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Mitigating water shortages in a multiple risk environment

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Abstract

This paper estimates the economic value of irrigation water shortfalls and mitigation responses of farmers in the Lower Rio Grande Valley of Texas. The water shortage levels closely correspond to supply shortfalls experienced by the U.S. during the 1990s when Mexico fell behind on treaty delivery obligations. 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 other structural considerations are incorporated in the estimation of the marginal value of irrigation water. Results show that South Texas farmers react to risk by diversifying their crop mix, with implications for the imputed value of water and soil resources. The inclusion of exogenous risk refines the prediction of what decision makers would have grown assuming strict Mexican treaty compliance. The resulting marginal values reflect grower adjustments for risk using crop mix, irrigation level, and irrigation technology. The aggregate damage estimates using this approach are realistically smaller than previous damage estimates that were based on fixed cropping patterns and average water values.

Keywords: Agricultural diversification; Irrigation; Irrigation water; Mexico; Optimization; Rio Grande; Risk management; Water shortages; Water values

Introduction

Water shortages in irrigated systems are not a unique event. The increasing demands made on freshwater systems coupled with natural drought events, make the shortage of water supplies, if not a frequent, then at least an unremarkable event (Burton, 1992; Zilberman *et al.*, 1998; Uccellini, 2004; USDI, 2004). And associated with each major water shortage event (whether actual or potential) there is a need to quantify the impacts as a precursor for choosing an appropriate level of policy intervention (Adams & Cho, 1998; Booker *et al.*, 2005; Ward *et al.*, 2006). Studies involved in this type of

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quantification analysis generally follow a resource-based modeling approach (Adams & Cho, 1998; Sunding *et al.*, 2002; Jaeger, 2004; Booker *et al.*, 2005; Ward *et al.*, 2006).

This study provides a risk-modeling approach to the issue of irrigation water shortages. It develops this perspective because agricultural producers encounter more risks than just irrigation water shortfalls and their response involves more that just adjusting irrigation levels. In our approach irrigators face a response to water shortages in an environment with output price risk and non-water related yield risk. In this study location, as well as in other areas with diverse cropping possibilities, changes in the cropping pattern are a possible (even likely) response to reduced water supplies and other revenue risks. This is in contrast to many temperate production regions where short run rigidities in cropping patterns from climate, equipment and management will often result in crop insurance payments on failed major crops, rather than switching crops and maintaining production.

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 (Robinson, 2002). 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 other structural considerations, to derive estimates of damages based on the marginal value of irrigation water for reference drought years. Our resulting water shortage valuations improve on previous estimates in several ways. The shadow prices capture the complexity of economic tradeoffs in substituting crops and inputs in a given year. Further, these valuations reflect the influence of multiple risks using a conventional risk programming framework. The study period included significant price volatility in a number of commodities, as well as non-water related production disasters. Thus the inclusion of risk should therefore give more realistic resource allocation and resulting water valuation.

Land and water

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 400 kilometres to the confluence with 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 in 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 162,000 hectares are irrigated for agricultural production using water from the Rio Grande when supplies are available. During the 1990s, cropland exceeded over 400,000 hectares, and roughly 30% of this area was irrigated cropland or orchards (Table 1) (USDA, 2007). The most extensive irrigated areas are in four counties—Cameron, Hidalgo, Starr and Willacy—of the Lower Rio Grande Valley (LRGV), with extensive irrigated row crops and vegetables, and over 12,000 hectares of both orchards and sugar cane. The typical irrigation application for row crops is 1,200 to 1,850 cubic meters per hectare per year, while furrow irrigated vegetables receive 1,850 to 2,400 cubic meters per hectare per year. Perennial sugar cane and citrus have the greatest irrigation water application at roughly 6.000 cubic meters per hectare per year. There is very little ground water available in the region, so the impact of Rio Grande surface water shortages

Table 1. Irrigated farms and land area for border counties below Amistad Reservoir.

	Irrigated farms		Harvested irrigated cropland (ha)		Irrigated vegetable (ha)		Irrigated orchard (ha)	
County	1992	1997	1992	1997	1992	1997	1992	1997
Cameron	609	615	48,460	42,480	2,454	1,084	1,177	1,478
Hidalgo	1,009	844	88,395	72,706	19,849	10,830	11,542	10,322
Maverick	126	111	4,210	3,367	631	344	1,380	1,272
Starr	28	40	3.225		1,983	1,365		
Webb	41	35	1.378	772			165	72
Willacy	78	67	6,383	6,910	883	888	89	65
Zapata	10	8	8,603	6,979				
TOTAL	1,901	1,720	160,653	133,214	25,800	14,511	14,353	13,207
Decline from 1992	− 9.5%		− 17.1%		− 43.8%		− 8.0%	

Note: the last two columns are the Census of Agriculture values for irrigated land in orchards.

on agriculture has the potential to significantly change production and reduce revenue and returns. Risk responses play a role in these changes.

The allocation of Rio Grande water resources is complex, in part because it is an international border with water resources used by two countries. First, 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. Regional water supplies are stored upstream in the Falcon and Amistad reservoirs. The allocation of U.S. surface water rights along the Lower and Middle Rio Grande below Amistad Dam is unique. Following extended litigation, Texas (U.S.) water rights in this section of the Rio Grande were adjudicated in the late 1960s so that domestic, municipal and industrial (DMI) rights have the highest priority in allocation. Irrigation rights held by over thirty irrigation districts represent a residual claim on available water, the amount of which is determined by inflows and reservoir levels. As the residual claimants on Rio Grande water, irrigation users bear the bulk of drought risk. This water supply risk was clearly illustrated by the declining regional irrigation allocation and use during the severe drought period of 1996–1999, compared to the relatively stable DMI usage over the same period (Table 2).

Second, the international allocation of water rights was institutionalized when the United States and Mexico signed a bilateral water-sharing treaty in 1944. The treaty specifies minimum inflow levels to the Lower Rio Grande from the Mexican tributaries, since about three quarters of the water that flows into the Rio Grande below El Paso drains from the Rio Conchos basin in the Mexican state of Chihuahua. According to the 1944 Treaty, Mexico agreed to provide an average minimum of 431.7 million cubic meters 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 1.26 billion cubic meters. By the end of the next five-year cycle in October 2002, Mexico's debt was roughly 1.85 billion cubic meters after a second cycle accumulation of 589.4 million cubic meters.

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

Table 2. Historical U.S. water supplies and usage for the middle-lower Rio Grande (thousand cubic meters), 1992–2004. (Note: This table covers approximately two five-year Treaty cycles during 1992–97 and 1997–02).

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
U.S. ownership*	4,486,174	4,296,218	3,738,684	2,595,246	1,931,633	1,470,311	1,455,509	1,734,276	1,644,232	1,758,945	1,417,271	1,622,029	–
Mexican deficit†	65,375	223,260	339,208	357,710	277,533	283,701	228,194	300,970	277,533	0	0	0	0
Use type													
Domestic	25,903	25,903	29,604	27,137	28,370	27,137	29,604	29,604	24,670	23,436	25,903	24,670	19,736
Municipal	214,626	225,727	230,661	234,362	244,229	238,062	265,199	262,732	282,467	278,767	294,802	260,265	266,432
Industrial	7,401	7,401	8,634	7,401	7,401	8,634	8,634	9,868	9,868	9,868	4,934	6,167	7,401
Total DMI	247,930	259,031	268,899	268,899	278,767	273,833	303,437	300,970	317,005	312,071	325,639	291,102	293,569
Other‡	1,233	1,233	1,233	1,233	0	0	0	0	0	0	7,401	4,934	7,401
Irrigation	897,975	1,423,438	1,455,509	1,335,861	1,201,411	793,129	900,442	826,433	1,300,090	1,274,187	821,499	690,750	708,019
Total use	1,147,138	1,683,703	1,725,641	1,605,994	1,480,178	1,066,962	1,202,645	1,128,636	1,618,328	1,586,258	1,149,605	983,085	1,000,354

* 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 acre-feet) and maintained reserves for DMI and system operation.

† Annual deficit reflecting the difference between Mexican deliveries and the treaty-stipulated 431.7 million cubic meter average annual delivery over a five-year cycle.

‡ Includes mining and recreation.

associated with water shortages at farm gate to equal 4,130 jobs per year and approximately $135 million in business activity per year[1].

Measuring the value of water shortages

Estimating the agricultural production value associated with reduced water supplies is much easier under conditions where reductions in water supplies result in corresponding reductions in irrigated area. After compensating for crop insurance payments and local market price adjustments, estimating the value of the forgone water is straightforward. This scenario is not the case in the LRGV or other areas where there is significant potential for mitigation strategies or changes in agricultural production. These changes and adjustments have important implications for measuring the value of forgone water. First, the possibility of mitigating behaviors by farmers greatly complicates the estimation of actual damages. In the past, the region's farmers have reacted to irrigation water shortages by either 1) shifting away from crops with large water requirements; 2) allocating water only to higher value irrigated crops while leaving other crops unirrigated; or 3) leaving land idle in order to allocate remaining water to planted irrigated crops. Second, the classification by USDA's Risk Management Agency (RMA) of water-shorted farmers as not having a reasonable expectation of irrigation resulted in many row crop farms with irrigated crops being re-classified as non-irrigated, with only minimal insured yields. This further complicates the response of irrigators to water shortfalls[2].

The challenge is how to estimate changes attributable to water shortages, whilst taking into account changes that occurred because of other factors, in particular other risk and market associated changes (this would seem to be our major contribution).

These considerations have led us to focus on re-allocating available land and water resources among alternative crops as the prime risk mitigation strategy in this region. The possibility for changing cropping patterns is real due to the diversity of agronomic and horticultural enterprises in this region. However, alternative crops and crop mixes come with varying levels of revenue risk. While there is extensive cultivation of traditional program crops (e.g., cotton and sorghum), there are tens of thousands of hectares of vegetable and orchard crops with no farm program and limited or no crop insurance coverage. Crop area 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. 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.

We developed a mathematical programming model of irrigated land and irrigation water allocation in the Middle/Lower Rio Grande Basin 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 a linear programming

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[1] Calculated using per acre foot impact estimates of 0.02 jobs and $652 in regional business activity. The measures incorporate a 41% loss from the reservoir to the farm gate (i.e., a 431.7 million cubic meter reservoir quantity equals a 254.7 million cubic meter farm gate quantity) (Robinson, 2002).

[2] In the 1990s there was a downward trend in insured value per acre, reflected in the lower non-irrigated value. And, since *ad hoc* disaster payments were calculated as a function of insurance claims, farmers who were reclassified as dryland for insurance purposes had reduced potential for insurance payments and disaster assistance.

formulation (Teague, 1985). The mean-variance formulation was chosen to induce a realistic crop mix without "hard" constraints on either the share or acreages of high-value/high-risk crops. This formulation also avoids specifying a cost adjustment value to force the model into "equilibrium" for a base year and then holding that value fixed through the valuation process. A summation notation version of the basic model is:

$$\text{Max} \sum_i \sum_j \sum_k \sum_l \left(\text{EREV}_{ijkl} * X_{ijkl} - \alpha \sum_j \sum_l Z_{jl} V_{jl} Z_{jl} \right) \tag{1}$$

$$\sum_i \sum_k X_{ijkl} \leq Z_{jl} \tag{2}$$

$$\sum_i \sum_j \sum_k \sum_l \text{WATERUSE}_{ijkl} * X_{ijkl} \leq \text{WATERRHS} \tag{3a}$$

$$\sum_j \sum_k \sum_l X_{ijkl} \leq \text{SOILSRRHS}_i \tag{3b}$$

$$\sum_j \sum_k \sum_l X_{i\text{"Sugarcane"}kl} \geq \text{MINMILLFLOW} \tag{4a}$$

$$\sum_j \sum_k \sum_l X_{i\text{"Sugarcane"}kl} \leq \text{GRINDRIGHTS} \tag{4b}$$

$$\sum_j \sum_k \sum_l X_{i\text{"Carrots"}kl} \leq \text{SPRINKLER} \tag{5}$$

$$\sum_j \sum_k \sum_l X_{i\text{"Cotton"}kl} \leq \text{COTBASE}\, 80\% \tag{6}$$

$$\sum_k \sum_l X_{i\text{"Cotton"}kl} - \sum_j \sum_k \sum_l X_{i\text{"Feedgrains"}kl} \leq 0 \tag{7a}$$

$$\sum_k \sum_l X_{i\text{"Sugarcane"}kl} - 0.2 * \sum_j \sum_k \sum_l X_{i\text{"Cotton"}kl} \leq 0 \tag{7b}$$

$$\sum_j \sum_k \sum_l X_{i\text{"Citrus"}kl} = \text{ORCHARDS} \tag{8}$$

$$X_{ijkl} \geq 0 \tag{9}$$

where

i = resources (six classes of soils and irrigation water)
j = irrigated crops (bellpepper, broccoli, cabbage, cantaloupe, 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)
X_{ijkl} is irrigated cropping activity defined by crop, irrigation technology, irrigation level, and soil class
Z_{jl} is the X_{ijkl} variable summed over resources i and cropping activities k
V_{jl} is the variance of historical crop returns to land, management, and fixed costs (hereafter referred to as net returns)

α is a non-zero risk aversion parameter
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 area (c. 256,576 hectares) of irrigable land, by soil class
MINMILLFLOW is 12,141 hectare lower limit on sugarcane land while GRINDRIGHTS is 17,807 hectare upper limit on sugarcane acres
SPRINKLER is the upper limit on sprinkler acreage in eastern Hidalgo County
COTBASE 80% is eighty percent of regional cotton program base acres
ORCHARDS is a fixed 12,141 hectare limit on perennial citrus orchard acreage

The objective function in Equation (1) follows Freund's (1956) approach to the standard mean-variance or optimal portfolio model that selects cropping activities to maximize net returns while penalizing risky cropping activities. The penalty for risky cropping activities is achieved by a non-zero risk aversion parameter, α, multiplied by the variance of historical crop net returns (McCarl & Spreen, 1997). Following Brink & McCarl (1978), the expected gross revenue used to develop the deviation matrix was a five-year moving average of historical gross revenues rather than the entire thirteen years. This was assumed to account for the grower weightings of recent experience and trends. This analysis was conducted with $\alpha = 0.0000008$, which was the parameter level resulting in the best fitting baseline model for 1998[3,4].

Equation (2) is an identity that summarizes cropping activities by crop and irrigation level only, to fit the available historical data in estimating the variance—covariance matrix. Equations (3a) and (3b) constrain aggregate usage of water for irrigation and usage of six soil classes for cropping to available resource levels.

Equations (4a,b) and (5) represent the upper limit constraints in the model, in contrast to typical modeling efforts involving multiple crops, especially vegetables. The lower and upper limits on sugar cane acreage are realistic reflections of sugar mill minimum and maximum capacity. Equation (5) reflects current and potential adoption of center pivot sprinklers in the LRGV. Equation (6) reflects the

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[3] Risk parameters over the range of 0.00000005 to 0.00000020 were considered in this study, before the reported value of 0.00000008 was selected. The latter produced results that best reflected the 1998 baseline regional crop mix. The use of parameter values to calibrate a model is well established in some modeling approaches. For example, Howitt (1995) in his description of Positive Mathematical Programming (PMP) includes a calculated "constraint set" that is added on the original problem that allows the model to "replicate" the "observed data within bounds without additional calibration constraints". Schaible (1997) uses a similar approach, but states that the calculated values represent "short-run economies of scope". Schaible goes on to state the values "do not equal market rental rates" but "amounts to performing a monotonic cost-structure transformation that enables the . . . model to rationalize the true technology and ensure that optimal solutions are consistent with competitive profit maximization". The logic behind both of these approaches is straightforward. To remove physical limits on the acres of current crop allocations, a calculated value is added to the objective function that equates the marginal value product across commodities. The values are calculated in a manner that replicates the observed data in recognition that rational producers value diversification and have physical limits that are not included in the model.

[4] While model parameterization for calibration purposes is common (Howitt, 1995; Schaible, 1997) it begs the question about how well this risk aversion coefficient reflects the risk preferences of decision makers in the LRGV. Recent risk modeling of representative LRGV cotton farms by Bise (2007) derived a risk aversion coefficient of 0.0000016 to represent "normally risk averse" decision makers according to Anderson and Dillon's (1992) risk aversion classification. The risk aversion parameter in our regional, multi-crop model falls between this level and risk neutral, perhaps as a result of aggregating across regional row crop and vegetable (i.e., more risk loving) producers.

requirements of the 1990 Farm Bill to plant at least 80% of one's cotton base to be eligible for deficiency payments. Although this policy did not apply after 1996, the constraint is retained in the model to embody the behavior of cotton producers in maintaining cotton planting history. Equation (7a) reflects the agronomic constraints of rotation between cotton and grassy feedgrain crops like sorghum or corn. Similarly, Equation (7b) reflects a typical five-year sugar cane and one year of cotton rotational pattern. Equation (8) fixes the acreage of perennial citrus orchard land, which is a major consumer of irrigation water (i.e., citrus acreage is constant in this short-run model time horizon).

Data development

The variance of historical net returns was calculated from county and regional crop price and yield data (USDA-NASS, 2005). These data were used to estimate the historic gross returns, by crop and irrigation level, for the reference year and the preceding thirteen years. Historical prices for program commodities were truncated at loan rates where applicable. 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, 2005). Historical net returns and associated variance—covariance matrix were then calculated.

Expected yields for fully irrigated crops, by soil class, along with the regional proportions of each soil class, were developed using a soil class productivity index developed by Teague (1985) and applied to crop yield parameters. 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 crop yields for deficit irrigated crops were derived from 48-year simulations of LRGV cropping systems using WinEPIC crop simulations (Harman *et al.*, 2005). Expected prices and production costs (excluding harvest costs) for a given year were taken from Extension budgets (Taylor, 1993; Robinson, 2004). 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; Robinson, 2004). Standard flood irrigation levels (i.e., 617 cubic meters per hectare per irrigation) per crop were determined by grower interview, and represent typical crop irrigation deliveries 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 irrigation level. The evidence for this is the commonly observed incidence of heavy tail water accumulations. Therefore, an additional adjustment of 10% was added to all furrow irrigated crops, regardless of the year, to account for un-metered, excess delivery associated with standard 617 cubic meter per hectare per furrow irrigations, as well as conveyance water requirements.

Expected variable costs, returns, and water demands for drip and sprinkler irrigated crops 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 has been adopting this technology. Sprinkler irrigation is uncommon due to constraints on field size. There is a limited acreage of carrots under center-pivot 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* (Rio Grande Regional Water Planning Group, 2001) that summarized Texas Water Development Board survey data on irrigable land 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 January 1 U.S. ownership balance was selected as the basis for developing available water for irrigation for each year. This period was chosen since reservoir balance information is widely reported and expectations about water availability for the upcoming spring planting would likely be formed around the January 1 balance. Available water supplies at the farm gate were estimated based on the quantity of water owned by the U.S. at the beginning of the calendar year, adjusted for non-irrigation uses and losses. For any given year, the difference between the January 1 balance and the amount actually diverted from the river for irrigation was assumed to account for non-irrigation uses and losses, including changes in downstream demands, reservations of non-agricultural priority users, reservoir evaporation, and inter-channel losses. The available water from assumed Mexican payback into the reservoir was reduced by the actual year's irrigation losses relative to the January 1 balance. Beyond the diversion point, expected intra-district conveyance loss was obtained by averaging district estimates developed by Extension irrigation engineers, with input from LRGV irrigation district managers (Fipps, 2004). The resulting 25% average intra-district loss matched previous findings (Brandes, 1999, 2004). In summary, the farm gate availability of water in any given year was modeled as a function of U.S. ownership at the beginning of the calendar year, in relation to how much was actually diverted, and further discounted for average intra-district conveyance loss.

The model in Equations (1) to (9) was formulated and solved in GAMS using the CONOPT solver for nonlinear programming (Brooke *et al.*, 1998). A series of validation runs were developed for the following reference years: 1993 and 1994 (large water supplies at the beginning of the Mexican deficit period) and 1997 and 1998 (low water supplies at the end of the first cycle with over one billion cubic meters in accumulated Mexican debt). These validation runs resulted in a reasonable depiction of the actual shifts in crop mixes over this time period (Robinson, *et al.*, 2005). Table 3 (discussed below) gives an example of model output for a dry year. In the current study, we analyze the value of water assuming strict treaty compliance by Mexico.

Under the strict compliance scenario, Mexico is assumed by October, 1997 to deliver or transfer 1.26 billion cubic meters into U.S. ownership (i.e., in the upstream reservoirs) to pay off the first cycle debt. A demand schedule for the Mexican payback was plotted by solving the model with zero payback, and then again with increasing increments of payback up to the point where either the payback was consumed or the shadow price of water reached zero. In this way, approximately 678.4 million cubic meters (reservoir quantity) could have been consumed in 1998 and still generate positive values. We therefore valued the remainder of the Mexican payback by depreciating it for annual evaporation (Rakesfstraw, 2004) and repeating the seasonal incremental valuation modeling for 1999. Assuming Mexican payback of the second cycle debt of 5.89.4 million cubic meters in October, 2002, a series of 2003 and 2004 model runs generated a similar valuation schedule of demand increments.

Results and discussion

Resource allocation

The baseline 1998 scenario shows shifts in water allocations and among crops allocated to soil groups with differing productivity (Table 4). In particular, the risk efficient solution involves a mix of fully and deficit irrigated crops, including alternative irrigation delivery methods, e.g., drip irrigated melons. This demonstrates how in the absence of adequate insurance or government programs, growers of a

Table 3. Incremental farm gate marginal valuation of strict treaty compliance (end-of-cycle debt repayment in cubic meters).

	Quantity demanded (cubic meters)				
Year	Reservoir[†]	Farm gate	Marginal value ($/cubic meter)	Incremental value, farm gate ($)	Different in obj. function ($)*
1998	123,348,200	56,943,697	0.0410	2,335,929	
	246,696,400	113,886,160	0.0197	2,238,983	
	370,044,600	170,829,856	0.0083	1,412,637	
	493,392,800	227,772,319	0.0045	1,034,087	
	616,741,000	284,716,016	0.0002	355,467	
	678,415,100	313,187,247	0.0000	392	
			TOTAL	$7,377,495	$8,835,508
1999	123,348,200	33,227,538	0.0508	1,688,995	
	246,696,400	66,453,843	0.0233	1,551,612	
	370,044,600	99,681,381	0.0137	1,363,048	
	493,392,800	132,908,919	0.0103	1,363,048	
	584,484,212	157,446,576	0.0061	958,854	
			TOTAL	$6,925,558	$7,219,739
2003	123,348,200	39,251,864	0.0397	1,559,288	
	246,696,400	78,503,728	0.0128	1,002,399	
	345,374,960	109,905,713	0.0004	40,732	
			TOTAL	$2,602,420	$3,574,665
2004	30,837,050	8,592,436	0.0054	45,976	
	61,674,100[‡]	61,674,100	0.0003	18,808	
			TOTAL	$64,784	$67,930

[*] Refers to the difference in the model objective function between the Full Payback and Zero Payback scenarios.

[†] Refers to assumed end-of-cycle Mexican payback over and above the historic U.S. ownership in Falcon and Amistad Reservoirs. Note that reservoir demands for 1999 and 2004 do not reflect depreciation for annual evaporation.

[‡] The assumption of payback consumption only in cases of shadow prices > 0 implies an unused balance in 2004 of 142,591,753 cubic meters (accounting for evaporation).

diverse cropping area react to water shortages by considering the trade-offs involved in crop water consumption, expected net returns, and historical risk.

Varying the available water supply also results in plausible shifts in crops and irrigation levels; for example, having the full 678.4 million cubic meters of payback in 1998, or 313.3 million cubic meters of more water at the farm gate, resulted in 18% of the acreage produced with a third or less of the normal irrigation level (full payback scenario) versus 65% of the acreage producing with this level of deficit irrigation in the no payback scenario. In general, as available farm gate water supplies increased in a given year, deficit irrigated acreage declines, fully irrigated acreage increases, and vegetable acreage increase slightly. A sensitivity analysis (not shown, but available) with the model risk aversion parameter shows that the mix of high value, high risk crop acreage gets more diverse, but shrinks in the aggregate, with increasing risk aversion. This result is expected in a portfolio type model.

Water demand schedules

The results for the strict treaty compliance, end-of-cycle payback are shown in Table 3 and Figure 1. The resulting values (shadow prices) of water are in the range of previous literature (Ward & Michelsen, 2002; Booker *et al.*, 2005), and decline with increasing levels of payback. It should be noted that these

Table 4. Risk efficient LRGV cropping patter representing 1998 baseline.

Crop	Irrigation type	Irrigation level (%)	Soil group	Hectares
Bell pepper	Furrow	100	S6	96
Cabbage	Furrow	100	S6	3,837
Cantaloupe	Drip	66	S6	2,287
Cantaloupe	Furrow	100	S6	3,307
Cotton	Furrow	100	S4	26,021
Cotton	Furrow	100	S5	9,717
Cotton	Furrow	66	S3	5,039
Cotton	Furrow	66	S4	10,990
Cotton	Furrow	33	S1	17,595
Cotton	Furrow	33	S2	1,948
Cotton	Furrow	33	S3	5,928
Cotton	Furrow	0	S4	16,408
Cotton	Furrow	0	S6	16,955
Sorghum	Furrow	66	S5	9,717
Sorghum	Furrow	33	S2	1,948
Sorghum	Furrow	0	S1	17,595
Sorghum	Furrow	0	S3	10,967
Sorghum	Furrow	0	S4	27,113
Sorghum	Furrow	0	S6	16,955
Sugarcane	Furrow	66	S4	63
Sugarcane	Furrow	66	S5	1,943
Sugarcane	Furrow	66	S6	3,391
Sugarcane	Furrow	33	S4	4,720
Orange	Furrow	100	S4	4,047
Grapefruit	Furrow	100	S4	8,094

demand schedules value additional water (i.e., hypothetical payback) above the baseline farm gate supply of water that was available in those reference years. With zero payback, the shadow price of water was in the range of four to five cents per cubic meter. The exception is 2004 which was a very wet year and hence had a very low marginal valuation for additional water. In contrast, 1998–99 and 2003 were very dry years. The flatter slopes of the 1998–99 water demand schedules (Figure 1) reflect the extremely low levels of U.S. ownership and available irrigation water in those years (Table 2). Thus the model allocated 678.4 million cubic meters of payback in 1998 and could have used more than the remaining balance in 1999. In contrast, the 2003 marginal valuation is relatively inelastic, owing to the larger baseline supply of irrigation water in 2003. The changing mix of crops from year to year also accounts for the different shapes of these curves.

Damages valuation

The marginal valuations of water provide a flexible and theoretically-based means of valuing these and other scenarios of Mexican repayment of a given quantity of water in a given year. The summation of incremental farm gate water valuations is one approach to nominal annual damages valuation (Table 3, Column 5). An alternative and more complete approach is to simply take the difference in the objective function value (net returns to water, land, and other fixed assets) between “no payback”

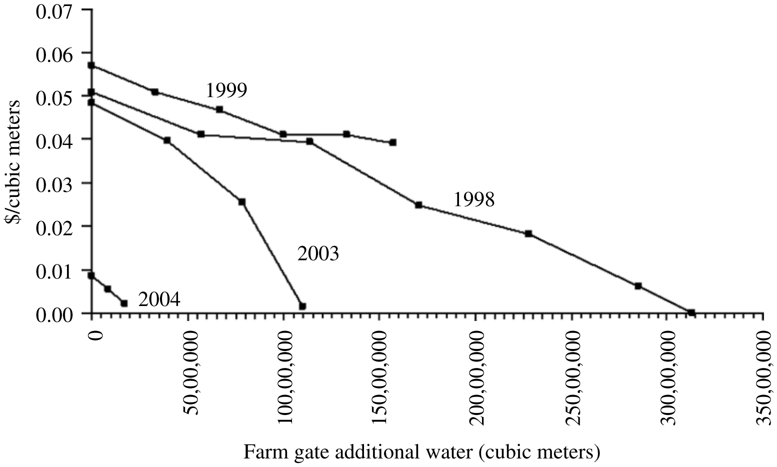

Fig. 1. Marginal valuation (Dollars per cubic meters) at the Farm Gate, above baseline water supplies, assuming Mexican payback with strict treaty compliance, selected years.

and "full payback" in a given year (Table 3, Column 6). In either case, the combined annual results are less than $20 million, considerably lower than previous annual estimates (see Robinson, 2002) of farm gate impacts which were (1) static, (2) based on average values instead of marginal values, (3) did not account for shifts in resource allocation, and (4) in some cases did not account for conveyance losses.

Additional damage considerations

The aforementioned damage estimates (Table 3, Column 5) may understate the actual damages of the Mexico water shortage for several reasons. This paper analyzed the value of Mexican water debt payback in specific years. Since Mexico did not actually make the payback on this schedule, the value of this water has an additional opportunity cost. Using Table 3 (Column 6) as a base, a monetary analogy is similar to Mexico having borrowed $4.4 million in 1998, $3.6 million in 1999, $1.8 million in 2003, and $0.03 million in 2004. Since Mexico paid off the water debt in 2004, the repayment of principle could be calculated as the difference between the valuations in this study and the valuation of the actual repayment (not shown, but likely to be very small). Ignoring this difference, and assuming a fixed 5% annual interest rate, as of December 31, 2006 Mexico would owe $3.6 million, $2.5 million, and $0.4 million in interest for 1998, 1999, and 2003, respectively. In addition to the opportunity cost on the water resource, our approach may miss a range of opportunity costs of fixed assets such as specialized equipment and management expertise. Losses on these resources occur when forced, short-term crop production mix shifts occur from water limitations.

Policy implications

These results highlight the fact that variations in the timing and manner of payback could give substantially different marginal valuations. For example, this paper examined payback under one strict treaty compliance scenario. Different results would have been obtained had we assumed annual

431.7 million cubic feet of inflows (i.e., no annual deficits at all). This study also shows that Mexican payback during the water surplus years of 2002–2004 would not likely have generated large shadow prices. In particular, the actual Mexican payback in 2004 occurred in a very wet year with low diversions (Rubinstein, 2004). The latter is very relevant because a 1969 follow-up agreement to the 1944 treaty called Minute Order 234 allows for a deficit accrued in one five-year cycle to be repaid in the next cycle in (un-defined) cases of "extraordinary drought". U.S. interpretations of Minute Order 234 (Taylor, 2002) imply a payback scenario of the both the 1.26 billion cubic meter debt of the first five-year cycle plus the 589.4 million cubic meter second cycle debt during or at the end of the second five-year cycle (i.e., in late 2002). Such a scenario would result in lower valuations using the approach in this paper.

Caveats and limitations

This analysis models what risk efficient irrigated farmers should have done, and values Mexican repayment accordingly. A major qualifier to these results is the assumption of collective and constant risk preferences and optimization behavior that is assumed to reflect the decision making behavior of the region's resource users. In reality, individuals differ in their risk tolerance to similar risks, as well as to different types of risks. In addition to the assumptions underlying the objective function, the water repayment and valuation scenarios assume that payback water will only be used to the point where the marginal value is zero, with the unused balance being carried over to the next period. In reality, growers may use water inefficiently, e.g., applying it to low value row crops in accordance with agronomic rules of thumb.

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