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Volumetric Pricing of Agricultural Water Supplies: A Case Study

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Models of water consumption by rice producers are conceptualized and then estimated using cross-sectional time series data obtained from 16 Texas canal operators for the years 1977–1982. Two alternative econometric models demonstrate that both volumetric and flat rate water charges are strongly and inversely related to agricultural water consumption. Nonprice conservation incentives accompanying flat rates are hypothesized to explain the negative correlation of flat rate charges and water consumption. Application of these results suggests that water supply organizations in the sample population converting to volumetric pricing will generally reduce water consumption.

The examination of water consumption by various sectors has been a topic of great concern for applied economists. This is especially true in the western states where water scarcity gives greater importance to the efficient allocation of limited supplies. Rapid industrial and population growth has brought this same problem to the Texas Upper Gulf Coast, a very humid region where rice is virtually the only crop irrigated. Historically, surface water supplies have been more than sufficient to meet the needs of all water users in the region. However, a high rate of population growth during the last 20 years (35% during the last decade) has placed increased pressure on the water resources of the area [*Skrabanek and Murdock*, 1981].

This study draws on the unique features of Gulf Coast irrigation water supply in order to provide information for future planning in the region as well as to develop some intuition for understanding agricultural water pricing systems elsewhere. Some interesting aspects of water supply in the Gulf Coast pertain to (1) the predominance of a single irrigated crop which narrows the number of output market determinants of input (water) demands, (2) the well-evolved system of regional surface water supply in which there are many water suppliers of different characteristics, and (3) the fact that a few of these suppliers use volumetric charges for irrigation water rather than a flat rate (per hectare). Historical data on water price and water consumption within these water supply systems facilitates an econometric analysis of the influence of volumetric pricing on irrigated water use.

RELATED STUDIES

Any assessment of optimal water allocations or water conservation for planning purposes requires some notion of existing demands [*Griffin and Stoll*, 1983]. As the nation's largest user of water, agriculture has been the subject of many studies relating to water demand. *Frank and Beattie* [1979] distinguish four approaches for identifying irrigation water demand: market analysis, production function analysis, linear programming, and budgeting. More generally, however, budgeting is a very simplistic form of linear programming, and linear programming is a type of production function analysis in which a fairly restrictive, yet tractable, depiction of technology is assumed. As a result, the linear programming approach permits simulation of irrigation water demand, while more general production function analyses require the analytical derivation of water demand functions from identified crop production functions which incorporate water as an input. Fundamental to each of these methods is the identification of the appropriate technology and the assumption of profit maximization to calculate hypothetical water demand [*Hexem and Heady*, 1978].

Market analysis denotes the common practice of utilizing actual market data in a statistical (econometric) analysis of market demand (and possibly supply). Though this is a practical technique for most commodities, the general absence of true water markets has largely constrained economists to production function analyses (including linear programming) for studying irrigation water demand. Representative production function studies of water demand include *Frank and Beattie* [1979], (analytical), *Christensen et al.*, [1981] (linear programming), and *Heady et al.* [1973] (linear programming). In addition, *Howitt et al.* [1980] have employed a quadratic programming approach in order to improve on the water demand elasticities which result from linear programming analysis. Market analysis studies of water demand are much rarer, for the reason stated above, but include *Gardner and Fullerton* [1968] and *Gardner and Miller* [1983]. These latter investigations pertain to two river basins with unique institutional settings in Utah and Colorado, respectively [*Maass and Anderson*, 1978].

WATER USE IN TEXAS RICE PRODUCTION

Both surface water and groundwater sources are utilized in Texas rice production, but in any particular locality one water source usually dominates. Some rice producers possess surface water rights to withdraw water from rivers, streams, or bayous, and privately owned reservoirs are not uncommon. Most surface water used for irrigation is owned and sold by a number of public or private water suppliers existing in the Texas Upper Gulf Coast region. In 1979 the 16 largest water suppliers in this region withdrew almost 14.8 million ha cm of water for irrigation purposes. This water was used to irrigate 116,000 ha of rice or 83% of all surface water irrigated rice in Texas. A large amount of this acreage is rattoon-cropped; that is, following harvest, more fertilizer and water are applied so that a rattoon rice crop can be grown and harvested.

The various water supply organizations differ widely in terms of size, structure, management objectives, and capital investments. The largest operation served over 16,000 ha of rice in 1982, while the smallest served less than 500 ha. These 16 "canal companies" provided much of the data used in this study. Nine of these organizations are operated by public or

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quasi-public institutions which have broad responsibilities for managing water resources under their control. Six of the nine public water suppliers also use their canals to supply industry with water. The remaining seven companies are privately owned and operated. Some private companies also lease land to rice producers, and one provides water to industrial users.

Agronomic research suggests that rice production is feasible using 75.3 ha cm of water in an average year [*Rice Farming*, 1982]. Interestingly, the principal reason for water use in rice production relates to weed control, not plant water requirements (G. M. McCauley, personal communication, 1983). Data obtained from the 16 water suppliers for 1977–1982 identifies water use as varying from 51.8 to 225.5 ha cm/ha, depending on year and canal company. It is notable that these figures usually include water lost in the transportation process after it enters the companies' canals.

Rice production is very water intensive, with water representing the largest single variable cost for rice farmers in Texas. According to 1980 crop enterprise budgets, the per hectare cost of water was $134.40 [*U.S. Department of Agriculture*, 1980]. The importance of water costs to rice producers leads to the speculation that water use is fairly sensitive to water price. Most of the 16 water suppliers use the traditional method of charging on the basis of land area rather than hectare centimeters. Some of these companies have a single flat rate per hectare of rice, most have an additional flat rate charge for rattoon-cropped acreage, and some have more complex rate schedules calling for flat rate charges for flushes and "excess" releases. A flush is a release of enough water into a field to enhance soil moisture, generally to aid seed germination during the preflood period. A release is a surface water release requested by the producer (usually to maintain a given flood level). During the cropping season, surface water is typically allowed to flow into a field for a few days and then turned off to permit other fields to be serviced.

Two of the 16 water suppliers charge on the basis of volumetric water use. For farmers served by these systems there is a single water rate per volume of water withdrawals. Impeller driven meters are employed by one of these suppliers while the other uses weirs. Both of these canal systems are operated by public institutions.

While economists are prone to argue that water wastage is encouraged by flat rate structures, it should be observed that many water suppliers using such rates are heavily involved in monitoring the water management practices of farmers. Wasteful practices are often discouraged, and water suppliers may penalize producers who do not adhere to accepted conservation practices.

THEORETICAL FRAMEWORK

The descriptive background given above provides perspective for an econometric investigation of factors which may influence the consumption of surface water for rice irrigation. Obviously, the prospect of continually increasing water scarcity in the study region contributes to the potential advantages of volumetric pricing. Even though only a few water suppliers use volumetric rates, and the sample is obviously unbalanced with respect to the occurrence of the two types of rate structures, there is an interesting opportunity to conduct a preliminary analysis of the relative influence of rate structure on water consumption. Accomplishing this objective requires that variables other than water rates be controlled in the analysis. The purpose of this section is to develop a simple model of water consumption which will serve as a basis for analysis. It is important to recognize at the onset that incorporated variables relate to a few supply factors in addition to several demand determinants. That is, there is simultaneity in the determination of water price and water consumption, in which case both supply and demand factors interact to determine "market" equilibria. Therefore the resulting model is not properly a water demand function; it is a water use model.

The consumption of water within a given canal company can be represented by the following equation

$$W = W_1 + W_2 \tag{1}$$

where W is total water consumption, W_1 is water consumed in the delivery process, and W_2 is water consumed by producers.

Delivery Consumption (W_1)

A great deal of water can be consumed in the process of delivering water to the farm. Delivery losses can be categorized into steady state losses and tansient losses [*Trout and Bowers*, 1981]. Steady state losses include evaporation and seepage. Transient losses include breaches, initial wetting up of the canal system, and dead storage remaining after the irrigation season. Vegetation within and along canals also contribute to water loss by transpiration and raised canal levels [*Akram and Kemper*, 1981].

These conveyance losses tend to be determined by physical canal system properties and management practices rather than by economic variables. Important physical properties include system design features, canal width, depth, and length, soil type and compaction, and vegetative growth. Canals in the Texas Gulf Coast are generally earthen, so concrete lining is rarely a factor. Canal management practices can influence transient losses and vegetation. Management practices also include monitoring the canal system for breaks within the system and excess water usage by producers (which pertains to farm consumption, W_2).

Data limitations prohibit a detailed consideration of many important canal properties and management practices. The total kilometers of main canals was used as the primary variable to explain delivery losses. Two water suppliers measure total agricultural water use at the farm gate, thereby excluding delivery losses. Main canal length was therefore set to zero for each of these two systems. Information regarding various management practices could not be readily assembled. A dummy variable for institution type (public versus private) was employed to investigate possible differences in overall management practices. A second dummy variable was included to distinguish between those water suppliers serving industry and rice producers within the same canal system. This latter variable was incorporated because discussions with canal company managers suggested that water deliveries to industry might influence conveyance losses attributed to agriculture, although the direction of this effect seems ambiguous.

Therefore we have the following model for delivery water consumption:

$$W_1 = W_1(C, I, R) \tag{2}$$

where C is kilometers of main canals, I is the institution dummy (0 for private and 1 for public), and R is the industrial dummy (0 if any water is supplied to industry and 1 otherwise). Initial hypotheses are that first derivatives of W_1 with respect to C or I will be positive. Other things being equal, increases in C should increase conveyance losses, and it is presumed that the profit motivations of private water suppliers might enhance water use efficiency in comparison to their public sector counterparts. No hypothesis is forwarded regarding the effect that the industrial dummy R might have on system water use.

Farm Consumption (W_2)

By assuming that the objective of rice farmers is to maximize profits we can write the individual farm's objective function as follows:

$$\max_{\mathbf{x}} \pi = p \cdot f(\mathbf{x}, \mathbf{z}) - \mathbf{r} \cdot \mathbf{x} - \mathbf{s} \cdot \mathbf{z} \qquad (3)$$

where p is the expected price of rice, $f(\ )$ is the rice production function, $\mathbf{x}$ is the $n \times 1$ vector of variable inputs, $\mathbf{z}$ is the $m \times 1$ vector of fixed or environmental (e.g., weather) inputs, and $\mathbf{r}$ and $\mathbf{s}$ are appropriate input price vectors. The input vector denoted by $\mathbf{x}$ is controllable, while the elements of $\mathbf{z}$ are exogeneous to the farm or have been fixed by previous decisions.

The solution to this profit maximization problem will identify the farm's factor demand functions:

$$\mathbf{x}_i = \mathbf{x}_i(p, \mathbf{r}, \mathbf{z}) \qquad i = 1, 2, \cdots, n \qquad (4)$$

In general, the price of rice, the unit costs of all controllable inputs, and the given quantities of all fixed inputs are relevant to input demands. Differing degrees of substitutability or complementarity between inputs will imply greater or lesser cross relationships between some inputs than others. Because surface water demand is our primary consideration, we have

$$\omega_2 = \omega_2(p, \mathbf{r}, \mathbf{z}) \qquad (5)$$

where ω_2 is surface water demand by an individual producer. By assuming that these farm-specific input demand functions can be aggregated across all farms served by a given water supplier, the farm demand for water can be written as

$$W_2 = W_2(p, \mathbf{r}, \mathbf{z}) \qquad (6)$$

With respect to surface water demand the most pertinent elements of $\mathbf{r}$ include the prices of surface water, groundwater, herbicides, and labor. For individual farms, $\mathbf{z}$ would include land area, slope, soil type, existing wells and pumps, existing irrigation equipment, rainfall, temperature, and other weather variables. Given the level of aggregation inherent in (6) and data availability, the following model for on-farm water demand is hypothesized for rice production:

$$W_2 = W_2(P_r, PW_v, PW_f, P_e, P_h, P_l, A1, A2, PE1, PE2) \qquad (7)$$

where P_r is the average price of rice during the 3 months before planting (dollars per metric ton), PW_v is volumetric water price expressed in dollars per hectare centimeters, PW_f is flat water price expressed in dollars per hectare (first crop only), P_e is an energy price index, P_h is a herbicide price index, P_l is the price of labor (dollars per hour), $A1$ is the land area of first crop rice receiving irrigation (thousands of hectares), $A2$ is the rattoon crop land area (thousands of hectares), $PE1$ is first crop pan evaporation in centimeters, and $PE2$ is rattoon crop pan evaporation in centimeters.

The two different water prices, PW_v and PW_f, are necessary to capture the differential impacts of price within each pricing scheme. By definition, $PW_v > 0$ whenever $PW_f = 0$ and vice versa. It is hypothesized that PW_f is a statistically insignificant variable in explaining water use because flat rates do not provide an incentive for water conservation. The energy price index serves as a proxy for short-run groundwater price. Expected rice price is expected to positively affect water consumption. Prices for herbicides and labor are included because they are the major variable inputs which are substitutes for water in the rice production process.

First and rattoon crop land areas are expected to contribute positively to total water use as are the pan evaporation variables. Rainfall is excluded from the above model because its affect is thought to be ambiguous. Whereas small to moderate rainfall events presumably reduce farm water demand, larger rainfalls often cause levees to wash out and thereby contribute to water demand. Temperature variables were excluded in favor of pan evaporation variables which are thought to more adequately describe water losses on flooded fields.

DATA

Combining (1), (2), and (7) results in the following model:

$$W = W_1(C, I, R) \\ + W_2(P_r, PW_v, PW_f, P_e, P_h, P_l, A1, A2, PE1, PE2) \qquad (8)$$

Units for all variables have been given with the exception of W which expresses thousands of hectare centimeters. Much of the data to econometrically estimate this relationship was obtained by personal interviews with the 16 water suppliers. From these interviews, 6 years of data (1977–1982) were obtained for the following variables: W, C, I, R, PW_v, PW_f, $A1$, and $A2$. Some of this data was reported to the Texas Department of Water Resources and was corroborated through this source.

The 6 years of data provided a pooled set of 36 observations. However, one of the private companies leases land to farmers and provides free water as part of the lease agreement. Another company provided large amounts of water for non-price purposes in 1977 only. These seven observations were removed from the sample leaving a sample size of 39 observations.

Rice price data and the energy price index were obtained from the *U.S. Department of Agriculture* [1982]. Herbicide prices were provided by a local industry source (R. Schmidt, personal communication, 1983). Labor prices were obtained from the Texas Crop and Livestock Reporting Service (M. D. Humphrey, personal communication, 1983). Class A pan evaporation data were provided by the Texas Department of Water Resources for five weather stations within the Texas Rice Belt (R. C. Williams, personal communication, 1982). A single weather station was chosen to represent each water supplier, and daily pan evaporation data was summed across May, June, and July for $PE1$ and across August and September for $PE2$.

MODEL FORMULATION

Two alternative functional forms for (8) were examined in order to gauge sensitivity to functional form. Both of these specifications are linear in parameters and include nonlinear terms. Model A treats system water use, W, as the dependent variable, and model B employs system water use per hectare of first crop rice, $W/A1$, as the dependent variable.

In each of these models the purely linear form of a given explanatory variable may not appear, because this term was thought to interact with another variable rather than "act" on its own. For example, increases in $PE1$ should increase W in model A, but the increase should be proportional to $A1$. Therefore $PE1$ was not linearly incorporated into the model. Likewise, the presence of industrial water deliveries was

TABLE 1. Correlation Matrix for Preliminary Model A

	W	C	I	CI	CR	P_r	P_h	P_e	P_l	PW_{af}	PW_a	$A1PE1$	$A1^2$	$A2PE2$	$A2^2$
W	1.00														
C	0.74	1.00													
I	0.15	0.09	1.00												
CI	0.59	0.72	0.64	1.00											
CR	0.52	0.70	−0.11	0.34	1.00										
P_r	0.03	−0.02	0.01	−0.01	−0.02	1.00									
P_h	0.00	−0.02	0.01	−0.01	−0.02	0.53	1.00								
P_e	−0.01	−0.02	0.01	−0.01	−0.01	0.57	0.80	1.00							
P_l	−0.00	−0.02	0.01	−0.01	−0.01	0.64	0.78	0.99	1.00						
PW_{af}	−0.17	−0.04	0.30	0.13	0.09	0.03	0.04	0.05	0.05	1.00					
PW_a	−0.11	0.05	−0.63	−0.29	0.07	0.11	0.18	0.19	0.19	−0.70	1.00				
$A1PE1$	0.91	0.78	0.10	0.55	0.49	0.01	−0.07	−0.06	−0.06	−0.06	−0.14	1.00			
$A1^2$	0.92	0.64	0.15	0.50	0.34	0.02	−0.06	−0.05	−0.05	−0.10	−0.20	0.96	1.00		
$A2PE2$	0.66	0.64	−0.01	0.35	0.79	0.09	0.05	0.08	0.08	−0.03	0.05	0.53	0.44	1.00	
$A2^2$	0.65	0.58	−0.00	0.35	0.72	0.08	0.03	0.04	0.05	−0.09	0.03	0.48	0.44	0.94	1.00

thought to decrease conveyance losses attributed to agriculture, but the amount of decrease should be related to the canal variable C. Quadratic terms were included for the $A1$ and $A2$ variables so that the technical efficiency of alternative system sizes could be examined.

The preliminary functional forms chosen to estimate models A and B are given as follows:

Model A

$$W = \beta_0 + \beta_1 C + \beta_2 I + \beta_3 CI + \beta_4 CR + \beta_5 P_r + \beta_6 P_h + \beta_7 P_e + \beta_8 P_l + \beta_9 PW_v + \beta_{10} PW_f + \beta_{11} A1PE1 + \beta_{12} A1^2 + \beta_{13} A2PE2 + \beta_{14} A2^2 \qquad (9)$$

Model B

$$W/A = \gamma_0 + \gamma_1 C/A1 + \gamma_2 I + \gamma_3 CI/A1 + \gamma_4 CR/A1 + \gamma_5 P_r + \gamma_6 P_h + \gamma_7 P_e + \gamma_8 P_l + \gamma_9 PW_v + \gamma_{10} PW_f + \gamma_{11} PE1 + \gamma_{12} A1 + \gamma_{13} A1^2 + \gamma_{14} A2PE2/A1 + \gamma_{15} A2^2/A1 \qquad (10)$$

Because of high simple correlations between some of the explanatory variables it was necessary to omit some of the variables from the models. Correlation matrices for preliminary models A and B are presented in Tables 1 and 2, respectively. While high correlations do not necessarily harm the predictive abilities of a model, the variances of parameter estimates are increased [*Judge et al.*, 1980, p. 453], which is an important concern for the present study. Labor price was dropped from both models because of extremely high correlation with energy price. As a result, estimators for P_e will represent the conjunctive influence of energy and labor prices. Fortunately, both labor and energy represent surface water substitutes and the expected direction of their price effects on water use are the same. Similarly, both quadratic terms in model A ($A1^2$ and $A2^2$) were omitted because of collinearity with $A1PE1$ and $A2PE2$, respectively. In model B, $A1^2$ was highly correlated with $A1$ and was therefore omitted from the final models which are as follows:

Model A

$$W = \beta_0 + \beta_1 + \beta_2 I + \beta_3 CI + \beta_4 CR + \beta_5 P_r + \beta_6 P_h + \beta_7 P_e + \beta_8 PW_v + \beta_9 PW_f + \beta_{10} A1PE1 + \beta_{11} A2PE2 \qquad (11)$$

Model B

$$W/A = \gamma_0 + \gamma_1 C/A1 + \gamma_2 + \gamma_3 CI/A1 + \gamma_4 CR/A1 + \gamma_5 P_r + \gamma_6 P_h + \gamma_7 P_e + \gamma_8 PW_v + \gamma_9 PW_f + \gamma_{10} PE1 + \gamma_{11} A1 + \gamma_{12} A2PE2/A1 + \gamma_{13} A2^2/A1 \qquad (12)$$

So that results can be more easily interpreted, expected

TABLE 2. Correlation Matrix for Preliminary Model B

	$W/A1$	$C/A1$	I	$CI/A1$	$CR/A1$	P_r	P_h	P_e	P_l	PW_{af}	PW_a	$PE1$	$A1$	$A1^2$	$A2PE2/A1$	$A2^2/A1$
$W/A1$	1.00															
$C/A1$	0.20	1.00														
I	0.01	−0.27	1.00													
$CI/A1$	0.17	0.45	0.68	1.00												
$CR/A1$	0.40	0.56	−0.27	0.20	1.00											
P_r	−0.00	−0.09	0.01	−0.05	−0.05	1.00										
P_h	0.12	0.01	0.01	0.03	−0.01	0.53	1.00									
P_e	0.05	−0.01	0.01	0.01	−0.02	0.57	0.80	1.00								
P_l	0.04	−0.01	0.01	0.01	−0.02	0.64	0.78	0.99	1.00							
PW_{af}	−0.37	−0.17	0.30	0.14	0.03	0.03	0.04	0.05	0.05	1.00						
PW_a	0.18	0.56	−0.63	−0.17	0.37	0.11	0.18	0.19	0.19	−0.70	1.00					
$PE1$	0.11	0.09	−0.01	−0.03	0.25	0.08	−0.14	−0.10	−0.11	−0.02	0.15	1.00				
$A1$	0.42	0.07	0.09	0.25	0.08	0.01	−0.06	−0.04	−0.04	−0.08	−0.12	−0.09	1.00			
$A1^2$	0.42	−0.10	0.15	0.14	−0.06	0.02	−0.06	−0.05	−0.05	−0.10	−0.20	−0.05	0.95	1.00		
$A2PE2/A1$	0.36	0.30	−0.09	0.05	0.68	0.13	0.14	0.15	0.16	−0.01	0.31	0.39	−0.03	−0.08	1.00	
$A2^2/A1$	0.55	0.17	−0.09	0.06	0.44	0.08	0.03	0.05	0.06	−0.09	0.12	−0.02	0.44	0.34	0.63	1.00

TABLE 3. Hypothesized Signs of First Derivatives of W

Explanatory Variable	Hypothesized Derivative	Explanatory Variable	Hypothesized Derivative
C	+	PW_v	−
I	+	$A1$	+
P_r	+	$PE1$	+
P_h	+	$A2$	+
P_e	+	$PE2$	+

signs of certain derivatives of these models are summarized in Table 3. It should be noted that these derivatives may not correspond to specific β or γ coefficients because some independent variables occur more than once in these two models. The second derivative of W with respect to $A2$ is expected to be positive (in model B only) over the range of most of the sample.

ORDINARY LEAST SQUARES RESULTS

Ordinary least squares parameter estimates and t statistics for both models are presented in Table 4. Intercepts have statistically insignificant coefficients in both models at the 5% level, as do P_r and P_e. Regarding rice price, while it is true that planting decisions are probably related to crop price(s), cultural practices involving water are not sensitive to rice price. The insignificance of energy price suggests that surface water demand does not respond to the costs of substitute groundwater (perhaps due to lags or short-run rigidities in groundwater development) or that energy price affects water supply in a manner to offset its affect on water demand.

Except for the following factors, all remaining variables are associated with parameter estimates which are significantly different from zero (at the 5% level). The industrial dummy R enters insignificantly in model A, and the institution dummy I and rattoon crop pan evaporation $PE2$ have insignificant parameters in model B.

First derivatives of W were evaluated for both models to assess the reasonableness of the hypotheses summarized in Table 3. For model B this necessitates multiplying both sides of the equation by $A1$ before the derivatives are calculated. All hypotheses are not refuted by model B where statistically significant parameters are involved, that is, for derivatives of W with respect to C, P_h, PW_v, and $PE1$. In addition, although no hypothesis was forwarded regarding the probable influence of the industrial variable R, model B results suggest that the presence of industrial water users has a negative impact on aggregate water consumption by agricultural users.

Interpreting model A results, derivatives involving statistically significant parameters fully support hypothesized signs for P_h, PW_v, $A1$, $PE1$, $A2$, and $PE2$. Furthermore, based on computed derivatives, increases in canal length increase system water consumption for public suppliers only, and public water suppliers use more water than private water suppliers if and only if main canal length is greater than 84.5 km (for the sample, mean canal length is 91.4 kms). Therefore except for the fact that increases in canal length decrease water use for private organizations (according to the sample and model specification), all other hypotheses cannot be rejected.

It is of special interest to economists that both water price coefficients are negative and significantly different from zero in both models. In fact, these two variables are among the most statistically significant variables in both models. While the significance of volumetric water charges is quite understandable, the significance of flat rate charges requires additional discussion. While the high negative correlation between PW_v and PW_f could be responsible for this result, subsequent (and unreported) analysis using only the flat rate water suppliers again yields highly significant negative parameter estimates for the PW_f term in both models.

We suggest that higher flat rate water charges are accompanied by one or more of the following circumstances which negatively affect(s) water consumption: more monitoring of farm water use by water suppliers, better management and control of canal losses, more producer awareness, concern, and attention for on-farm water conservation, or some other nonprice water conservation incentives. Clearly, flat rate price structures do not, in and of themselves, provide any motivation for water conservation. Therefore it must be true that higher flat rate water charges are paralleled by the more inten-

TABLE 4. Least Squares Estimates for Models A and B

Model A			Model B		
Variable	Parameter	t Statistic	Variable	Parameter	t Statistic
Intercept	−12.42	−0.04	Intercept	−39.03	−0.87
C	−5.777	−4.40	$C/A1$	3.115	2.61
I	−513.6	−4.08	I	27.43	1.24
CI	9.785	6.04	$CI/A1$	−2.550	−1.76
CR	1.506	1.18	$CR/A1$	5.226	4.84
P_r	−1.011	−1.33	P_r	−0.064	−0.91
P_h	36.43	2.55	P_h	4.287	3.23
P_e	58.96	0.58	P_e	7.350	0.78
PW_v	−875.5	−7.09	PW_v	−96.20	−6.95
PW_f	−7.729	−4.71	PW_f	−0.923	−4.34
$A1PE1$	2.039	14.33	$PE1$	0.850	2.11
			$A1$	0.790	1.33
$A2PE2$	1.863	6.49	$A2PE2/A1$	−0.458	−1.26
			$A2^2/A1$	3.127	2.91
	$n = 89$			$n = 89$	
	$R^2 = 0.95$			$R^2 = 0.69$	
	$R^{-2} = 0.94$			$R^{-2} = 0.64$	
	F statistic = 126.5			F statistic = 13.0	
	rmse = 255			rmse* = 216	

TABLE 5. Estimated Effects of Instituting Volumetric Pricing

Canal System	Change in Water Use Per Hectare ha cm	Change in Sales Revenue per Hectare, %
A	−82.2	+3.7
B	−61.0	+4.4
C	−24.7	−0.2
D	−18.4	+0.9
E	−26.2	+2.2
F	−39.3	+3.6
G	−40.0	+4.0
H	−33.4	+5.5
I	−27.3	+0.9
J	+10.3	+4.3
K	−59.5	+22.3
L	−33.7	−0.6

sive employment of noneconomic convervation incentives which affect water supply and/or demand.

MODEL COMPARISON

On the basis of F statistics, both models are judged to be highly significant. In spite of satisfactory fits of both models to the sample, residual plots indicate that models A's explanatory powers are quite limited when applied to small water suppliers. Model B escapes this problem because the dependent variable has been normalized to prohibit greater weight being given implicitly to large water suppliers in the least squares procedure.

Because models A and B have different dependent variables, it is not possible to employ R^2 or $\bar{R}^2$ to compare the explanatory abilities of the two estimated models. Root mean squared error (rmse) can be properly used to contrast two such models, providing the appropriate adjustments are made. Table 4 reports rmse for model A. Adjusted root mean square error, rmse*, is identified for model B in order to facilitate a direct comparison of the two models:

$$\text{rmse}^* = [(\mathbf{A1}^*\mathbf{e}_b)'(\mathbf{A1}^*\mathbf{e}_b)/(t-k)]^{1/2} \qquad (13)$$

In equation (13) **A1** is the $t \times 1$ vector of observed first crop land area, the asterisk denotes a term-by-term vector product, $\mathbf{e}_b$ is the $t \times 1$ vector of residuals from model B, t is the number of observations, and k is the number of explanatory variables for model B. On the basis of this information, model B is clearly the functional form with superior explanatory ability.

APPLICATION

The water use models developed here have several potential applications other than the examination of explanatory variables conducted above. One such application is a method for checking for measurement error in reported water use data. For example, residual plots for models A and B clearly identify one water supplier as an outlier during the study period. Model B overestimates annual per hectare water use by 30–60% for this canal organization in all 6 years. The magnitude of these residuals justifies the omission of this supplier from the sample so that the models can be reestimated for the purpose of conducting the forthcoming application. While it is necessary to include these observations in order for standard errors and t statistics to be valid, the importance of having reliable parameter estimates requires that this data be omitted [*Maddala*, 1977, p. 89]. The reestimated model is as follows:

$$W/A1 = -2.834 + 2.462C/A1 + 25.14I - 1.887CI/A1$$
$$+ 4.158CR/A1 - 0.064P_r + 4.050P_h + 6.757P_e$$
$$- 98.30PW_v - 0.870PW_f + 2.853A2^2/A1 \qquad (14)$$

Adjusted root mean squared error is 215 for the revised model B.

Either of the above models can be used to evaluate the effect of employing volumetric water rates in a previously flat rate system. The revised model B can be used to estimate changes in per hectare water use and water revenues consequent to a switch from flat to volumetric rate structures. The following two total derivatives approximately apply for changes in per hectare water use, $\Delta(W/A1)$, and per hectare water sales, $\Delta(S/A1)$, due to a change in water rates:

$$\Delta(W/A1) \simeq \frac{\partial(W/A1)}{\partial PW_v}\Delta PW_v + \frac{\partial(W/A1)}{\partial PW_f}\Delta PW_f \qquad (15)$$

$$\Delta(S/A1) \simeq \Delta PW_f + [(W/A1) + \Delta(W/A1)]\Delta PW_v \qquad (16)$$

Both of these relationships presume that nonprice conservation incentives which accompany flat rate systems will be discontinued upon adoption of volumetric rates.

These expressions can be evaluated for each water supplier if revised model B parameters are used for the partial derivatives in (15), the negative of mean per hectare water prices are used for ΔPW_f, each system's mean per hectare water use is used for $W/A1$, and some choice is made for ΔPW_v. The choice of a per hectare centimeter water price is arbitrary at this point, since it is hypothetical, but it seems reasonable to choose a price level within the range of observed volumetric water prices. Sensitivity analysis could be employed to demonstrate the responsiveness of per hectare water use and per hectare water revenues to alternative volumetric water charges, but the investigation of a single water price is sufficiently demonstrative for present purposes. By assuming that a water price of \$1.15/ha cm is established, (15) and (16) are successively evaluated for each nonmetered surface water supplier to obtain the results contained in Table 5. Nearly all canal organizations experience decreases in average water use and increases in average water revenues as a result of this prospective change. For these 12 suppliers average annual water consumption during the study period falls from 15,059,000 to 10,655,000 ha cm. This represents an average decrease of 44.0 ha cm/ha. Total average annual revenue is increased by 4.3 million dollars.

While these results certainly are suggestive of probable impacts of volumetric pricing in the region, several important limitations of the procedure should be noted. Foremost among these is the small subsample of metered canals. This casts some doubt on the estimated slope parameter for PW_v. Second, the total derivatives represented by (15) and (16) are approximately valid for small price changes only. If, however, $W/A1$ is actually linear in PW_f and PW_v (as assumed in model B), then (15) and (16) are valid for large price changes as well. Third, water revenues generated as a result of rattoon cropping have been ignored. Also, certain cost considerations had to be excluded; the costs of meter installation and maintenance and the cost savings of significantly reduced water pumping have not been considered. The relative magnitudes of these contrasting influences on net revenue is uncertain.

CONCLUSIONS

Results from this econometric study involving price-quantity information from several different water supply operations are very supportive of initial hypotheses. The two investigated functional forms provide similar results regarding the influence of various physical, institutional, and economic factors on water use for Texas rice production. Among these findings is the fact that volumetric water rates have a very significant effect on water use. More notable is high statistical significance of the effect of flat (per hectare) water rates on water consumption. Volumetric and flat rates are inversely related to system water consumption. These relationships are not necessarily due to impacts upon water demand, because demand and supply characteristics are subsumed in both models.

Even though both volumetric and flat water rates exert a negative influence on water use, a hypothetical change to volumetric pricing would lower water consumption for 11 out of the 12 presently unmetered water suppliers. Aggregated results for these 12 suppliers show that average annual water consumption during the 1977–1982 study period would have decreased substantially. Overall, gross revenues are estimated to increase slightly because of this change, but the true impact on net revenues is ambiguous because of unavoidable omissions in the analysis.

These findings illustrate the potential of volumetric pricing as a simple device for conserving water supplies. The dramatic influence of water price on water consumption makes price a very practical managment tool. Regulatory approaches (such as mandatory restrictions or enforced management practices) to bring about reduced water consumption are unlikely to be potential Pareto improvements when compared to pricing. The results of this investigation demonstrate that large water savings can be obtained through pricing. Moreover, changes in gross revenues and costs to rice producers can be small depending on adopted water rates. It is quite possible that energy savings could be sufficient to pay for meter installation with little change in net revenues for the canal operator and costs for the producer. A fuller welfare analysis incorporating separate water supply and demand relationships is needed to identify more precisely the impacts of prospective rate changes on canal organizations and the producers they serve.

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