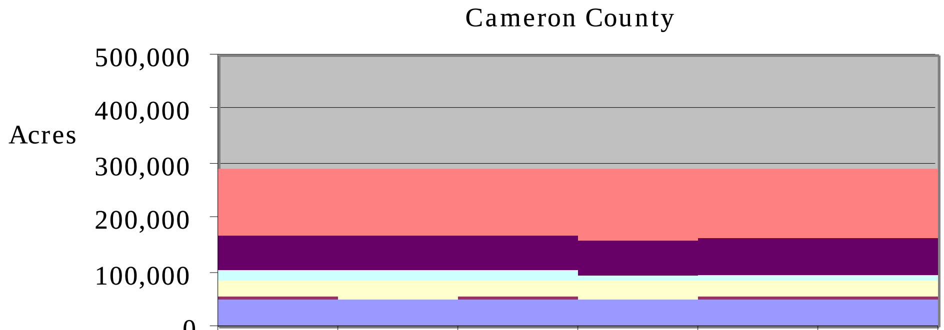
Hidalgo County



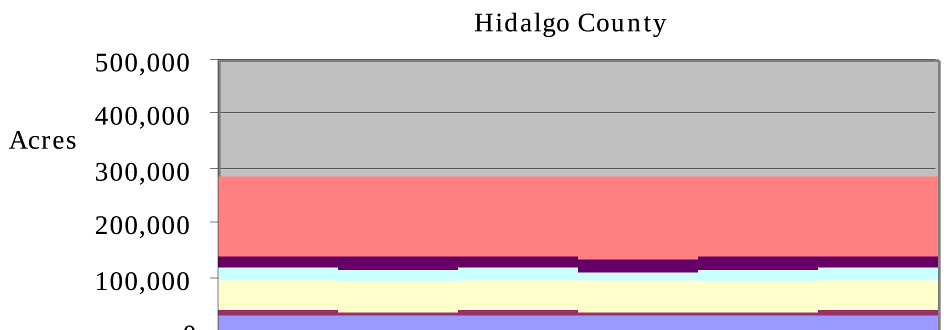
	1993	1994	1995	1996	1997	1998
Dry sorghum	149,260	151,060	149,382	156,209	151,060	149,260
Dry cotton	20,700	20,700	20,700	20,700	20,700	20,700
Sugarcane	23,000	23,000	23,000	17,851	23,000	23,000
Sorghum	54,700	54,700	54,700	54,700	54,700	54,700
Onions	9,300	7,500	9,178	7,500	7,500	9,300
Cotton	29,200	29,200	29,200	29,200	29,200	29,200

Figure A-1. (Cont.) How the simulation allocated land

High risk factor, improved irrigation efficiency, no market



	1993	1994	1995	1996	1997	1998
Dry sorghum	121,670	122,770	121,670	131,770	130,670	130,670
Dry cotton	66,600	66,600	66,600	66,600	66,600	66,600
Sugarcane	19,800	19,800	19,800	10,800	10,800	10,800
Sorghum	30,700	30,700	30,700	30,700	30,700	30,700
Onions	2,000	900	2,000	900	2,000	2,000
Cotton	49,700	49,700	49,700	49,700	49,700	49,700

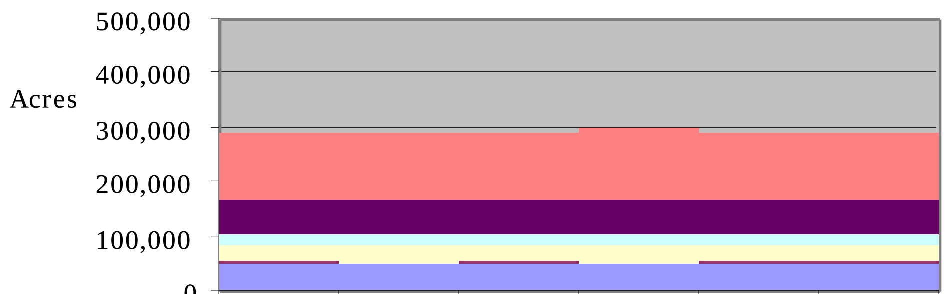


	1993	1994	1995	1996	1997	1998
Dry sorghum	149,260	151,060	149,382	156,209	151,060	149,260
Dry cotton	20,700	20,700	20,700	20,700	20,700	20,700
Sugarcane	23,000	23,000	23,000	17,851	23,000	23,000
Sorghum	54,700	54,700	54,700	54,700	54,700	54,700
Onions	9,300	7,500	9,178	7,500	7,500	9,300
Cotton	29,200	29,200	29,200	29,200	29,200	29,200

Figure A-1. (Cont.) How the simulation allocated land

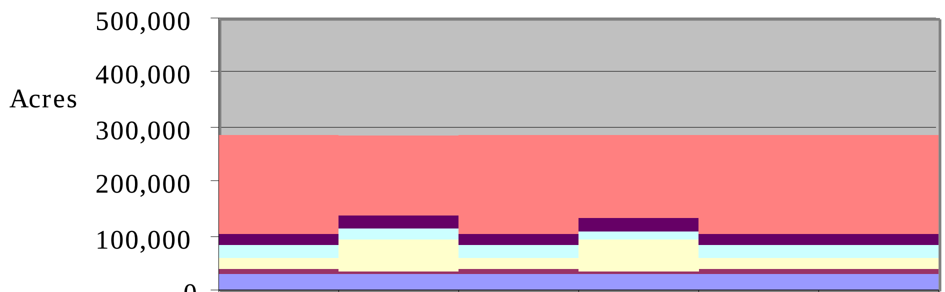
Low risk factor, improved irrigation efficiency, market

Cameron County



	1993	1994	1995	1996	1997	1998
Dry sorghum	121,670	122,770	121,670	132,116	121,670	121,670
Dry cotton	66,600	66,600	66,600	66,600	66,600	66,600
Sugarcane	19,800	19,800	19,800	19,800	19,800	19,800
Sorghum	30,700	30,700	30,700	30,700	30,700	30,700
Onions	2,000	900	2,000	900	2,000	2,000
Cotton	49,700	49,700	49,700	49,700	49,700	49,700

Hidalgo County

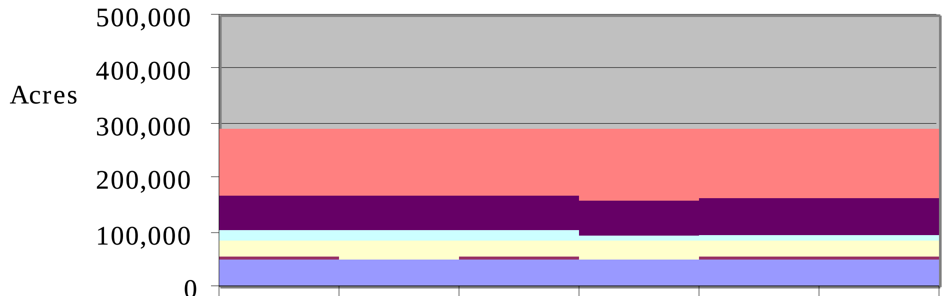


	1993	1994	1995	1996	1997	1998
Dry sorghum	182,960	151,060	182,960	155,914	183,403	182,960
Dry cotton	20,700	20,700	20,700	20,700	20,700	20,700
Sugarcane	23,000	23,000	23,000	18,146	23,000	23,000
Sorghum	21,000	54,700	21,000	54,700	21,000	21,000
Onions	9,300	7,500	9,300	7,500	8,857	9,300
Cotton	29,200	29,200	29,200	29,200	29,200	29,200

Figure A-1. (Cont.) How the simulation allocated land

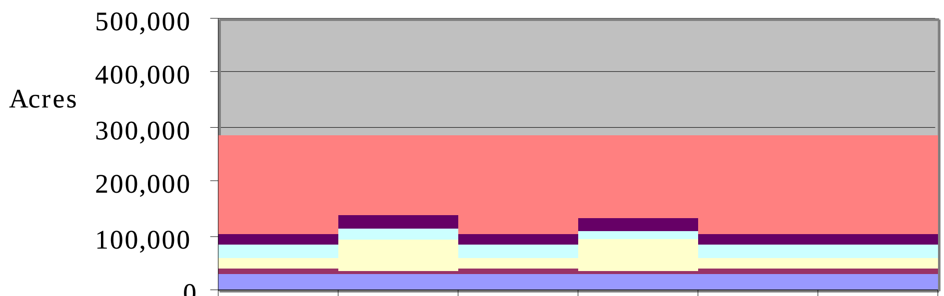
Low risk factor, improved irrigation efficiency, no market

Cameron County



	1993	1994	1995	1996	1997	1998
Dry sorghum	121,670	122,770	121,670	131,770	130,670	130,670
Dry cotton	66,600	66,600	66,600	66,600	66,600	66,600
Sugarcane	19,800	19,800	19,800	10,800	10,800	10,800
Sorghum	30,700	30,700	30,700	30,700	30,700	30,700
Onions	2,000	900	2,000	900	2,000	2,000
Cotton	49,700	49,700	49,700	49,700	49,700	49,700

Hidalgo County

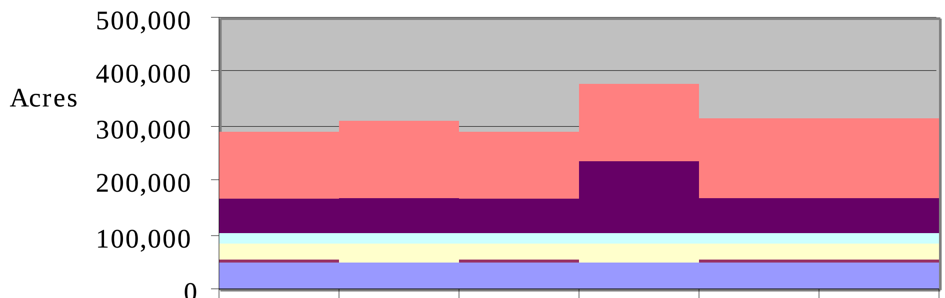


	1993	1994	1995	1996	1997	1998
Dry sorghum	182,960	151,060	182,960	155,914	183,403	182,960
Dry cotton	20,700	20,700	20,700	20,700	20,700	20,700
Sugarcane	23,000	23,000	23,000	18,146	23,000	23,000
Sorghum	21,000	54,700	21,000	54,700	21,000	21,000
Onions	9,300	7,500	9,300	7,500	8,857	9,300
Cotton	29,200	29,200	29,200	29,200	29,200	29,200

Figure A-1. (Cont.) How the simulation allocated land

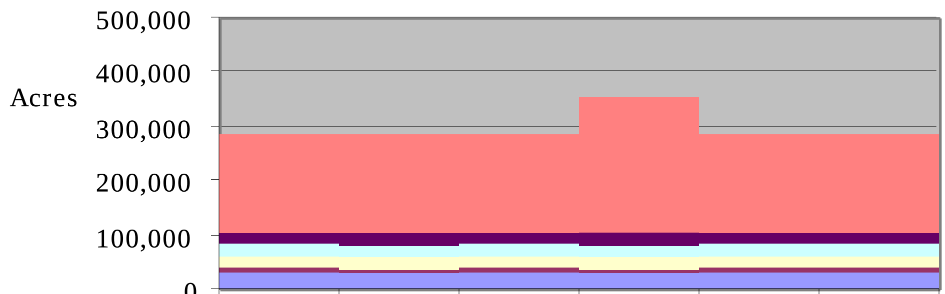
No risk factor, improved irrigation efficiency, market

Cameron County



	1993	1994	1995	1996	1997	1998
Dry sorghum	121,670	143,300	121,670	143,300	143,300	143,300
Dry cotton	66,600	66,600	66,600	134,600	66,600	66,600
Sugarcane	19,800	19,800	19,800	19,800	19,800	19,800
Sorghum	30,700	30,700	30,700	30,700	30,700	30,700
Onions	2,000	900	2,000	900	2,000	2,000
Cotton	49,700	49,700	49,700	49,700	49,700	49,700

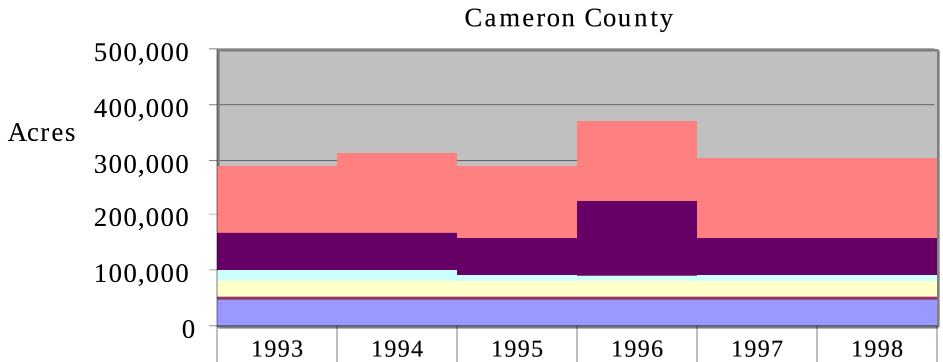
Hidalgo County



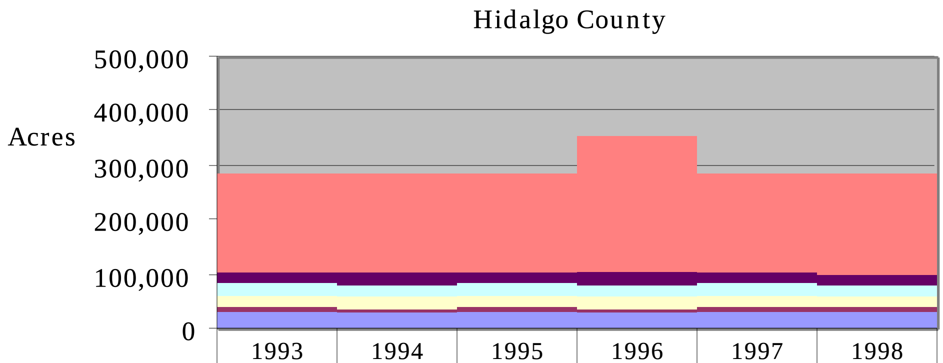
	1993	1994	1995	1996	1997	1998
Dry sorghum	182,960	184,760	182,960	250,400	182,960	182,960
Dry cotton	20,700	20,700	20,700	20,700	20,700	20,700
Sugarcane	23,000	23,000	23,000	23,000	23,000	23,000
Sorghum	21,000	21,000	21,000	21,000	21,000	21,000
Onions	9,300	7,500	9,300	7,500	9,300	9,300
Cotton	29,200	29,200	29,200	29,200	29,200	29,200

Figure A-1. (Cont.) How the simulation allocated land

No risk factor, improved irrigation efficiency, no market



	1993	1994	1995	1996	1997	1998
Dry sorghum	121,670	143,300	130,670	143,300	143,300	143,300
Dry cotton	66,600	66,600	66,600	134,600	66,600	66,600
Sugarcane	19,800	19,800	10,800	10,800	10,800	10,800
Sorghum	30,700	30,700	30,700	30,700	30,700	30,700
Onions	2,000	900	2,000	900	2,000	2,000
Cotton	49,700	49,700	49,700	49,700	49,700	49,700



	1993	1994	1995	1996	1997	1998
Dry sorghum	182,960	184,760	182,960	250,400	182,960	188,732
Dry cotton	20,700	20,700	20,700	20,700	20,700	20,700
Sugarcane	23,000	23,000	23,000	23,000	23,000	17,228
Sorghum	21,000	21,000	21,000	21,000	21,000	21,000
Onions	9,300	7,500	9,300	7,500	9,300	9,300
Cotton	29,200	29,200	29,200	29,200	29,200	29,200

Table A-1. Reduced gradients on crop variables

		1993	1994	1995	1996	1997	1998
		Irrigated cotton					
Cameron County							
φ=.5, λ=0	market	-200	-215	-137	-100	-204	-253
	no market	-200	-215	-234	-197	-301	-341
φ=.5, λ=2.5×10^{-8}	market	-323	-394	-260	-292	-341	-478
	no market	-323	-394	-356	-387	-438	-478
φ=.5, λ=5×10^{-8}	market	-446	-517	-383	-413	-506	-600
	no market	-446	-517	-479	-509	-560	-600
φ=.6, λ=0	market	-200	-215	-137	-100	-204	-244
	no market	-200	-215	-137	-181	-284	-325
φ=.6, λ=2.5×10^{-8}	market	-323	-394	-260	-292	-341	-382
	no market	-323	-394	-260	-371	-422	-462
φ=.6, λ=5×10^{-8}	market	-446	-517	-383	-413	-465	-505
	no market	-446	-517	-383	-492	-544	-584
Hidalgo County							
φ=.5, λ=0	market	-101	-156	-31	-25	-112	-262
	no market	-101	-156	-31	-25	-112	-171
φ=.5, λ=2.5×10^{-8}	market	-158	-214	-89	-90	-181	-318
	no market	-158	-214	-89	-90	-274	-318
φ=.5, λ=5×10^{-8}	market	-212	-273	-142	-148	-335	-375
	no market	-212	-273	-142	-211	-335	-375
φ=.6, λ=0	market	-101	-156	-31	-25	-112	-158
	no market	-101	-156	-31	-25	-112	-158
φ=.6, λ=2.5×10^{-8}	market	-158	-214	-89	-90	-170	-216
	no market	-158	-214	-89	-90	-170	-216
φ=.6, λ=5×10^{-8}	market	-212	-273	-142	-148	-229	-269
	no market	-212	-273	-142	-148	-229	-269

Table A-1. (Cont.) Reduced gradients on crop variables

		1993	1994	1995	1996	1997	1998
		Onions					
Cameron County							
φ=.5, λ=0	market	3,165	-485	1,351	-804	692	1,670
	no market	3,165	-485	1,272	-882	614	1,599
φ=.5, $\lambda=2.5\times10^{-8}$	market	3,089	-524	1,275	-847	602	1,539
	no market	3,089	-524	1,227	-903	554	1,539
φ=.5, $\lambda=5\times10^{-8}$	market	3,013	-507	1,200	-837	528	1,494
	no market	3,013	-507	1,182	-855	508	1,494
φ=.6, λ=0	market	3,165	-485	1,351	-804	692	1,678
	no market	3,165	-485	1,351	-882	614	1,599
φ=.6, $\lambda=2.5\times10^{-8}$	market	3,089	-524	1,275	-847	602	1,588
	no market	3,089	-524	1,275	-903	554	1,539
φ=.6, $\lambda=5\times10^{-8}$	market	3,013	-507	1,200	-837	527	1,512
	no market	3,013	-507	1,200	-855	508	1,494
Hidalgo County							
φ=.5, λ=0	market	3,205	-484	1,390	-804	725	1,631
	no market	3,205	-484	1,390	-804	725	1,700
φ=.5, $\lambda=2.5\times10^{-8}$	market	2,443	-1,039	628	-1,353	0	891
	no market	2,443	-1,039	628	-1,353	0	891
φ=.5, $\lambda=5\times10^{-8}$	market	1,795	-1,594	0	-1,894	-535	151
	no market	1,795	-1,594	0	-1,954	-535	151
φ=.6, λ=0	market	3,205	-484	1,390	-804	725	1,710
	no market	3,205	-484	1,390	-804	725	1,710
φ=.6, $\lambda=2.5\times10^{-8}$	market	2,443	-1,039	628	-1,353	0	949
	no market	2,443	-1,039	628	-1,353	0	949
φ=.6, $\lambda=5\times10^{-8}$	market	1,795	-1,594	0	-1,894	-386	300
	no market	1,795	-1,594	0	-1,894	-386	300

Table A-1. (Cont.) Reduced gradients on crop variables

		1993	1994	1995	1996	1997	1998
Irrigated sorghum							
Cameron County							
φ=.5, λ=0	market	-91	-16	-92	-1	-70	-76
	no market	-91	-16	-161	-70	-138	-138
φ=.5, $\lambda=2.5\times10^{-8}$	market	-79	-62	-80	-58	-72	-142
	no market	-79	-62	-150	-128	-142	-142
φ=.5, $\lambda=5\times10^{-8}$	market	-67	-51	-68	-48	-91	-130
	no market	-67	-51	-138	-118	-130	-130
φ=.6, λ=0	market	-91	-16	-92	-1	-70	-70
	no market	-91	-16	-92	-58	-127	-127
φ=.6, $\lambda=2.5\times10^{-8}$	market	-79	-62	-80	-58	-72	-72
	no market	-79	-62	-80	-117	-130	-130
φ=.6, $\lambda=5\times10^{-8}$	market	-67	-51	-68	-48	-60	-60
	no market	-67	-51	-68	-106	-119	-119
Hidalgo County							
φ=.5, λ=0	market	-55	-21	-58	-8	-43	-116
	no market	-55	-21	-58	-8	-43	-52
φ=.5, $\lambda=2.5\times10^{-8}$	market	-18	8	-21	14	-15	-79
	no market	-18	8	-21	14	-81	-79
φ=.5, $\lambda=5\times10^{-8}$	market	8	37	5	42	-49	-43
	no market	8	37	5	0	-49	-43
φ=.6, λ=0	market	-55	-21	-58	-8	-43	-43
	no market	-55	-21	-58	-8	-43	-43
φ=.6, $\lambda=2.5\times10^{-8}$	market	-18	8	-21	14	-7	-6
	no market	-18	8	-21	14	-7	-6
φ=.6, $\lambda=5\times10^{-8}$	market	8	37	5	42	15	21
	no market	8	37	5	42	15	21

Table A-1. (Cont.) Reduced gradients on crop variables

		1993	1994	1995	1996	1997	1998
		Sugarcane					
Cameron County							
φ=.5, λ=0	market	108	214	100	34	20	0
	no market	108	214	-106	-172	-185	-185
φ=.5, $\lambda=2.5\times10^{-8}$	market	143	196	135	7	41	-153
	no market	143	196	-59	-190	-153	-153
φ=.5, $\lambda=5\times10^{-8}$	market	179	235	171	44	0	-106
	no market	179	235	-13	-139	-106	-106
φ=.6, λ=0	market	108	214	100	34	20	20
	no market	108	214	100	-137	-151	-151
φ=.6, $\lambda=2.5\times10^{-8}$	market	143	196	135	7	41	41
	no market	143	196	135	-156	-119	-119
φ=.6, $\lambda=5\times10^{-8}$	market	179	235	171	44	77	77
	no market	179	235	171	-105	-72	-72
Hidalgo County							
φ=.5, λ=0	market	120	183	110	7	27	-179
	no market	120	183	110	7	27	0
φ=.5, $\lambda=2.5\times10^{-8}$	market	109	179	100	0	0	-183
	no market	109	179	100	0	-180	-183
φ=.5, $\lambda=5\times10^{-8}$	market	101	174	93	0	-177	-187
	no market	101	174	93	-121	-177	-187
φ=.6, λ=0	market	120	183	110	7	27	27
	no market	120	183	110	7	27	27
φ=.6, $\lambda=2.5\times10^{-8}$	market	109	179	100	0	17	16
	no market	109	179	100	0	17	16
φ=.6, $\lambda=5\times10^{-8}$	market	101	174	93	0	18	8
	no market	101	174	93	0	18	8

Table A-1. (Cont.) Reduced gradients on crop variables

		1993	1994	1995	1996	1997	1998
		Dry cotton					
Cameron County							
φ=.5, λ=0	market	-60	-75	-7	22	-65	-99
	no market	-60	-75	-7	22	-65	-99
φ=.5, $\lambda=2.5\times10^{-8}$	market	-177	-247	-123	-163	-196	-230
	no market	-177	-247	-122	-161	-196	-230
φ=.5, $\lambda=5\times10^{-8}$	market	-293	-363	-240	-277	-312	-345
	no market	-293	-363	-238	-276	-311	-345
φ=.6, λ=0	market	-60	-75	-7	22	-65	-99
	no market	-60	-75	-7	22	-65	-99
φ=.6, $\lambda=2.5\times10^{-8}$	market	-177	-247	-123	-163	-196	-230
	no market	-177	-247	-123	-161	-196	-230
φ=.6, $\lambda=5\times10^{-8}$	market	-293	-363	-240	-277	-313	-347
	no market	-293	-363	-240	-276	-311	-345
Hidalgo County							
φ=.5, λ=0	market	-50	-103	-2	-16	-63	-94
	no market	-50	-103	-2	-16	-63	-94
φ=.5, $\lambda=2.5\times10^{-8}$	market	-108	-159	-60	-78	-120	-151
	no market	-108	-159	-60	-78	-120	-151
φ=.5, $\lambda=5\times10^{-8}$	market	-162	-215	-114	-133	-177	-208
	no market	-162	-215	-114	-133	-177	-208
φ=.6, λ=0	market	-50	-103	-2	-16	-63	-94
	no market	-50	-103	-2	-16	-63	-94
φ=.6, $\lambda=2.5\times10^{-8}$	market	-108	-159	-60	-78	-121	-152
	no market	-108	-159	-60	-78	-121	-152
φ=.6, $\lambda=5\times10^{-8}$	market	-162	-215	-114	-133	-176	-206
	no market	-162	-215	-114	-133	-176	-206

Table A-1. (Cont.) Reduced gradients on crop variables

		1993	1994	1995	1996	1997	1998
		Dry sorghum					
Cameron County							
φ=.5, λ=0	market	0	57	0	68	15	15
	no market	0	57	0	68	15	15
φ=.5, $\lambda=2.5\times10^{-8}$	market	0	0	0	0	0	0
	no market	0	0	0	0	0	0
φ=.5, $\lambda=5\times10^{-8}$	market	0	0	0	0	0	0
	no market	0	0	0	0	0	0
φ=.6, λ=0	market	0	57	0	68	15	15
	no market	0	57	0	68	15	15
φ=.6, $\lambda=2.5\times10^{-8}$	market	0	0	0	0	0	0
	no market	0	0	0	0	0	0
φ=.6, $\lambda=5\times10^{-8}$	market	0	0	0	0	0	0
	no market	0	0	0	0	0	0
Hidalgo County							
φ=.5, λ=0	market	0	0	0	7	0	0
	no market	0	0	0	7	0	0
φ=.5, $\lambda=2.5\times10^{-8}$	market	0	0	0	0	0	0
	no market	0	0	0	0	0	0
φ=.5, $\lambda=5\times10^{-8}$	market	0	0	0	0	0	0
	no market	0	0	0	0	0	0
φ=.6, λ=0	market	0	0	0	7	0	0
	no market	0	0	0	7	0	0
φ=.6, $\lambda=2.5\times10^{-8}$	market	0	0	0	0	0	0
	no market	0	0	0	0	0	0
φ=.6, $\lambda=5\times10^{-8}$	market	0	0	0	0	0	0
	no market	0	0	0	0	0	0

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