# Impact of Water Supply Limitations from Federal Decisions in South Texas

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# Impact of Water Supply Limitations from Federal Decisions in South Texas

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This study extends and refines a previous model and provides estimates of the economic value of water shortages from shortfalls in Mexican deliveries to the U.S. In the process, we identify and evaluate a range of crop choices, appropriate irrigation technology use, water source substitution, and other mitigation strategies used by farmers to deal with water shortages. The effects of exogenous crop price and yield risk, as well as and other structural considerations are incorporated in deriving the marginal value of irrigation water for reference drought years. Results show that South Texas farmers react to risk by diversifying their crop mix, which in turn has implications for the imputed value of water and soil resources. The derived shadow price of water under 1998 conditions was larger than the average value of water used in previous estimates of damages from Mexican water treaty non-compliance. The higher estimated value of water and losses are driven in part by empirical evidence and the associated model conditions that producers are willing to pay high costs to protect their investment in orchards and perennial crops such as sugar cane and that hydrologic and institutional constraints severely limit access and transfers of water especially under shortage conditions. Assuming hypothetical Mexican inflows up to 500,000 ac-ft into the U.S. reservoirs in 1998, the shadow price of water at the farm gate would have declined from over \$400 per ac-ft to below \$100 per ac-ft.

Key words: water, irrigation, Rio Grande, optimization

The Middle and Lower Rio Grande River basin is comprised of the southernmost counties on the Texas-Mexico Border—Cameron, Hidalgo, Kinney, Maverick, Webb, Willacy, Starr, and Zapata. Geographically, the region transitions from the upriver riparian areas into the Rio Grande river delta, stretching east-southeast for approximately 250 miles to the confluence with

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the Gulf of Mexico. The regional soil types are predominately alluvial clays, clay loams, and sandy loams, which are extremely productive under irrigated cultivation in the semi-arid and subtropical climate.

The major land use of the region remains agricultural, although the trend toward urbanization is the most rapid in the state and one of the most rapid in the United States. In South Texas below Amistad International Reservoir almost 400,000 acres are irrigated for agricultural production using water from the Rio Grande when supplies are available. During the 1990s, total cropland was a little over one million acres, and roughly 30% of this wais irrigated cropland or orchards (USDA, 1997). In view of the total irrigated land area for the region (Table 1), 30% to 35% of the land is classified as cropland. The most extensive irrigated areas are in the four county Lower Rio Grande Valley (LRGV), comprised of Cameron, Hidalgo, Starr and Willacy Counties. In addition to row crops and vegetables, this portion of the region also contains roughly 30,000 and 44,000 acres, respectively, of citrus and sugar cane. The typical irrigation requirements of row crops are 1 to 1.5 acre-feet, while furrow irrigated vegetables use 1.5 to 2 acre-feet. Perennial sugar cane and citrus use the most irrigation water at roughly 5 acre-feet.

*Institutional Background*. Because the Rio Grande is an international border, the allocation of its water resources is complex. The international allocation of water rights was institutionalized when United States and Mexico signed a bilateral water-sharing treaty in 1944. This gives the U.S. Department of State primary responsibility over issues related to treaty non-compliance (see discussion on shortages below). The allocation of U.S. surface water rights along the Lower and Middle Rio Grande below Amistad Dam is unique to Texas, having been adjudicated in the late 1960s following extended litigation. Domestic, Municipal, and Industrial (DMI) rights have the highest priority in the allocation procedures. The irrigation rights are held by over thirty irrigation districts, and represent a residual claim on inflows to the reservoirs. There is very little ground water available in the region, so the impact of Rio Grande surface water shortages on agriculture has the potential to be very significant.

Federal, state and local institutions are involved in the allocation on inflows to the Rio Grande (Stubbs et al., 2003). At the international and federal levels, the IBWC maintains daily records of inflows, releases and volumes of both the Falcon and Amistad reservoirs, while the Texas Commission on Environmental Quality (TCEQ) Watermaster enforces compliance rules in Texas and oversees the current water rights system for the region's irrigation districts. The Watermaster ensures that certain levels of reserves are maintained for DMI users and general operation (Table 2). As the residual claimant on inflows to the reservoirs, irrigation users bear the risk of drought. This water supply risk clearly illustrated by the declining regional irrigation use during the severe drought period of 1996-1999, compared to the relatively stable DMI usage over the same period (Table 2).

*Water shortages*. The Rio Grande is the primary source of water for almost all agricultural, municipal, and industrial users in the Middle and Lower Rio Grande Valley region. The regional water supplies are stored upstream as surface water in Falcon and Amistad international reservoirs. Below El Paso, about three quarters of the water that flows into the Rio Grande drains from the Rio Conchos basin in the Mexican state of Chihuahua. In recognition of this, the 1944 treaty specifies minimum amounts of water to be allowed to flow into the Rio Grande from the Mexican tributaries. According to the 1944 Treaty, Mexico agreed to provide an average minimum of 350,000 ac-ft per year to the U.S. from the Rio Conchos Basin and other small tributaries that feed into the Rio Grande. During the 1990s, Mexico began a series of annual deficits of the required minimum inflows (Table 2). By the end of the treaty-stipulated five-year accounting cycle of 1992-1997, Mexico had accumulated a debt of 1,024,000 ac-ft. By the end of the next five-year cycle in October 2002, Mexico's debt was roughly 1.5 million ac-ft.

The annual shortages of irrigation water during the late 1990s have had serious economic impacts on the region's agricultural industries. Robinson estimated a static, average "farm gate" value of delivered irrigation water per acre-foot, which has been the basis of all recent impact assessment of the water shortage situation in this region (Robinson, 2002). Robinson estimated the average regional losses associated with water shortages at farm gate to equal 4,130 jobs per year and approximately $135,000,000 in business activity per year[2].

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[2] Calculated using per acre-foot impact estimates of 0.02 jobs and $652 in regional business activity. The measures incorporate the farm gate quantity of water shortages to be 41% losses from reservoir to the farm gate (i.e., a 350,000 ac-ft reservoir quantity equals a 206,500 ac-ft farm gate quantity) (Robinson).

*Risk Management*. The uniqueness and diversity of this region has serious implications for implementing standard risk mitigating policies like crop insurance or *ad hoc* disaster program based on annual production loss damages. First, the possibility of mitigating behaviors by farmers greatly complicates the estimation of actual damages. The region's farmers have reacted to irrigation water shortages by either 1) shifting away from crops that require more water, or 2) allocating water only to higher value irrigated crops while leaving other crops dryland, or 3) leaving land idle in order to allocate remaining water to planted irrigated crops. Second, the classification by USDA-RMA of water-shorted farmers as not having a reasonable expectation of irrigation resulted in many row crop farms with irrigated crop APH being re-classified as dryland and assigned minimal t-yield fractions. This resulted in inadequate and costly crop insurance coverage, as well as reduced the level of federal *ad hoc* disaster assistance provided in the late 1990s[3]. These limitations have led to a focus on re-allocating available land and water resources among alternative crop mix the prime risk mitigation strategy in this region.

*Crop Diversity.* The possibility for changing cropping pattern is greater in this region due to the diversity of agronomic and horticultural enterprises. However, alternative crops and crop mixes come with varying levels of revenue risk. While there is extensive acreage of federally subsidized program crops (e.g., cotton and sorghum), there are tens of thousands of acres of vegetable and orchard crops with no farm program and limited or no crop insurance coverage. Crop acreage in the region has always fluctuated due to changes in relative prices of crops, changes in government programs, and changes in natural growing conditions such as widespread freezes and pest outbreaks. Some notable highlights in the last fifteen years include 1989 freeze, the historically high cotton prices during 1994-95, the devastating beet armyworm infestation of cotton in 1995, the implementation of Freedom to Farm in 1996, and the particularly severe drought years in 1996 and 1998. All of these events influenced harvested crop acreage of the year they occurred or planted acreage the following year. A 2001 report issued by the USDA Office of the Chief Economist (2002) acknowledged that these issues largely confound efforts to estimate damage estimation in the conventional approach of actual production losses.

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[3] The Clinton era *ad hoc* disaster payments were calculated as a function of insurance claims. Thus, farmers who were reclassified as dryland for insurance purposes had reduced potential for disaster assistance.

*Rationale*. This study refines previous estimates of the economic value of water shortages from shortfalls in Mexican deliveries to the U.S. during the mid-late 1990s. In the process, we identify and evaluate a range of crop choices, appropriate irrigation technology use, water source substitution, and other mitigation strategies used by farmers to deal with water shortages. This study incorporates the effects of exogenous crop price and yield risk, as well as and other structural considerations, in deriving the marginal value of irrigation water for reference drought years. The next section describes the development of a mathematical programming model of resource allocation in the study area, followed by a discussion of results and implications.

## Model Development

*Formulation*. A mathematical programming model of irrigated land and irrigation water allocation in the Middle/Lower Rio Grande Basin was developed to analyze the impact of water shortages while accounting for exogenous price/yield risk and structural complexities. This work represents an expansion and refinement of previous risk modeling studies of the LRGV region using MOTAD (Teague, 1985) and E-V analysis (Bryant et al., 1994). A summation notation version of the basic model is:

$$\text{Max} \ \Sigma_i \Sigma_j \Sigma_k \Sigma_l \, EREV_{ijkl} * X_{ijkl} - \Sigma_j \Sigma_l \, Z_{jl} V_{jl} Z_{jl}' ) \qquad [1]$$

$$\Sigma_i \Sigma_k X_{ijkl} \leq Z_{jl} \qquad [2]$$

$$\Sigma_i \Sigma_j \Sigma_k \Sigma_l \, WATERUSE_{ijkl} * X_{ijkl} \leq WATERRHS \qquad [3a]$$

$$\Sigma_j \Sigma_k \Sigma_l X_{ijkl} \leq SOILSRRHS_i \qquad [3b]$$

$$\Sigma_i \Sigma_k \Sigma_l X_{i\text{"Sugarcane"}kl} \leq GRINDRIGHTS \qquad [4]$$

$$\Sigma_i \Sigma_k \Sigma_l X_{i\text{"Carrots"}kl} \leq PIVOT \qquad [5]$$

$$\Sigma_i \Sigma_k \Sigma_l X_{i\text{"Cotton"}kl} \leq COTBASE80\% \qquad [6]$$

$$\Sigma_k \Sigma_l X_{i\text{"Cotton"}kl} - \Sigma_j \Sigma_k \Sigma_l X_{i\text{"Feedgrains"}kl} \leq 0 \qquad [7a]$$

$$\Sigma_k \Sigma_l X_{i\text{"Sugarcane"}kl} - 0.2 * \Sigma_j \Sigma_k \Sigma_l X_{i\text{"cotton"}kl} \leq 0 \qquad [7b]$$

$$\Sigma_i \Sigma_k \Sigma_l X_{i\text{"Citrus"}kl} = ORCHARDS \qquad [8]$$

$$X_{ijkl} \geq 0 \qquad [9]$$

where

- i = resources (six classes of soils and irrigation water)
- j = irrigated crops (bellpepper, broccoli, cabbage, cantaloup, carrot, cucumber, honeydew, lettuce, onion, tomato, watermelon, corn, soybean, cotton, sorghum, hay, sugarcane, orange, grapefruit, pasture)
- k= technology for irrigation {e.g., furrow, sprinkler, drip}
- l = level of irrigation (full and various levels of deficit irrigation, including no irrigation)
- $\mathbf{X_{ijkl}}$ is irrigated cropping activity defined by crop, irrigation technology, irrigation level, and soil class
- $\mathbf{Z_{jl}}$ is a less indexed summary of $\mathbf{X_{ijkl}}$ for the VarCov matrix

- $\mathbf{V_{jl}}$ is the variance of historical net returns for cropping activities
- $EREV_{ijkl}$ and $WATERUSE_{ijkl}$ are technical coefficients reflecting, respectively, expected net returns and on-farm water demand for cropping activities
- WATERRHS is the regional available storage of irrigation water, net of expected priority uses, expected conveyance losses, and expected in-flows/credits.
- $SOILSRRHS_i$ is available acres, ca. 634,000, of irrigable land, by soil class
- GRINDRIGHTS is 44,000 acre upper limit on sugar cane acres
- PIVOT is upper limit on center pivot acreage in eastern Hidalgo County
- COTBASE80% is eighty percent of regional cotton program base acres
- ORCHARDS is fixed level of perennial citrus orchard acreage.

The objective function in Equation [1] follows Freund's approach to the standard mean-variance or optimal portfolio model that selects cropping activities to maximize net returns while penalizing risky cropping activities. The latter is achieved by a non-zero risk aversion parameter, $\alpha$, multiplied times the variance of historical crop net returns (McCarl and Spreen, 1997). Equation [2] is an identity that summarizes cropping activities by crop and irrigation level only, to fit the available historical data in estimating the VarCov matrix. Equations [3] constrain aggregate water usage for irrigation and usage of six-soil class for cropping to available right-hand-side levels.

Equations [4] and [5] represent the only upper limit constraints in the model, in contrast to typical modeling efforts involving multiple crops, especially vegetables. The mean variance formulation was chosen to induce a realistic crop mix without "hard-wiring" the outcome with numerous upper limits on high-value/high risk crops. The upper limit on grinding rights is a realistic reflection of available sugar mill capacity. Equation [5] is a realistic assessment of existing and potential adoption of center pivots in the LRGV. Equation [6] reflects the requirements of the 1990 farm bill to plant at least 80% of one's cotton base to be eligible for deficiency payments. Equation [7a] reflects the agronomic constraints of rotation between cotton and grassy feedgrain crops like sorghum or corn. Similarly, Equation [7b] reflects a agronomically realistic five years sugar cane: one-year cotton rotation pattern. Equation [8] simply fixes the acreage of perennial citrus orchard land, which is a major consumer of irrigation water .

*Data development*. To estimate the variance of historical net returns, county and regional crop price and yield data were collected from USDA (e.g., USDA-NASS, 1993) and used to estimate historic gross returns, by crop and irrigation level, for the years 1980 through 1992. Historical prices for program commodities were truncated at loan rates where applicable, and deficiency payments, if positive, were calculated and added into gross returns. Since production cost data series are incomplete prior to 1990, crop enterprise budget estimates were adjusted back to prior years, by input category, using a producer prices paid index (USDA-NASS, 1993). Historical net returns and associated VarCov matrix were then calculated.

Expected yields by soil class, along with the regional proportions of each soil class, were developed using soil class productivity index developed by Teague (1985) and applied to published crop yield parameters (Taylor, 1993). Teague's soil productivity index uses NRCS soil survey yield indices to classify the region's irrigable soils into six classes of varying productivity. For example, the lowest productivity class contained heavy clay and/or saline soils. Expected prices and production costs (sans harvest costs) were also patterned after 1993 Extension budgets (Taylor, 1993). These parameters were used to derive expected net revenue for the objective function.

Expected water demands per crop were based on crop technical coefficients from Extension budgets. (Taylor, 1993) The levels of standard 6" flood irrigation per crop were determined by grower interview, and represent typical crop irrigation demands with average rainfall conditions (Taylor, 2004). In addition, un-metered furrow irrigation in the 1990s has long been suspected of over delivery of irrigations, beyond the standard 6" order. The evidence for this is commonly observed incidence of heavy tail water accumulations. Therefore, an additional inflation factor of 30% was applied to all furrow irrigated crops, regardless of the year, to account for un-metered, excess delivery associated with standard 6" furrow irrigations, as well as push water requirements.

Expected costs, returns, and water demands for drip and sprinkler irrigated crops (not available for 1993) were obtained from current Extension budgets (Robinson, 2004). It was assumed that drip or sprinkler irrigated crops had the same yield as furrow irrigated, but used less water. Drip irrigation was allowed for melon crops as the melon industry ahs been adopting this technology.

Sprinkler irrigation is uncommon due to constraints on field size. There is a limited acreage of carrots under sprinkler irrigation, so this activity was defined in the model.

Available soil and water resources were developed based on information published in the Region M Water Planning report (2001) that summarized Texas Water Development Board survey data on irrigable acres within irrigation districts. Observations on monthly U.S. reservoir ownership, historical monthly inflows and evaporation, and annual Mexican deficit values were obtained from IBWC (Rakestraw, 2004). The Jan. 1 U.S. ownership balance for the year being modeled was selected as the basis for developing available water for irrigation. This is reasonable in modeling the region's farmer/decision makers since reservoir balance information is widely reported, and expectations about water availability for the upcoming spring planting would likely be formed around the Jan. 1 balance. TCEQ Watermaster's office provided information on historical annual water usage, from which expectations were developed for likely adjustments to the Jan. 1 ownership balance, e.g., expected inflows, evaporation, DMI reservations, and no charge pumping credits. It was assumed that expectations for the upcoming year would be based on the preceding year's inflows, evaporation, etc.

Further adjustments to expected water supply were made using estimates of river channel losses and intra-district conveyance losses. River channel losses between Falcon reservoir and various river reaches were obtained from Brandes (1999, 2004) and geographically matched to downstream irrigation districts. An average river channel loss parameter, weighted by authorized water rights, was derived for the entire Lower Rio Grande. Estimates of intra-district conveyance losses between the diversion point and the farm gate ranged from 10% to 60% loss. Extension irrigation engineers developed these estimates, with input from LRGV irrigation district managers (Fipps, 2004).

*Model solution*. The model in Equations [1] through [9] was formulated and solved in GAMS using the CONOPT solver for nonlinear programming. The risk efficient crop mix and resource use was evaluated over a range of risk aversion parameters. The following section presents results for the risk efficient crop mix and resource allocation for 1994, a historically wet/normal year with ample irrigation supplies in the previous year (and, as it turns out, in the 1994 growing season too). This year also represents the second calendar year when Mexico began running deficits under the 1944 treaty. Additional runs were made to evaluate the effects of dry years with substantial Mexican deficits (1997 and 1998). The latter two runs were repeated using an updated historical yield/price information in the variance-covariance matrix. In summary, the scenarios evaluated in this study include:

- Scenario 1. The complete baseline run, which has variance covariance matrix based on historical yields and prices from 1980-92, and uses expected budget and water supply parameters for 1994. For reference, 1994 was a normal-wet year following two wet years.

- Scenario 2. A partial baseline run, using the same baseline risk history, but with 1997 budget and water supply parameters. For reference, 1997 was a dry year following a dry year.

- Scenario 3. Another partial baseline run, using the same baseline risk history, but uses 1998 budget and water supply parameters. For reference, 1998 was an exceptionally dry year following a dry year. It represents the lowest available water supply.

- Scenario 4. Same as Scenario 3 but now with an updated variance covariance matrix This would capture a number of notable things like some of the drought impacts, the 1995 insect devastation of cotton, and the dramatically high prices for cotton and feedgrains in 1995-6.

Comparing Scenarios 2 or 3 to Scenario 1 isolates the effect of changing water supply. Comparing Scenarios 3 and 4 isolates the effect of risk on resource allocation and marginal values.

**Baseline Model Results and Validation**

The results from the baseline model run are presented below in Tables 3 and 4. The cropping activities in the risk efficient solution are defined by crop, type of irrigation (f=furrow, d=drip, s=sprinkler) , level of irrigation (full or deficit irrigation,), and the soil class (where S1 is poorest quality and S6 is highest). The four rightmost columns of Table 3 show alternative risk efficient cropping patterns for increasing level of risk aversion.

*No Risk Aversion*. The zero level of risk aversion corresponds to a linear programming solution.

As is typical of such models, it selects the most profitable activities (e.g., over 22,544 acres of fully irrigated honeydews on S5) subject to the various structural constraints. The poorer quality soil classes are planted to cotton and feedgrains, some of which was deficit irrigated. Without the cotton base and rotation constraints, honeydews would have been planted. (Citrus acreage, both bearing and non-bearing, was also fixed to reflect the perennial nature of that crop.) This high value/high risk outcome results in hugely inflated shadow prices for land (Table 4), i.e., how much more a decision-maker would be willing to pay above a normal land rental rate. The unrealistic nature of this outcome reflects the role and impact of risk on cropping decisions and optimal resource allocation.

*Risk adverse scenarios*. As the risk aversion parameter is increased, the model diversifies the portfolio from high value, high-risk crops to a more realistic mix of vegetable crops, row crops, and sugar cane (Table 3, right-most three columns). With an increasing risk parameter, the risk efficient mix of vegetables declines and shifts more to sugarcane, a historically more stable source of net revenue relative to vegetables. These higher value crops are allocated to the more productive soil groups. The shadow prices of water (i.e., the non-pecuniary marginal value of water over and above the $1.33 per ac-in paid by irrigators) is zero because of the excess water supplies for the year being modeled. However, the shadow prices for the six land classes are much more reasonable for the risk averse scenarios (Table 4)

*Risk model validation*. Validation of the overall model and the appropriate risk aversion parameter is accomplished by comparing the results from Tables 3 and 4 with historical data from 1993 and 1994. Table 5 shows harvested acreage data from USDA (1993) . The model outcomes using $\alpha$= 0.00000035, 0.00000045, and 0.00000055 show all had less than the actual levels of 1994 sugar cane acreage. The $\alpha$=0.00000045 model predicted actual honeydew/cantaloupe at approximately 75% of the actual, but it under predicted vegetables by 70%. Qualitatively, these risk levels produced a realistically diverse crop mix, particularly for vegetable and melon crops. The only notable missing crops are onions and watermelons, but the reason for this is their relatively un-profitable expected budget parameters.

The allocation of land to cotton and sorghum reflects the shift from high value/high risk crops to lower value/lower risk. Cotton and feedgrains are lower risk, in part because of the stabilizing effect of loan rates and deficiency payments. Most of cotton and feedgrain acreage was deficit-irrigated, implying a partial re-allocation of irrigation water to higher value crops. It should be noted, however, that such reallocation is, in reality, more limited due to various rules of transferring water outside irrigation districts.

Given these considerations, the risk model with a $\alpha$=0.00000045 model risk aversion parameter is the best fitting baseline model. The next section compares this baseline solution of Scenario 1 with the drought conditions of Scenarios 2 through 4. The year 1997 reflected a dry year following a dry year, while 1998 reflected a dry, severe drought year. The years preceding 1997 and 1998 included crop price swings, pest outbreaks, and changes in farm policy. All of these items should be reflected in a revised variance covariance matrix of historical net returns for Scenarios 4 and 5.

**Drought Conditions Results and Discussion**

Unlike the Baseline run, which had slack irrigation water, the runs under 1997 with 1998 drought conditions reflected, respectively, in slight and severe water shortages. At the same level of risk aversion, preliminary model results showed greatly reduced sugar cane (a relatively high water consuming crop) and maintaining acreage of melons, vegetables and row crops. Elimination of sugar cane is not a tenable result, however, because of the implicit costs of terminating a perennial crop. Therefore Scenarios 2 through 4 were run with an additional lower limit of sugar cane acreage to 30,000 acres. The resulting solution is shown in Table 6 using the $\alpha$= 0.00000045 risk aversion parameter in all four scenarios.

At the same risk aversion level ($\alpha$=0.00000045), after planting the required 30,000 acres of sugar cane, the model allocated much less land to vegetables (less than 10% of 1998 harvested acres) and melons. Melon and vegetable crops included sprinkler and drip irrigated crops, reflecting a substitution to water saving irrigation technologies, despite the higher cost. The other relevant result was the re-allocation of water from row crops (especially sorghum) to higher value crops. This result was commonly observed in South Texas during the late 1990s where irrigation was withheld from sorghum and cotton to provide for citrus, sugar cane, and vegetables. In general, the model reflected the general trend in decreased irrigated acreage for 1998 compared to 1994.

The shadow price of land was lower in the water shortage scenarios relative to the Baseline scenario (Table 7). The somewhat trivial conclusion is that the returns to irrigated land are lower in the absence of adequate irrigation water. In contrast, the marginal value (beyond the pecuniary $1.33/ac-ft cost of water) of additional acre-feet of irrigation water ranged from $60 to over $400 per acre-foot. The shadow price of water increased with higher risk aversion levels, probably because higher risk aversion induced more sugar cane acreage, thus increasing demand for water. Another explanation of this result is that irrigation water is a risk-reducing input, in addition to being a productive input. That being the case, a risk adverse decision maker would have a higher willingness to pay for a risk–reducing input.

Regardless of their theoretical rationale, an important policy implication of these shadow prices is that the marginal value of irrigation water, including both the $16/ac-ft in pecuniary value and the $400+/ac-ft imputed value, exceeds the $318/ac-ft average value used in previous damage estimates (Robinson, 2002); Thus, the value of irrigation water withheld by Mexico beginning in 1992-93 would be extremely valuable during the severe drought periods of the latter 1990s. In 1998 Mexico had a deficit of 229,700 ac-ft plus accumulated debt from previous annual deficits. However, if Mexico had begun paying down its debt, the marginal value would decrease as the crop mix shifted back to the point where the only excluded or precluded corps were fully-irrigated cotton and sorghum. Figure 1 shows how the shadow price of water declines with additional 10,000 ac-ft inflows into the U.S. reservoirs under 1998 conditions. If Mexico had let 500,000 ac-ft flow into Falcon/Amistad in 1998, the results would have been a farmgate supply of 710,000 ac-ft of irrigation water, a crop mix similar to Scenario 3, and a shadow price of about $90 per ac-ft.

*Damage valuation*. The results of this research can be applied towards damages estimation in two ways. First, comparisons of changes in regional profit (i.e., the objective function) could be made between the baseline scenario and subsequent years. It would be more accurate however to take the predicted crop mix and value it with actual yields and actual prices, rather than the expected values. The marginal valuations of water provide a more flexible means of valuing what-if scenarios about Mexican repayment of a given quantity of water in a given year. For example, the value of the average annual 350,000 ac-ft amount could be calculated as the sum product of marginal values and incremental inflows above a specified baseline amount.

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**Table 1. Irrigated Farms and Acreage for Border Counties Below Amistad Reservoir.**

| *COUNTY* | Irrigated Farms 1992 | Irrigated Farms 1997 | Harvested Irr. Cropland 1992 | Harvested Irr. Cropland 1997 | Irrigated Vege. Acres 1992 | Irrigated Vege. Acres 1997 | Irrigated Orchard Acres 1992 | Irrigated Orchard Acres 1997 |
|---|---|---|---|---|---|---|---|---|
| Cameron | 609 | 615 | 119,744 | 104,969 | 6,063 | 2,678 | -- | -- |
| Hidalgo | 1,009 | 844 | 218,423 | 179,657 | 49,048 | 26,762 | 28,520 | 25,505 |
| Maverick | 126 | 111 | 10,404 | 8,320 | 1,559 | 849 | 3,410 | 3,142 |
| Starr | 28 | 40 | 7,968 | -- | 4,900 | 3,372 | -- | -- |
| Webb | 41 | 35 | 3,405 | 1,908 | -- | -- | 408 | 177 |
| Willacy | 78 | 67 | 15,773 | 17,075 | 2,182 | 2,195 | -- | -- |
| Zapata | 10 | 8 | 21,257 | 17,244 | -- | -- | -- | -- |
| TOTAL | 1,901 | 1,720 | 396,974 | 329,173 | 63,752 | 35,856 | 32,338 | 28,824 |
| Decline from '92 | | -9.5% | | -17.1% | | -43.8% | | -10.9% |

*Note: the last two columns represent Census numbers for irrigated land in orchards. It obviously neglects citrus land in Cameron County, but it does pick up declines in orchard (probably pecan) in Maverick and Webb.*

**Table 2. Historical U.S. Water Supplies and Usage for the Middle-Lower Rio Grande (Acre-Feet), 1992-2000.**

| | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 |
|---|---|---|---|---|---|---|---|---|---|---|
| **U.S. Ownership**[1] | 3,636,707 | 3,483,105 | 3,031,259 | 2,104,112 | 1,566,337 | 1,191,561 | 1,180,125 | 1,405,755 | 1,333,081 | 1,426,067 |
| **Mexican Deficit**[2] | 53,000 | 181,200 | 274,500 | 290,200 | 225,100 | 229,700 | 184,900 | 244,300 | 224,600 | 0 |
| **Use Type:** | | | | | | | | | | |
| Domestic | 20,833 | 20,927 | 23,676 | 22,192 | 22,539 | 21,719 | 23,634 | 23,682 | 19,511 | 18,742 |
| Municipal | 174,412 | 183,124 | 186,829 | 189,755 | 197,674 | 193,482 | 215,196 | 212,673 | 229,391 | 226,412 |
| Industrial | 6,189 | 6,392 | 7,145 | 6,480 | 6,036 | 6,547 | 6,695 | 7,847 | 8,089 | 7,838 |
| Irrigation | 727,879 | 1,154,043 | 1,180,278 | 1,082,835 | 973,525 | 642,678 | 729,659 | 670,205 | 1,054,397 | 1,033,088 |
| Mining | 486 | 903 | 995 | 484 | 321 | 359 | 146 | 138 | 312 | 306 |
| Recreation | 197 | 99 | 96 | 77 | 39 | 28 | 0 | 0 | 87 | 62 |
| **Total Use** | 929,996 | 1,365,487 | 1,399,018 | 1,301,824 | 1,200,134 | 864,815 | 975,330 | 914,545 | 1,311,787 | 1,286,450 |

[1] *Reflects January 1 balance of combined U.S. storage in Amistad and Falcon reservoirs. Available irrigation storage balance (i.e., still subject to conveyance loss) is residual following accounting for U.S. dead storage (4,600 ac-ft) and maintained reserves for DMI and system operation.*
[2] *Annual deficit reflecting the difference between Mexican deliveries and the treaty-stipulated 350,000ac-ft average annual delivery over a Five-year cycle. This Table covers approximately two 5-year Treaty cycles during 1992-97 and 1997-02.*

**Table 3. Baseline Risk Efficient Cropping Pattern (Acres) for 1994.**

| CROP | IRR TYPE | IRR LEVEL | SOIL CLASS | *Risk Aversion Parameter Level* 0.00000000 | 0.00000035 | 0.00000045 | 0.00000055 |
|---|---|---|---|---|---|---|---|
| bellpepper | .f | .full | .S6 | | 2101 | 1690 | 1388 |
| broccoli | .f | .full | .S4 | | 7784 | 6289 | 5146 |
| cabbage | .f | .full | .S6 | | 306 | 206 | 168 |
| cantaloup | .f | .full | .S6 | | 2308 | 1780 | 1456 |
| carrot | .s | .df66 | .S6 | | 1508 | 1184 | 969 |
| honeydew | .d | .df66 | .S5 | | 4399 | 3425 | 2802 |
| honeydew | .f | .full | .S5 | 22544 | 3357 | 2537 | 2076 |
| lettuce | .f | .full | .S6 | | 728 | 514 | 420 |
| cotton | .f | .full | .S3 | 19517 | | | |
| cotton | .f | .df33 | .S1 | | 43477 | 43477 | 43477 |
| cotton | .f | .df33 | .S2 | 4813 | 4813 | 4813 | 4813 |
| cotton | .f | .df33 | .S3 | | 19517 | 19517 | 19517 |
| cotton | .f | .df33 | .S4 | 139124 | 135562 | 134030 | 133093 |
| cotton | .f | .df33 | .S5 | 13763 | 20485 | 21300 | 21793 |
| cotton | .f | .df33 | .S6 | 52595 | 49436 | 50153 | 50597 |
| cotton | .f | .df0 | .S1 | 43477 | | | |
| sorghum | .f | .df33 | .S1 | | 39629 | 40484 | 41028 |
| sorghum | .f | .df33 | .S2 | 4813 | 4813 | 4813 | 4813 |
| sorghum | .f | .df33 | .S3 | 19517 | 19517 | 19517 | 19517 |
| sorghum | .f | .df33 | .S4 | 139124 | 135562 | 134030 | 133093 |
| sorghum | .f | .df33 | .S5 | 13763 | 20485 | 21300 | 21793 |
| sorghum | .f | .df33 | .S6 | 52595 | 49436 | 50153 | 50597 |
| sorghum | .f | .df0 | .S1 | 43477 | 3848 | 2993 | 2449 |
| sugarcane | .f | .full | .S4 | 16728 | 16068 | 10817 | 6064 |
| sugarcane | .f | .full | .S5 | 2753 | 4097 | 4260 | 4359 |
| sugarcane | .f | .full | .S6 | 10519 | 9887 | 10031 | 10119 |
| sugarcane | .f | .df33 | .S4 | | | 9812 | 17581 |
| orange | .f | .full | .S4 | 3800 | 3800 | 3800 | 3800 |
| nborange | .f | .full | .S3 | 5320 | 5320 | 5320 | 5320 |
| grapefruit | .f | .full | .S4 | 7032 | 7032 | 7032 | 7032 |
| nbgrapefrt | .f | .full | .S3 | 9845 | 9845 | 9845 | 9845 |
| Total | .Acres | .0% | .DefIrr | 86954 | 3848 | 2993 | 2449 |
| Total | .Acres | .33% | .DefIrr | 440108 | 542731 | 553398 | 561712 |
| Total | .Acres | .66% | .DefIrr | | 5907 | 4609 | 3771 |
| Total | .Acres | .100% | .Irr | 98057 | 72634 | 64120 | 57188 |
| Total | .All | .pasture | .Acres | | | | |
| Total | .All | .Row_Crops | .Acres | 576579 | 576631 | 581498 | 584703 |
| Total | .All | .Vegetable | .Acres | | 12428 | 9883 | 8086 |
| Total | .All | .Melon | .Acres | 22544 | 10064 | 7742 | 6334 |

**Table 4. Risk Efficient Resource Allocation for Baseline 1993 Model**

| | *Risk Aversion Parameter Level* | | | |
|---|---|---|---|---|
| | 0.00000000 | 0.00000035 | 0.00000045 | 0.00000055 |
| | *Soil Resource Use (Thousands of Acres)* | | | |
| S1.Acres .Planted | 87.0 | 87.0 | 87.0 | 87.0 |
| S1.Shadow.Price | 2291.3 | 22.5 | 19.5 | 19.5 |
| S2.Acres .Planted | 9.6 | 9.6 | 9.6 | 9.6 |
| S2.Shadow.Price | 2355.1 | 89.0 | 86.0 | 86.0 |
| S3.Acres .Planted | 54.2 | 54.2 | 54.2 | 54.2 |
| S3.Shadow.Price | 2432.4 | 148.5 | 145.6 | 145.6 |
| S4.Acres .Planted | 305.8 | 305.8 | 305.8 | 305.8 |
| S4.Shadow.Price | 2483.3 | 217.2 | 214.3 | 214.3 |
| S5.Acres .Planted | 52.8 | 52.8 | 52.8 | 52.8 |
| S5.Shadow.Price | 2517.5 | 251.3 | 248.4 | 248.4 |
| S6.Acres .Planted | 115.7 | 115.7 | 115.7 | 115.7 |
| S6.Shadow.Price | 2619.3 | 353.1 | 350.2 | 350.2 |
| | *Water Resource Use (Thousands of Acre-Feet)* | | | |
| Shadow.Price | EPS* | EPS | EPS | EPS |
| Acre .Foot | 720.0 | 738.5 | 745.6 | 749.5 |

*Note: "EPS" refers to a near-zero value of epsilon.

**Table 5. USDA-NASS Acres for Selected Years and Selected Crops In the Study Region,**

| | 1993 | 1994 | 1997 | 1998 |
|---|---|---|---|---|
| Corn | 33,500 | 26,000 | 23,500 | 25,000 |
| Cotton | 123,000 | 137,000 | 60,000 | 89,000 |
| Sorghum | 76,000 | 110,000 | 97,000 | 87,000 |
| Sugarcane | 43,500 | 42,400 | 27,300 | 32,900 |
| **Total Row Crops** | **276,000** | **315,400** | **207,800** | **233,900** |
| | | | | |
| Cantaloupe | 7,220 | 6,010 | 2,100 | 3,200 |
| Honeydew | 4,800 | 4,300 | 2,000 | 2,500 |
| Watermelon | 14,070 | 13,900 | 6,100 | 9,500 |
| **Total Melons** | **26,090** | **24,210** | **10,200** | **15,200** |
| | | | | |
| Cabbage | 5,500 | 6,300 | 5,000 | 4,600 |
| Onions | 12,440 | 21,700 | 13,200 | 10,550 |
| Bell Peppers | 3,300 | 3,600 | 3,100 | 1,000 |
| **Total Selected Vegetables** | **21,240** | **31,600** | **21,300** | **16,150** |

**Table 6. Risk Efficient Cropping Pattern (Acres) for Drought Scenarios (Alpha = 0.00000045).**

| CROP | IRR TYPE | IRR LEVEL | SOIL CLASS | Scenario 2<br>Baseline Risk & 1997 E($H_2O$) | Scenario 3<br>Baseline Risk & 1998 E($H_2O$) | Scenario 4<br>Updated Risk & 1998 E($H_2O$)<br>299 |
|---|---|---|---|---|---|---|
| bellpepper | .f | .full | .S6 | 1669 | | |
| broccoli | .f | .full | .S4 | 6199 | | 298 |
| cabbage | .f | .full | .S6 | 219 | | 1343 |
| cantaloup | .d | .df66 | .S6 | | | 2175 |
| cantaloup | .f | .full | .S6 | 1820 | | 1358 |
| carrot | .s | .df66 | .S6 | 1248 | 839 | |
| honeydew | .d | .df66 | .S5 | 3444 | 2138 | 1399 |
| honeydew | .f | .full | .S5 | 2594 | 1660 | |
| lettuce | .f | .full | .S6 | 556 | | 618 |
| cotton | .f | .full | .S3 | | | |
| cotton | .f | .df33 | .S1 | 41800 | 33355 | 35279 |
| cotton | .f | .df33 | .S2 | 4813 | 4813 | 4813 |
| cotton | .f | .df33 | .S3 | 19517 | 19517 | 19517 |
| cotton | .f | .df33 | .S4 | 135805 | 139938 | 139870 |
| cotton | .f | .df33 | .S5 | 21265 | 22284 | 23374 |
| cotton | .f | .df33 | .S6 | 50090 | 52214 | 50437 |
| cotton | .f | .df0 | .S1 | | 1169 | |
| sorghum | .f | .df33 | .S1 | 36023 | | |
| sorghum | .f | .df33 | .S2 | 4813 | | |
| sorghum | .f | .df33 | .S3 | 19517 | | |
| sorghum | .f | .df33 | .S4 | 135805 | | |
| sorghum | .f | .df33 | .S5 | 21265 | 4263 | |
| sorghum | .f | .df33 | .S6 | 50090 | | |
| sorghum | .f | .df0 | .S1 | 5777 | 34524 | 35279 |
| sorghum | .f | .df0 | .S2 | | 4813 | 4813 |
| sorghum | .f | .df0 | .S3 | | 19517 | 19517 |
| sorghum | .f | .df0 | .S4 | | 139938 | 139870 |
| sorghum | .f | .df0 | .S5 | | 18021 | 23374 |
| sorghum | .f | .df0 | .S6 | | 52214 | 50437 |
| sugarcane | .f | .full | .S4 | 9783 | | |
| sugarcane | .f | .full | .S5 | 4253 | | |
| sugarcane | .f | .full | .S6 | 10018 | | |
| sugarcane | .f | .df66 | .S4 | | 9404 | 15238 |
| sugarcane | .f | .df66 | .S5 | | 4457 | 4675 |
| sugarcane | .f | .df66 | .S6 | | 10443 | 10087 |
| sugarcane | .f | .df33 | .S4 | 7387 | 5697 | |
| orange | .f | .full | .S4 | 3800 | 3800 | 3800 |
| nborange | .f | .full | .S3 | 5320 | 5320 | 5320 |
| grapefruit | .f | .full | .S4 | 7032 | 7032 | 7032 |
| nbgrapefrt | .f | .full | .S3 | 9845 | 9845 | 9845 |
| pasture | .f | .df0 | .S1 | 3354 | 17907 | 16397 |
| Total | .Acres | .0% | .DefIrr | 9132 | 288102 | 289687 |
| Total | .Acres | .33% | .DefIrr | 548188 | 282081 | 273290 |
| Total | .Acres | .66% | .DefIrr | 4692 | 27281 | 33574 |
| Total | .Acres | .100% | .Irr | 63108 | 27657 | 28570 |
| Total | .All | .pasture | .Acres | 3354 | 17907 | 16397 |
| Total | .All | .Row_Crops | .Acres | 578019 | 576579 | 576579 |
| Total | .All | .Vegetable | .Acres | 9891 | 839 | 1215 |
| Total | .All | .Melon | .Acres | 7859 | 3798 | 4932 |

**Table 7. Risk Efficient Resource Allocation for Drought Scenarios.**

| | Scenario 2<br>Baseline<br>Risk &<br>1997 E($H_2O$) | Scenario 3<br>Baseline<br>Risk &<br>1998 E($H_2O$) | Scenario 4<br>Updated<br>Risk &<br>1998 E($H_2O$) |
|---|---|---|---|
| | *Soil Resource Use (Thousands of Acres)* | | |
| S1.Acres .Planted | 87.0 | 87.0 | 87.0 |
| S1.Shadow.Price | 2.5 | 2.5 | 2.5 |
| S2.Acres .Planted | 9.6 | 9.6 | 9.6 |
| S2.Shadow.Price | 69.0 | 69.0 | 48.5 |
| S3.Acres .Planted | 54.2 | 54.2 | 54.2 |
| S3.Shadow.Price | 128.6 | 117.5 | 100.4 |
| S4.Acres .Planted | 305.8 | 305.8 | 305.8 |
| S4.Shadow.Price | 197.3 | 182.1 | 159.8 |
| S5.Acres .Planted | 52.8 | 52.8 | 52.8 |
| S5.Shadow.Price | 231.4 | 211.3 | 185.3 |
| S6.Acres .Planted | 115.7 | 115.7 | 115.7 |
| S6.Shadow.Price | 333.2 | 314.7 | 278.2 |
| | *Water Resource Use (Thousands of Acre-Feet)* | | |
| Acre .Foot | 727.1 | 480.0 | 480.0 |
| Shadow.Price | 3.6 | 408.2 | 468.5 |

**Figure 1. Marginal Value of Irrigation Water Under By Level of Hypothetical Mexican Inflow, 1998 Conditions**