Agricultural Water Conservation and Water Use Efficiency:

Findings and Conclusions of the Challenge Grant Program: Collaborative Field Demonstrations of the Efficacy and Practicality of Financial Incentives for Agricultural Water Conservation

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Agricultural Water Conservation and Water Use Efficiency

Executive Summary

How Farmers Respond to Changes in Water Price

The dimensions of response to changes in financial incentives for water use include fallowing, adoption of conservation technology, crop shifting, and ground water pumping. A farmer's optimal combination of responses depends on factors such as the magnitude and expected duration of scarcity, environmental conditions, human capital characteristics such as experience and educational attainment, the type of crop grown, and the availability and quality of ground water.

A review of California growers' response to the 1987–1992 drought suggests that in that episode farmers dealt with scarcity by reducing demand (i.e., by fallowing and adopting conservation technology—drip and microsprinkler, especially) and by procuring supplemental water, primarily from ground water pumping (Zilberman et al., 1995). Water trading also increased in volume, and in importance (Howitt, 1994; Olmstead et al., 1997). For instance, the State's Drought Water Bank transferred water from north to south, to both farms on the western side of the San Joaquin Valley and to cities in Southern California.

More growers did not adopt technology during the drought because they were unsure of how long it would last (implying that they had some uncertainty about the stream of economic returns from the investment), and because many farmers were already operating quite efficiently.

More evidence on how farmers respond to changes in the price and availability of water is provided by the Challenge Grant project's activities in the Arvin-Edison Water Storage District, where the District reduced the standby charge for water (e.g., the per-acre assessment) and increased the volumetric charge in an effort to improve water use efficiency. The District also eliminated the acreage entitlement within the surface water service area. Members of the Challenge Grant team tracked cropping patterns, technology adoption and water use before and after the price change. Review of the Arvin-Edison data on farmer response to changes in water price shows that, as expected, farmers shifted towards crops earning more profit per acre foot of water used. However, the ultimate effect on water use was small since these crops also used more water per acre than others, implying that the elasticity of demand for irrigation water is small.

Adoption of Conservation Technology

The Challenge Grant team conducted a detailed study of irrigation technology adoption in Arvin-Edison to better understand the factors that prompt farmers to use precision technologies.

Using advanced statistical techniques, the team demonstrated that while water price does have a significant impact on technology adoption, interestingly, other factors appear to influence technology choice more. For instance, landscape characteristics (e.g., slope, soil permeability) and microclimate (e.g., number of frost-free days) appear to have far more influence. Further, adoption of conservation technology is crop-specific as precision irrigation has different types of benefits for different crops. In some instances, precision application of fertilizers and pesticides increases yields and lowers per-acre costs, while for other crops these benefits may be modest or nonexistent. Thus, one should not expect farmers to respond uniformly to changes in water price. Rather, responses will vary by location, by the type of crop produced, and by the characteristics of the farmer.

Another finding of the Challenge Grant research in Arvin-Edison that challenges conventional wisdom on technology adoption is the importance of the age and family structure of the farmer in determining the response to water price changes. The team conducted a longitudinal analysis of irrigation technology choice in the District by asking various farmers when they changed their irrigation hardware, and why. The 76–77 and 87–92 droughts were important factors prompting adoption. Changes in cropping patterns were also important. The factor most likely to prompt a change in irrigation technology, however, was when the farm management was passed on from parent to child. This finding underscores the importance of the human element in technology adoption, and suggests that responses to changes in price or scarcity may play out over a long period of time.

Yield Effects of Conservation Technology

For years, water policy analysts and hydrologists have questioned the benefits of agricultural water conservation in a conjunctive use system. They argue that technology adoption or other improvements that reduce deep percolation do not produce any additional water for the system since ground water is just future supply. The only time conservation matters, it is argued, is when ground water is unusable or when the farm is in a coastal area. For example, Dr. Robert Hagen of UC Davis used to advocate the “98 Percent Rule” postulating that California agriculture was 98 percent efficient in its water use.

This claim is coming under increasing scrutiny from academics, even though it is still widely accepted in the policy community. The Challenge Grant team has investigated perhaps the most important aspect of the debate: whether adoption of precision technology like drip and microsprinkler irrigation has yield benefits. That is, if it is true that precision technology increases the amount of farm output produced with a given amount of water application, then water can be reallocated from agriculture without appreciable impacts to farmers or rural communities (for example, there are no employment effects). The only cost of the policy would be the cost of the technology itself, and any changes in marginal operating costs, which should be negligible or even negative. This line of research is significant, even if the yield benefits are small since a 5 or 10% reallocation from agriculture to the environment would solve many instream quality problems.

Working with field level data, the Challenge Grant team is statistically estimating the relationship between technology choice and yield per acre. Preliminary estimates indicate that, controlling for environmental conditions, processing tomato yields are 10-15% higher when drip irrigation is used than when furrow or sprinkler is used.

This finding is consistent with the history of the marketing of drip irrigation in California. Drip irrigation systems were originally marketed before the 76–77 drought in areas like the east side that had no scarcity problem. The original marketing pitch had nothing to do with water conservation and was based instead on yield effects. This aspect of drip irrigation (and other precision techniques) has been somewhat lost as dealers emphasized water use efficiency. However, farmers interviewed as part of the study, as well as agronomists and soil scientists at UC Davis, believe that the yield effect is real. Large-scale field experiments are underway now to document the yield effect systematically.

Reliability and Conservation

Increasingly, farmers and water policy analysts understand that the reliability of water supply available to farmers is at least as important as its average price. Working again with data from Arvin-Edison, Challenge Grant researchers have shown how water supply reliability price affects the choice of irrigation technology.

Conceptually, the team has shown that the influence of reliability on water use efficiency depends on how cultivated acreage responds to temporary fluctuations in the price of water. If acreage is highly responsive to the current price of water, then increasing the degree of price risk strengthens the incentive to adopt conservation technology. However, if acreage is unresponsive to the price of water, then an increase in volatility has the opposite effect.

This hypothesis was tested and verified by examining field-level data on irrigation technology choice collected in Arvin-Edison. The Challenge Grant team measured how reliability interacts with the responsiveness of acreage to the current price of water. Responsiveness was measured by the type of crop grown: perennials or annuals. Variability of the price of water was measured by the service area in which the field is located. As predicted by the conceptual model, increasing the variability of water deliveries increases the rate of precision technology adoption for annuals and decreases it for perennials.

These results again point out that farmers have individualized responses to changes in water supply conditions, including price. The results also suggest that in some areas at least, water price stabilization through financial means or through infrastructure is complementary to water use efficiency.

Water Pricing and Allocation at the Retail Level

Retail pricing by water agencies is usually based on average cost and is likely to lead to economic inefficiency. The costs associated with this inefficiency are likely to increase as water availability declines. Block rate pricing and water trading have been important components of proposals for water pricing reform. The Challenge Grant team compared various policy options available to retail water agencies to deal with problems of scarcity and allocation. These policies are (i) average cost pricing with the administration of quota allocation; (ii) block rate pricing; and (iii) a transferable water rights regime within the retail utility (i.e., an internal water market among retail customers).

The Challenge Grant researchers obtained some important theoretical results. An internal water market will result in an efficient allocation of water among retail customers if the following conditions exist: information is perfect, trading is costless and the management allocates "initial endowments" of water according to the historical rights of the farmers. When trading is not costless and information is imperfect, an alternative policy option of "passive trading" with internal price quotation by the management achieves the same level of efficiency. It is also shown that under realistic assumptions, tiered pricing results in a second-best allocation.

The absence of well-defined property rights to water and high transaction costs remain barriers to the development and efficacy of internal water markets. According to Coase (1992) "if the costs of making an exchange are greater than the gains which that exchange would bring, that exchange would not take place, and the greater production that would flow from specialization would not be realized." The "passive trading" policy enables a trade of water use rights with low transaction costs. Passive trading enables an efficient allocation with minimal losses by farmers and therefore minimal political resistance by them. This is made possible by increasing the welfare resulting from the use of water and establishing quasi rights related to historical use. The greater the "pie" the easier it is to redistribute it between the farmers. In the long run the increased "pie" enables the diversion to higher value products and water saving technologies.

Water institutions and their laws in many states do not allow trading in water use rights. Tiered prices have recently been suggested as an efficient pricing method. It is shown in this section that under reasonable assumptions, tiered prices lead to a "second best" solution. Passive trading results in a Pareto efficient allocation and does not require new water legislation. Such a policy could also be useful in other price pooling systems, such as production and marketing boards.

Water Allocation at the Regional Level

Water is not currently allocated by price in most areas of California. As a result, there are wide disparities in water price and availability in California agriculture. Markets are emerging in California and elsewhere throughout the west in response to these factors, and also in response to increasing scarcity.

Challenge Grant researchers have argued that increased flexibility in water trading would help farmers cope with supply cutbacks needed to improve instream quality. This result follows from the observation that markets allocate the burden of a supply reduction to the party most able to bear it. In the case of water, a water market would allocate the cut to the grower making the least productive use of his water.

Economic research of California agriculture suggests that the benefits of a market are large. For example, Sunding et al. (1995) and others have shown that the most productive 25% of the water used in California agriculture accounts for 50% of the sector's revenue. Conversely, the least productive 20% of the water used in California agriculture produces less than 5% of its revenue.

The WaterLink System

Previous analyses in this report point out the promise of water trading within agriculture, even within single water districts. These analyses also point out that the effectiveness of water trading is limited by problems of transaction costs and limited information. In a practical effort to demonstrate that these problems can be overcome, the Challenge Grant team initiated a major effort to establish and assess the first electronic water market. The *WaterLink* system, built by the Challenge Grant team in Westlands Water District in 1996, has begun to reduce market transaction costs and improve information flows. Recent private sector efforts have begun to extend this technology to other water districts and other settings in the western United States.

The major features of the *WaterLink* system are the following:

- Water Trading

  Growers have the opportunity to post bids and asks in a central location. These are then made available to other growers, either to find a trading partner or simply to keep tabs on water trading activity. Information included in a posting: the amount of water, delivery time frame, the type of water to be traded, a bid/ask price (optional), and a contact person. Growers can then negotiate electronically over the *WaterLink* system, or can talk off-line by phone or in person.

- Water Market Summary

  WaterLink makes available the following market summary information: volume traded in the previous month, annual trading volume, price in the previous month. This information is useful to market participants and to growers who are considering making a purchase or sale.

- Transfer Approval

  Significant cost savings have been realized by the *WaterLink* system's ability to facilitate the transfer approval process. Once growers have agreed on the terms of a transfer, they notify the district staff via-e-mail about the terms of their proposed trade. The district can then complete the transfer process.

- Water Ordering

  Perhaps the most commonly used feature of the *WaterLink* system in Westlands is the water ordering program. Growers can fill out and send the district an electronic form to order water deliveries to their farm. Well over half of all the irrigated acres in the district order their water via *WaterLink*. The district also reports cost savings from this feature.

- District and USBR Information

  The Westlands newsletter is available via the *WaterLink* system, as is USBR supply and storage information.

- Links to Irrigation-Related Sites
  WaterLink identifies other irrigation-related sites, including the California Irrigation Management Information System (CIMIS) that gives reference ET data for numerous weather stations in the Westlands service area, as well as weather forecasts.

- Bulletin Board
  Growers can post information on this site. The bulletin board has been used to sell farm machinery, for example.

In 1998, *WaterLink* was expanded to include 10 additional water districts in the San Luis & Delta-Mendota Water Authority. Users of the system include staff of the participating districts, authority personnel and USBR staff. The features of the system are similar to the intra-district system used in Westlands, with one notable exception: the inter-district version of *WaterLink* allows district managers to receive on-line approval for proposed inter-district transfers. This feature of the system is quite popular since delay in receiving USBR approval for proposed transfers retarded development of a more active spot water market in this area.

Response to the *WaterLink* system has been overwhelmingly positive. The Westlands version of *WaterLink* is currently used by most of the largest growers in the district. Water ordering is the most commonly used feature of the program, but then water is ordered more often than it is traded. With regard to trading, at any given time during the growing season there are several current bids and asks listed on *WaterLink*. The electronic market has not proven to be "thin." Also, the district sometimes procures water via the *WaterLink* system, mostly to meet operational needs.

Significantly, there are at least four private companies that are attempting to sell *WaterLink*-like technology to other water districts. These companies, including commodities giant Enron, have developed web-based operations and trading platforms for use by retail water utilities, and have cited the success of *WaterLink* explicitly in their marketing and investor relations materials.

The inter-district version of *WaterLink* has only operated for part of one growing year, so it has a more limited track record. Yet the on-line approval feature has caught the attention of district staff. The first two transfers submitted to the Bureau's office were approved in a single afternoon. Like the rest of the economy, water users in California are beginning to take advantage of improvements in information technology to minimize costs and improve resource use decisions.

Agricultural Water Conservation and Water Use Efficiency: Lessons from the Challenge Grant

I. Farmer Response to Changes in Financial Incentives

The dimensions of response to changes in water price include fallowing, adoption of conservation technology, crop shifting, and ground water pumping. A farmer's optimal combination of responses depends on factors such as magnitude and expected duration of scarcity, environmental conditions, farmer characteristics, crop grown, availability and quality of ground water.

A review of California growers' response to the 87–92 drought conducted by the Challenge Grant team suggests that farmers dealt with scarcity by reducing demand (fallowing and adoption of conservation technology—drip and microsprinkler, especially) and by procuring supplemental water (primarily ground water). Water trading also increased in volume, and in importance. For instance, the state's Drought Water Bank transferred water from north to south, to both farms in the San Joaquin Valley and cities in southern California.

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More evidence is provided by the Challenge Grant experience in Arvin-Edison, where the district reduced the standby charge and increased the volumetric charge. The district also eliminated the acreage entitlement within the surface water service area. Members of the Challenge Grant team tracked cropping patterns, technology adoption and water use before and after the price change. Review of the Arvin-Edison data on farmer response to changes in water price shows that farmers did shift towards crops earning more profit per acre foot of water used. However, the ultimate effect on water use was marginal since these crops also used more water per acre than others.

II. Adoption of Conservation Technology

Adoption of modern irrigation technologies is often cited as a key to increasing water use efficiency in agriculture and reducing the use of scarce inputs (Cason and Uhlaner, 1991) while maintaining current levels of production. Policy makers have tried to encourage adoption of modern technologies in several ways. For example, the California legislature recently enacted a measure (A.B. 3616) requiring irrigation districts in the state to draft "best management practices" for the use of irrigation water, including farm-level measures such as irrigation systems. Water price reforms are also increasingly used to encourage improvements in irrigation efficiency through technology adoption. The federal Central Valley Project Improvement Act requires the U.S. Bureau of Reclamation to adopt increasing block pricing for water provided to irrigation districts.

1. Adoption of Precision Irrigation Technology

In this section, we develop a version of the model of Caswell and Zilberman (1986), who outline the influence of environmental quality and economic factors on the decision to adopt alternative irrigation technologies. As will be discussed later, the model is applicable to other examples of precision technology.

To begin, we develop some useful notation. Let

$$
\begin{aligned}
&y = \text{output/acre}\\
&e = \text{effective input/acre}\\
&a = \text{appliedinput/acre}\\
&i = \text{technologyindicator}\begin{cases} i=0 & \text{for traditional}\\ i=1 & \text{for modern}\end{cases}\\
&\boldsymbol{a} = \text{landquality}\\
&p = \text{outputprice}\\
&w = \text{inputprice}\\
&k_i = \text{peracrecostof technology } i, k_1 > k_0
\end{aligned}
$$

The production function is $y = f(e)$ with $f'(e) > 0$ and $f''(e) < 0$. The input efficiency function, $h_i(\boldsymbol{a})$, is the fraction of the applied input consumed by the crop under technology i on land quality $\boldsymbol{a}$. The technologies are such that

$$
\begin{aligned}
&0 \le h_0(\boldsymbol{a}) = \boldsymbol{a} \le h_1(\boldsymbol{a}) \le 1\\
&h_i'(\boldsymbol{a}) > 0 \quad \textit{and} \quad h_i''(\boldsymbol{a}) < 0.
\end{aligned}
$$

The technology choice problem is as follows:

$$
\begin{aligned}
&\max_{d_i, a_i} \quad \sum_{i=0}^{1} \boldsymbol{d}_i \left[Pf\left(h_i(\boldsymbol{a}) a_i\right) - Wa_i - k_i \right],\\
&\text{s.t.} \quad \boldsymbol{d}_i \in \{0,1\}\\
&\qquad 0 \le \sum_{i=0}^{1} \boldsymbol{d}_i \le 1.
\end{aligned}
$$

The search for a maximum consists of two stages. First, the optimal amount of applied input (a continuous choice) is determined conditional on each technology. Then, the highest-profit technology is identified.

The applied input choice is determined by the following:

$$\boldsymbol{p}_i = \max_{a_i} Pf\left(h_i\left(\boldsymbol{a}\right)a_i\right) - Wa_i - k_i .$$

The FOC is

(II.1) $$Pf' = \frac{W}{h_i} .$$

In words, this optimization condition implies that the VMP of effective water must equal the marginal price of effective water. Once the second-stage, continuous problem is solved, the discrete choice problem of technology selection must be addressed, choosing

$$\begin{array}{lll} \boldsymbol{d}_1 = 1 & \text{if} & \boldsymbol{p}_1 > \boldsymbol{p}_0 \quad \text{and} \quad \boldsymbol{p}_1 > 0. \\ \boldsymbol{d}_0 = 1 & \text{if} & \boldsymbol{p}_0 > \boldsymbol{p}_1 \quad \text{and} \quad \boldsymbol{p}_0 > 0. \\ \boldsymbol{d}_1 = \boldsymbol{d}_0 = 0 & \text{if} & \boldsymbol{p}_1, \boldsymbol{p}_2 < 0. \end{array}$$

The model generates a number of testable hypotheses about the influence of environmental and market conditions on adoption of precision technology. Consider first the role of land quality. The marginal impact on profits under technology *i* of a change in $\boldsymbol{a}$ is as follows:

$$\frac{d\Pi_i}{d\boldsymbol{a}} = Pf h_i'(\boldsymbol{a})a_i = \frac{W\boldsymbol{h}_i a_i}{\boldsymbol{a}} > 0 ,$$

where $\boldsymbol{h}_i = h_i'(\boldsymbol{a})\boldsymbol{a}/h_i(\boldsymbol{a})$. It follows that the difference in profits between the two technologies is equal to

$$\frac{d\Delta\Pi}{d\boldsymbol{a}} = W\left[\frac{\boldsymbol{h}_1 a_1 - a_0}{\boldsymbol{a}}\right].$$

Now, this expression can be signed by taking a Taylor's series approximation of *a* as follows:

$$a_1 = a_0 + \frac{\partial a}{\partial \boldsymbol{a}}\left(h_1(\boldsymbol{a}) - \boldsymbol{a}\right),$$

recognizing that adoption of the precision technology is equivalent to a shift in land quality from $\boldsymbol{a}$ to $h_1(\boldsymbol{a})$. Substituting the elasticity expressions above, it follows that

$$a_1 = a_0\left(1 - \frac{1 - 1/\boldsymbol{f}}{\boldsymbol{a}}\right),$$

where $\boldsymbol{f} = -f''e/f'$. Substituting this equation into (2), it follows that

$$\frac{d\Delta\Pi}{d\alpha} = W\left[\frac{\eta_i a_0\left(1 - \frac{1 - 1/f}{\alpha}\right) - a_0}{\alpha}\right] < 0\,.$$

Thus, the profit gap between the modern and traditional technologies decreases as land quality improves. In this sense, the modern technology is land quality-augmenting. A further result helps to understand the influence of land quality on adoption. At the highest level of land quality (i.e., $\alpha = 1$), the modern technology will not be adopted. To see this, simply note that at this land quality $h_1(1) = h_0(1) = 1$, and $\Delta\Pi(1) = k_0 - k_1 < 0$.

Modern technology is adopted for levels of land quality below $\alpha = \alpha^s$ and the traditional technology elsewhere. Note that the modern input technology also has an extensive margin effect in that it enables profitable operation on lower levels of land quality than does the traditional technology (i.e., $\alpha_1^{\,m} < \alpha_0^{\,m}$).

With respect to market parameters, total differentiation of the equation implicitly defining the switch point α^s reveals that

$$\frac{d\alpha^s}{dW} = \frac{\left(a_1 - a_0\right)\alpha^s}{W\left[\eta_1 a_1 - a_0\right]} > 0 \text{ if } f > 1 \text{ and}$$

$$\frac{d\alpha^s}{dP} = \frac{\left(y_1 - y_0\right)\alpha^s}{W\left[\eta_1 a_1 - a_0\right]} > 0\,.$$

Despite the importance placed on micro-level variations in the theoretical literature, most empirical studies of irrigation technology adoption suffer from the use of regional average data on technology choices, and resort to comparing percentages of adoption among states or counties. Previous empirical studies have not been able to match terminology choice on a one-to-one basis with micro-level variables, such as water-holding capacity, field gradient and size, water price, and water supply source. Averaging data on a regional basis has a homogenizing influence on both grower behavior and physical characteristics; it may obscure the effect of micro-variables, and, as a result, it may seriously bias statistical estimates of adoption behavior.

In the Challenge Grant study, a microparameter approach based on field-level data is used to assess irrigation technology choices. This study has several advantages over previous empirical analyses of irrigation technology adoption: (i) a multinomial model is used rather than a binomial model so it is possible to examine switching between modern technologies, in addition to switching from traditional to modern technologies; (ii) the empirical model includes a complete set of physical characteristics observed at the field-level, thereby avoiding misspecification problems inherent in earlier models based on grouped data; (iii) all members of the data set face the same institutions and input and output markets, so it is not necessary to use regional dummy variables that obscure important statistical relationships; (iv) both annual and perennial crops are included, whereas previous studies only included one or the other; and (v) the soil data variables are continuous rather than ranked, as is the case in most other studies. As a result of the disaggregated microparameter approach, we obtain more accurate conclusions regarding the effect of soil characteristics and water price on irrigation technology adoption, and overthrow or significantly modify some of the conventional wisdom regarding irrigation technology adoption.

We first present a discrete choice model and show how it relates to the grower's decision problem. Then cross-section data from a central California irrigation water district are employed to estimate an empirical model. This is followed by a discussion of the results, paying special attention to variables that are the most influential to irrigation technology choice.

2. Model of the Adoption Decision

The grower decides which irrigation technology to adopt on the *j*th field by calculating expected profits under each of the *i* technologies, while taking into account what type of crop is grown and the field's physical characteristics. The grower chooses the technology that maximizes perceived profits, given that crop choice already has been made.[1] In this study crop and technology choice are modeled as sequential. An alternative assumption would be to model the crop and technology choice simultaneously, as suggested by Negri and Brooks (1990), and by Lichtenberg (1989). While this may be appropriate for grain crops, it does not appear to be appropriate for high-value fruits and vegetables. The distinction is that the production of high-value crops involves extremely specialized capital, where grains are not as highly specialized. Therefore, even though the actual investment in a new crop and technology physically may be made at the same time, the decision to invest is made sequentially. To test this, a model of simultaneous crop and technology choice was estimated. The model had inconsistent results, predicted poorly, and was statistically insignificant.

Given the assumption of sequential choice, the per acre profits are given by

$$\boldsymbol{p}_{ij} = \boldsymbol{b}_i' \mathrm{X}_j + \boldsymbol{e}_{ij}$$

where $\boldsymbol{b}_i$ is a vector of estimable parameters, X_j is a vector of observed field characteristics (including crop choice), and $\boldsymbol{e}_{ij}$ is an unobserved scalar associated with unmeasured characteristics. Setting the index of the traditional technology to $i = 0$, the grower selects the *i*th modern technology if

$$\boldsymbol{b}_i' \mathrm{X}_j - \boldsymbol{b}_0' \mathrm{X}_j > \boldsymbol{e}_{0j} - \boldsymbol{e}_{ij} .$$

To estimate the model parameters, it is necessary to choose a distribution for the $\boldsymbol{e}_{ij}$'s and, thus, the distribution of the difference of the error terms. Two common assumptions are either the

[1] Though much of the more general literature on technology adoption examines profit risk, this is not of great concern in the irrigation technology adoption literature. Note that pressurized irrigation technologies generally increase uniformity of input application, decrease output variability, and increase expected yields. The net result of these attributes to risk considerations is ambiguous since they affect risk in opposite directions.

normal or the Weibull distributions (Domencich and McFadden, 1975). Normal random variables have the property that any linear combination of normal variates is normal. The difference between two Weibull random variables has a logistic distribution, which is similar to the normal, but with larger tails. Thus, the choice is somewhat arbitrary, especially with large sample sizes. We assume that the e_{ij} 's follow a low Weibull distribution. Given this assumption, the probability that the *i*th technology is adopted on the *j*th field is

$$P_{ij} = \frac{e^{b_i X_j}}{\sum_i e^{b_i X_j}}; \quad i = 0, I; \quad \text{and} \quad j = 1, J. \tag{II.2}$$

These give the estimation equations for the standard multinomial logit model that is based on the characteristics of the field, not the characteristics of the choice. In this model the parameters vary across technology choices, but not across field characteristics. Thus, the number of estimated parameters is equal to the number of characteristics times the number of choices.

The effect of each of these variables is captured in the estimated parameter vector b. The difference in characteristics across fields affects the technology choice via the perceived effect on the profitability of production on a specific field. This differs from previous studies that have looked at how regional differences affect profitability. While the previous results have given insight to regional differences, they do not correspond to individual grower choices given the field characteristics they face.

3. Data

The model is applied to the Arvin Edison Water Storage District (the District) located in the southern San Joaquin Valley in central California. Because of the regional climate and favorable soils, growers in the District benefit from an early harvest season that allows for diverse cropping patterns, as shown in Table II.1. In addition, there has been a large degree of irrigation technology adoption—30% furrow or flood, 37% high-pressure sprinkler, and 33% low-pressure drip and micro-sprinkler (Table II.1). The distribution of crops and irrigation technologies makes the District ideal for analysis; yet, the area is relatively small, so the growers participate in many of the same markets and institutions.

The data on crop choice, irrigation technology, price of water, and water source were collected by the District. The study considers four crop categories: truck crops, citrus trees, deciduous trees, and grape vineyards. Taken together, these crops constitute 76% of the cultivated acreage in the District. The remaining acreage is distributed among grains, irrigated pasture, cotton, and dry land crops.

Irrigation technologies are consolidated into three groups based on the required level of pressurization. These are as follows: (1) furrow, flood, and border, which are considered the traditional or gravity technology, and are used on all types of crops; (2) high-pressure sprinklers, which are used primarily on truck and deciduous crops; and (3) low-pressure systems like drip, micro-sprinklers, and fan jets, which are also used in each crop group.

Table II.1. Irrigation and Acreage by Crop.

		Percentage of Acreage by Irrigation Technology		
Crop	Acreage	Furrow	Sprinkler	Drip
Citrus	12,065	15%	1%	84%
Deciduous	11,700	27%	33%	40%
Grapes	23,665	61%	2%	37%
Truck Crops	27,283	11%	86%	3%
Total	74,713	30%	37%	33%

There are several important points to be raised concerning low-pressure technologies and perennial crops in the District. First, low-pressure systems such as drip only wet a small area of soil. As a result, perennial crops under drip irrigation form a smaller root system than if a traditional irrigation system were used. Many growers feel that this makes the crop more susceptible to disease and the accumulation of salts, which reduces the attractiveness of these systems. Second, many of the perennial crops were established prior to the introduction of low-pressure systems. Because different types of root systems are developed under the different types of technologies, growers are reluctant to switch technologies on an established crop for fear of damaging the crop. To combat these potential problems, growers have used multiple emitters for each tree to achieve a larger area of water dispersion.

The marginal price of ground water is estimated by the District based on depth to ground water and the energy cost for the size of pump needed to lift water from a given depth. The marginal price for surface water is the variable component of the District charge for each acre-foot that is actually delivered. In 1993, marginal water price ranged from $2 to $57 per acre-foot for surface water, and $40 to $88 per acre-foot for ground water. Though the marginal price of ground water is about $25 more per acre-foot than surface water, the fixed component of the District charge for surface water is set so that the total price for ground and surface water is approximately the same, ranging from $50 to $110 per acre-foot.

The Kern County Natural Resource Conservation Service collected data on soil permeability and field slope to define land quality for each quarter section. To match the quarter sections (which are 160-acre plots) to the specific fields, District land maps were used to identify the exact location of each field. Permeability and slope were given in inches per hour and percentage, respectively. The data indicate that the distribution of irrigation technology for a given slope ranges; when the slope increases so does the percentage of acreage under drip irrigation. This indicates that the grower's irrigation technology choice is conditioned on land characteristics. The effect of soil permeability on technology choice is not as distinct.

The econometric model explains the use of the different types of irrigation technologies as a function of the characteristics of the fields for which they are used. The estimation equations in (II.2) provide a set of probabilities for the $I+1$ choices faced by the decision maker. However, to proceed it is necessary to remove an indeterminacy in the model. A convenient normalization is to assume that $\boldsymbol{b}_0$ is a vector of zeros. We can then take the log and estimate the log odds ratio of choosing the *i*th technology on the *j*th field. This is given by

$$\text{(II.3)} \qquad \ln \frac{P_{ij}}{P_{0j}} = \boldsymbol{b}_i' X_j, \quad i = 1,2, \quad \text{and} \quad j = 1,2,...,1,493.$$

The coefficients can be interpreted as the marginal impact of the variable on the log odds of selecting a modern technology relative to the benchmark technology.

The data for the study are from the 1993 growing year and there are 1,493 fields cultivated by approximately 350 growers. Though we are unable to identify which growers cultivated which fields, based on sample interviews we determined that most growers had fewer than four fields and grew at least two different crops. Growers that had a large number of fields grew at least five crops. There are eight independent variables: four continuous—(a) field size, (b) field slope, (c) soil permeability, and (d) price of water; and four binary—(e) water source (i.e., ground water or both ground and surface water), (f) citrus crop, (g) deciduous crop, and (h) grape vineyard. Without loss of generality, truck crops and gravitational technology are used as benchmarks for crops and technology choice.

4. Results

The Limdep statistical package is used to estimate the parameters of the model using maximum likelihood estimation and Newton's method. We report the coefficients, asymptotic t-statistics, and three statistical tests to evaluate the performance of the model. To allow comparison of adoption rates, among traditional, sprinkler, and drip technologies, we calculate the probability of adoption, the elasticity of the continuous variables, and the percent change in probability of the discrete variables if they were to change from 0 to 1. These are all reported in Table II.2.

Of the coefficient estimates in Table II.2, more than half are significant at the 0.0001 level, and all but two were significant at the 0.07 level. To measure the performance of the model, the McFadden R^2, the log-likelihood ratio test, and the percentage of correct predictions are reported. The McFadden R^2 is calculated as $R^2 = 1 - L_\Omega / L_w$, where L_Ω is the restricted maximum log-likelihood and L_w is the restricted maximum log-likelihood with all slope coefficients set equal to zero (Amemiya, 1981). The log-likelihood ratio test is given by $2\left(L_\Omega - L_w\right)$ and is asymptotically distributed as a chi-squared random variable. The percentage of correct predictions is calculated as the total number of correct predictions as a percentage of the number of observations. Each of these measures indicated that the model has strong explanatory power.

The statistical results indicate that the adoption of irrigation technologies is highly dependent on crop choice. The coefficients on the perennial crop variables in the sprinkler technology equation are all negative, large, and highly significant. This result implies that the probability of adopting sprinkler rather than the traditional technology is low for perennials, and reflects the physical characteristics of perennial crops. For example, high-pressure sprinklers disperse water over a large area saturating the tree and causing fruit decay, which is not a problem for many annual crops such as potatoes. Crop choice also strongly affects drip adoption, although in nearly the opposite way as for sprinklers. Perennial crops, especially citrus trees, are more likely to be grown under drip irrigation than annuals. The influence of crop type on technology choice is also reflected in the change in probability figures in Table II.2. These results show that a grower producing perennial crops is much more likely to adopt drip than furrow or sprinkler irrigation. For example, growing citrus trees increases the probability of adopting drip by 58%, holding all other variables at their mean value. Previous studies that focused on a small number of crops (Lichtenberg, 1989; Shrestha and Gopalakrishnan, 1993) could not fully identify the importance of crop type on irrigation technology adoption.

Table II.2. Estimation Results, Elasticities, and Probabilities.

	Estimation Results*		Elasticities**		
Variable	Sprinkler	Drip	Furrow	Sprinkler	Drip
Constant	1.9855	–4.5480			
	(3.372)	(–7.701)			
Water price ($/acre-foot)	–0.0130	0.0257	–0.24	–0.84	0.96
	(–1.333)	(3.151)			
Surface water (0/1)	–0.5099	0.9706	[–0.11]	[–0.12]	[0.23]
	(–1.636)	(3.930)			
Soil permeability (in/hr)	0.0002	0.0529	–0.04	–0.04	0.11
	(0.005)	(2.082)			
Field slope (%)	0.2210	0.6277	–0.32	0.01	0.61
	(1.846)	(8.081)			
Field size (acres)	0.0101	0.0065	–0.19	0.34	0.15
	(4.714)	(4.028)			
Crops					
Citrus (0/1)	–5.1537	2.1117	[–0.21]	[–0.37]	[0.58]
	(–8.380)	(6.095)			
Deciduous (0/1)	–2.3600	1.3872	[–0.16]	[–0.23]	[0.39]
	(–11.186)	(4.064)			
Grapes (0/1)	–6.3777	0.6760	[0.24]	[–0.57]	[0.33]
	(–12.061)	(2.052)			
Probability of adoption evaluated at variable means			0.54	0.18	0.28
Observations	1,493				
McFadden R^2	0.44				
Likelihood ration test: χ^2_{16}	1.441.16				
Correct prediction	74%				

*Terms in parenthesis are asymptotic t-statistics.
**Terms in brackets are not elasticities. They are the percent change in the probability of adoption as the discrete variable changes from 0 to 1.

Economic factors are also important in determining irrigation technology choices. The coefficient on the water price variable in the drip equation is positive and significant, confirming previous findings that water-saving technology will be adopted as water price increases. However, the coefficient on water price in the sprinkler equation is negative. Figure II.1 shows the change in the probability of adoption as a function of the price of water, with all other variables set at their mean values. This figure demonstrates that, as the price of water increases, growers switch from both furrow and sprinkler irrigation technologies to drip.

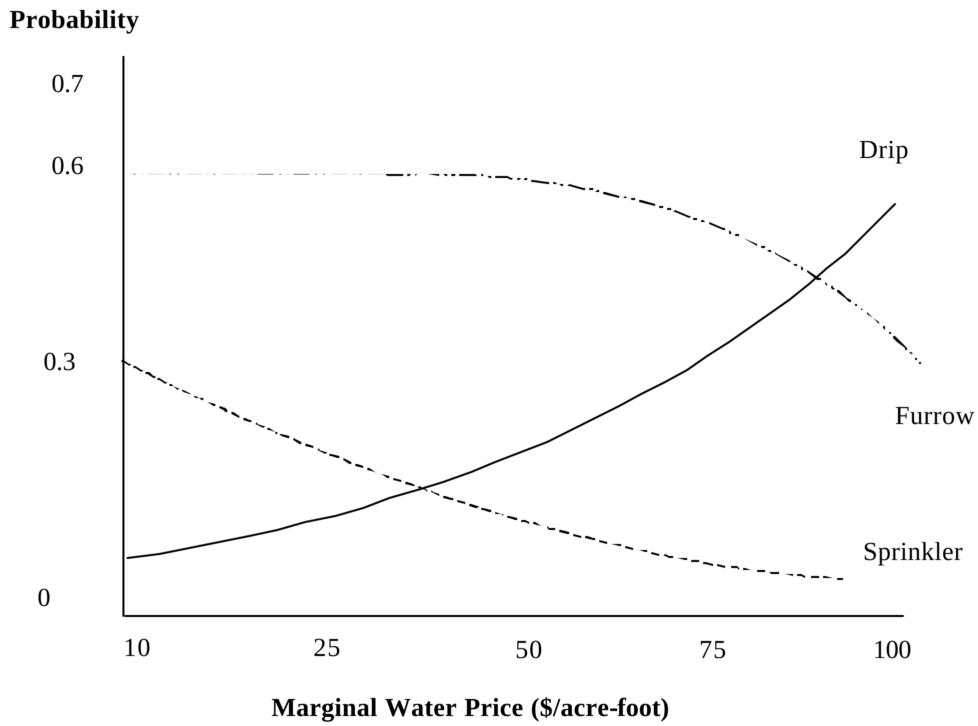

Figure II.1. Probability of Adoption by Marginal Water Price.

The results in Table II.2 and Figure II.1 are in sharp contrast to the results of previous studies that have found similar adoption patterns for high- and low-pressure irrigation systems. For example, Caswell and Zilberman (1985) reported coefficients of 0.03 on marginal water price in equations explaining both drip and sprinkler adoption, and Cason and Uhlaner (1991) estimated water price coefficients between 0.02 and 0.07 for all technologies, depending on the region. The results differ from these studies for several reasons. Examining several technology choices simultaneously gives a more complete picture of grower decision-making behavior and allows for explicit estimation of marginal probabilities. Further, growers in this study farm in an arid, hot climate and pay more for water than irrigators in many other areas. As a result, the diffusion process for pressurized technologies is more advanced in the District than in other regions, and sprinkler technologies appear to be nearing the end of their product life cycle. Sprinkler irrigation has been employed in the District since the early 1960s and is widely utilized on crops that grow well with this technology. In particular, Table II.1 shows that truck crops are grown largely under sprinkler irrigation. However, potato growers in the District are now beginning to convert to low-pressure systems (especially drip tape) in response to changes in water price. This observation is consistent with the findings of Dinar and Yaron (1992). In their model of technology adoption and abandonment, Dinar and Yaron estimate the technology cycle of hand-move sprinklers to range from twenty-two to twenty-four years.

The coefficients on the land quality variables—soil permeability and field slope—are of the expected sign and magnitude. Again, however, there are important differences between technologies in terms of the effect of land quality variables. Sprinkler adoption is not as sensitive to land quality as drip irrigation, which is especially dependent on field slope. Prior to the introduction of drip irrigation, it was difficult and costly to grow irrigated crops on lands with steep slopes. As a result, the introduction of drip has allowed cultivation of land that had previously been unproductive. This relationship is best seen in Figure II.2, which shows that variations in slope have a dramatic effect on the probability of adopting furrow and drip irrigation.

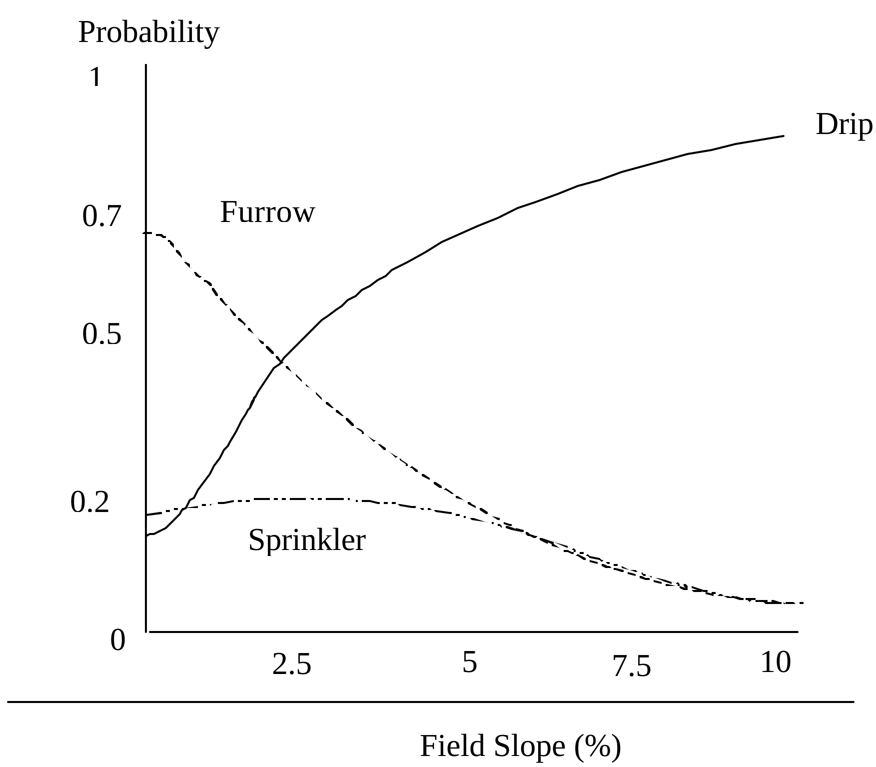

Figure II.2. Probability of Adoption by Field Slope.

Caswell and Zilberman (1986) show theoretically that modern irrigation technologies are less likely to be adopted on fields with surface water supplies rather than ground water supplies on the assumption that surface water is supplied at lower pressure than ground water. The statistical results show that sprinkler adoption is less likely to be adopted in areas with surface water supplies, but that drip adoption is more likely with surface supplies. While the District is one of the few California districts supplying pressurized surface water to its growers, the pressure is not consistent and is only sufficient to run a low-pressure system such as drip.

5. Policy Implications

The results of this study point out that cross-section technology adoption coefficients must be interpreted with the dynamic diffusion process in mind and also show that the effect of economic factors such as price on adoption is path-dependent. For example, in the results, we obtained a negative coefficient on the water price variable for adoption of sprinkler irrigation, which would seem to refute the theoretical and empirical literature. However, high-pressure sprinklers are widely adopted in the study area, and because these technologies are far from the beginning of their life cycle in the District, abandonment of sprinkler technologies is more sensitive to water price increases than adoption. In another area where growers rely more on gravitational systems, and hence sprinklers are at the beginning of their life cycle, the opposite should be true. This demonstrates that the coefficients cannot be interpreted at face value and that it is important to consider the underlying diffusion process when considering the policy implications of an analysis.

The results show that water price is not the most important factor governing irrigation technology adoption; physical and agronomic characteristics appear to matter more. As a result, the distributional impacts of irrigation water pricing reforms will be significant, with changes in producer welfare following the spatial distribution of environmental characteristics. To the extent that micro-level factors condition irrigation technology choice, policies that change the price of irrigation water to reflect its off-farm value will result in a pure loss for some producers while encouraging adoption of modern irrigation technologies for other producers. This demonstrates the importance for economists to bear in mind the equity implications of water pricing reform proposals when interacting with decision makers.

This study has important implications for the design of water pricing and delivery policies. The statistical results of the model show that large increases in the price of water generally stimulate the adoption of drip irrigation systems; that adoption patterns are heavily influenced by crop type; and that the adoption decision is also strongly conditioned by slope, but is only slightly affected by variations in water-holding capacity. These results are a significant departure from previous studies which have generally failed to account for differences in adoption behavior within the group of pressurized technologies and for the influence of crop type on adoption behavior, and which have inadequately measured physical characteristics and water prices by relying on regional data.

The study clearly shows that microparameters are crucially important to understanding agricultural technology adoption and can best be statistically assessed using micro-level data. Since many of the important microparameters concern environmental conditions, the study also shows the value of integrating economic and environmental data when predicting grower behavior. Much relevant environmental data (e.g., soil characteristics, microclimate, and cropping patterns) can be captured on a Geographic Information System (GIS). Fortunately, GIS systems are increasingly common and are decreasing in price, so that there are good prospects for incorporating environmental conditions when performing highly disaggregated analyses of agricultural technology choices.

Finally, it is important to note that this study supports the finding that heterogeneity of asset quality is critical in the general study of technology adoption. One of the major contributions of past studies of agricultural technology adoption to the general adoption literature is that they emphasize the role of heterogeneity of asset quality in the adoption process (Bellon and Taylor, 1993; Perrin and Winkelmann, 1976). Heterogeneity is a crucial element of the threshold model of diffusion (Davies, 1979; Stoneman and Ireland, 1986), but many of the early threshold models focus exclusively on variations in wealth or related factors such as farm size. The agricultural technology problem highlights the importance of differences in physical or geographical conditions in explaining adoption behavior and points out that geographic information must be combined with economic data to accurately predict adoption patterns.

6. Further Research: The Yield Effect of Precision Technology

The traditional approach to the irrigation technology choice problem is to assume a production function with the form

$$y = \min_{i\in\{1,\ldots,n\}}\left[\frac{\alpha_i x_i}{b_i}\right],$$

where y is crop output, α_i is the efficiency of technology i, x_i is the amount of the water applied and b_i is some parameter. Effective water, or the amount of water available to the crop, is given by $e_i = \alpha_i x_i$.

According to this traditional approach, the technology choice problem is as follows:

$$\max_i \; p\frac{\alpha_i x_i}{b_i} - w_i x_i - k_i .$$

An additional feature of the problem is that crop output has a “linear-plateau” form, or

$$y = \min\left[\frac{\alpha_i x_i}{b_i}, \bar{y}\right].$$

Maximum yield, or the height of the plateau, is presumed to be invariant with respect to the choice of irrigation technology. Under this assumption, the amount of water applied is simply a function of the technology chosen: the farmer irrigates with the minimum amount of water that achieves maximum yield, or does not irrigate at all.

III. Water Supply Reliability and Water Use Efficiency

1. Introduction

In recent years, growing concern for the environment has placed increasing emphasis on resource conservation. Hausman (1979) was one of the first papers to address the issue of conservation technology adoption. Hausman investigates consumer behavior with respect to choice of air-conditioners. He models consumer behavior in a two-stage model, where the consumer makes two decisions: initial capital choice and utilization. His empirical analysis finds that consumers indeed balance fixed costs with operating costs. Furthermore, he estimates consumer's discount rates to be quite high relative to "engineering calculations." His analysis suggests that a successful conservation policy should consider the complex relationship between individual characteristics and the capital-utilization trade-off associated with adopting conservation technology.

This section addresses how input price risk affects conservation technology adoption given the capital-utilization trade-off discussed by Hausman. We show theoretically and empirically that price risk does have a large influence on adoption of conservation technology, even if individuals are risk-neutral. Using Hausman' s framework, we develop a general model of the effect of input price risk on conservation technology adoption. We derive a general model to predict the adoption response to changes in input price risk in a model general enough to be applied to a number of settings. We test the model empirically using field-level irrigation technology data compiled in cooperation with the staff of the Arvin-Edison Water Storage District.

One feature of our model is to make the so-called "rebound effect" of conservation technology adoption explicit. Claims of environmental benefit from the adoption of conservation technology are premised on the belief that conservation technology reduces the use of natural resources. However, the adoption of conservation technology also has the effect of lowering the ex post marginal cost of operation, thereby increasing the optimal level of output; this is the rebound effect. The output effect of conservation technology use may significantly reduce the ultimate amount of resource savings from its adoption (Greene et al., 1999; Wirl, 2000). By endogenizing the utilization level into the technology adoption decision, our model incorporates the rebound effect. In particular, we are able to show that the influence of factor price risk on the adoption decision depends critically on the magnitude of the rebound effect.

In Section 2, we develop a model that distinguishes between long-term investments in conservation technology and short-term decisions about the level of utilization. We show that the relationship between input price uncertainty and technology adoption is complex. We identify cases in which increasing price risk can increase or decrease the incentive to adopt conservation technology. One of our main conceptual results is that the responsiveness of utilization to changes in the input price has an important impact on adoption behavior. For example, we show that the impact of a mean-preserving spread of input price on conservation technology choice depends on the elasticity of utilization with respect to the input price. One implication of this is that changes in the distribution of input price have different effects on different types of economic activities.

In Section 3 we present our empirical analysis. We estimate an ordered probit to test the conceptual model presented in Section 2 using irrigation technology data from California. Our empirical results strongly support our model. We consider the effects of a mean-preserving spread of the input price distribution. Our empirical model predicts that the incentive to adopt conservation technology increases when utilization is relatively elastic with respect to input price (i.e., annual crop production). The incentive to adopt decreases for an activity that is relatively inelastic with respect to input price (i.e., permanent crop production). In Section 4 we conclude and discuss the policy implications of our findings.

2. Model

We define conservation technology as technology that has the lowest input requirement per unit of output, relative to the alternative technologies. The technology is characterized as putty-clay in terms of input use intensity: The input-output ratio is fixed in the short-run, but malleable in the long-run, and in the long-run, technologies can be substituted with different types of technologies (Johansen, 1959; Atkeson and Kehoe, 1999). For example, resource-intensive technologies can be substituted with resource-conserving technologies. Since we are interested in individual behavior with respect to conservation, we model the decision at the microunit, that is, the individual production unit. This can be a consumer choosing an automobile or home appliance, a firm choosing a machine for a particular process, or a farmer choosing irrigation technology for a field.

Following Hausman (1979), the agent makes a two-stage decision. In the short-run, the agent chooses the level of utilization, for example, miles driven, degree-hours cooled, or acres in production. In the long-run, the agent chooses conservation by choosing the input-output coefficient, a, of the technology. Given the broad range of conservation practices available, from investing in new equipment to changing habits, we model the technology choice as a continuum of technologies measured by the choice of the input-output coefficient.

The agent faces a stochastic input price, p, assumed to be the constant marginal cost of the input (i.e., gasoline, electricity, water, etc.). The probability distribution of the input price can be affected by climatic conditions as well as by policy. While the policy maker may not be able to affect when resource shocks occur, she can affect the probability distribution of resource supply through various policies. These may include policies in response to the shocks, investment in infrastructure, and policies to protect the environment. Here we focus on the policy impact on the input price probability distribution. We assume that p has a known distribution $F\left(p;\boldsymbol{q}\right)$, where $\boldsymbol{q}$ is the policy parameter which reflects how policy affects the price distribution. The support of $F\left(p;\boldsymbol{q}\right)$ is $\left[\overline{p}, \overline{p}\right]$ and we assume p is *IID*.

1. Short-Run Equilibrium: The Utilization Decision

In the short-run, efficiency of the technology is fixed and input price is known. The agent chooses utilization, x, to maximize short-run welfare. Utilization is chosen in terms of the input. Short-run welfare is defined as short-run benefits from utilization less operating costs given a fixed input-output coefficient, $\overline{a}$. The agent's short-run optimization problem is given by

(III.1) $$\max_x W^{SR} = B(x) - p\bar{a}x - z(\bar{a})$$

where $B(x)$ is the benefit from production of services. We assume that $B(x)$ is concave in x. The function $z(\bar{a})$ is the annualized cost of technology adoption, as a function of the input-output coefficient. A higher input-output coefficient implies a lower level of conservation, and technologies with lower input-output coefficients (higher conservation) require larger investments. Thus, expenditure on technology is decreasing in a, that is, $z'(\bar{a}) < 0$.

The first order condition for the agent's short-run problem is

(III.2) $$B'(x) - p\bar{a} = 0,$$

which implicitly defines the optimal level of x as a function of p and $\bar{a}$,

(III.3) $$x^* = x(p, \bar{a}).$$

From the optimality condition in (III.2), we obtain the comparative statics

(III.4) $$\frac{dx}{d\bar{a}} = \frac{P}{SOC_{SR}} < 0,$$

and

(III.5) $$\frac{dx}{dp} = \frac{\bar{a}}{SOC_{SR}} < 0,$$

where $SOC_{SR} = B''(x) < 0$, the short-run second order condition for an interior maximum. Equation (III.4) reflects the rebound effect, which implies that utilization changes in the opposite direction to the input-output ratio, or in terms of conservation, utilization increases with conservation. Equation (III.5) is negative, as expected for an input demand.

We define the shut-down input price, $\hat{p}$, as

$$\hat{p}(a) = \{p | B(x) - p\bar{a}x = 0\}.$$

At any input price above $\hat{p}$, the technology will not be utilized.

2. Long-Run Equilibrium: Technology Decision

Now we turn to the long-run investment choice, in which the agent chooses efficiency to maximize long-run expected welfare. The long-run problem can be expressed as

$$\text{(III.6)} \qquad \max_a W^{LR} = \int_{\bar{p}}^{\hat{p}(a)} \left[B\left(x^*\right) - pax^* \right] f\left(p; \mathbf{q}\right) dp - z\left(a\right),$$

where x^* is the short-run optimal utilization given in equation (III.3). The first term in the long-run objective function, equation (III.6), is the net benefit of efficiency in states of nature when it is economical to utilize the technology. Expenditure on conservation technology is incurred in all states of nature.

The optimality condition for the long-run problem is

$$\text{(III.7)} \qquad \begin{aligned} &\frac{\partial \hat{p}}{\partial z}\left[B\left(x\left(\hat{p}, a\right)\right) - \hat{p}ax\left(\hat{p}, a\right)\right] \\ &+ \int_{\bar{p}}^{\hat{p}(a)} \left\{ \left[B'\left(x^*\right) - pa \right] \frac{\partial x\left(p, a\right)}{\partial a} \right\} f\left(p; \mathbf{q}\right) dp \\ &- \int_{\bar{p}}^{\hat{p}(a)} px^* f\left(p; \mathbf{q}\right) dp - z\left(a\right) = 0. \end{aligned}$$

By definition of $\hat{p}$, the first term in (III.7) is zero. The second term is zero by the Envelope Theorem. Thus, (III.7) simplifies to

$$\text{(III.8)} \qquad \int_{\bar{p}}^{\hat{p}(a)} -px^* f\left(p; \mathbf{q}\right) dp - z'\left(a\right) = 0\,.$$

The optimality condition sets the expected marginal value of conservation, that is, the expected cost savings from investing in conservation technology, equal to the marginal cost of the technology. This condition defines the long-run equilibrium level of the input-output coefficient, and thus the optimal choice of conservation technology. We use this condition to evaluate the impact of a price shock on the choice of conservation technology.

3. Impact Analysis

The equilibrium condition derived in equation (III.8) is illustrated in Figure III.1. At the initial price distribution, *F*, the optimal input-output coefficient is given by the intersection of the marginal cost of conservation, $z'\left(a\right)$, and the expected marginal value of conservation, $E_F v_0$. Suppose that a policy change induces a shift in the price distribution from a relatively stable distribution, *F*, to a more volatile distribution, *H*. For example, regulation that restricts water diversions from a river to protect in-stream uses, or electric deregulation. From equation (III.8), the expected marginal value of conservation may increase or decrease with price, therefore the choice of *a* may also increase or decrease with the price shock. In this subsection, we determine cases in which conservation increases or decreases with changes in input price risk.

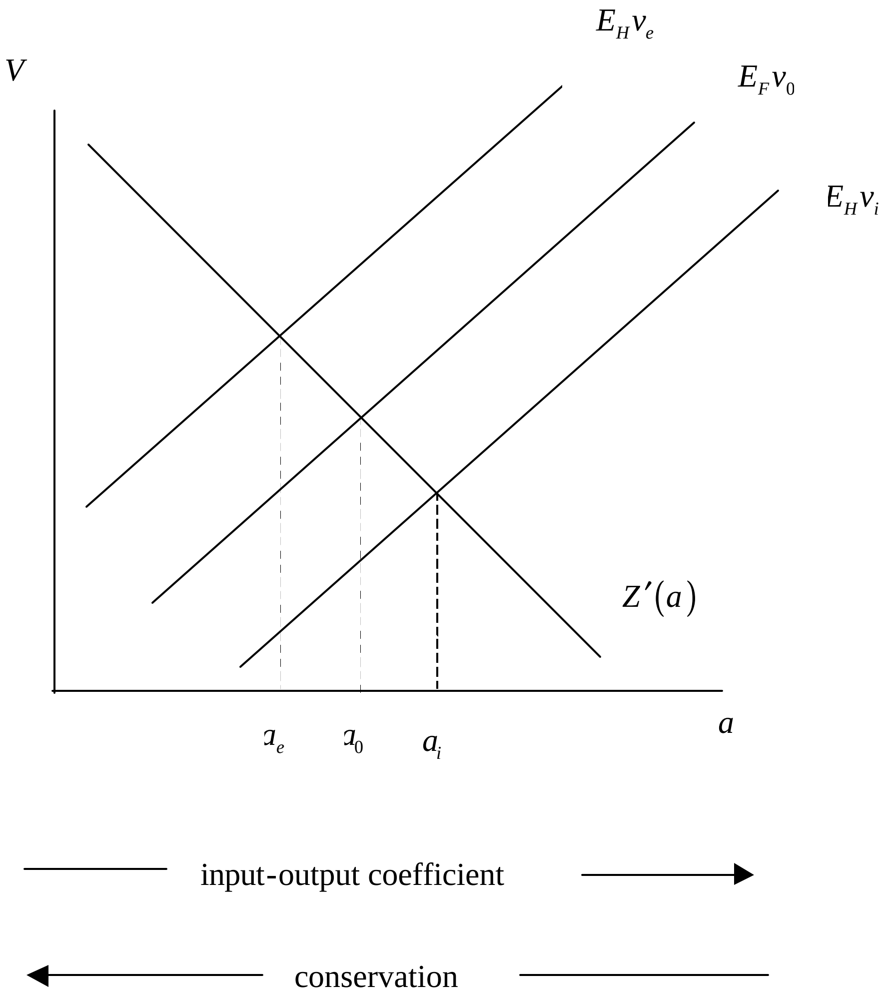

Figure III.1. Long-Run Equilibrium

This analysis is similar to the ranking theorems derived by Rothschild and Stiglitz (1970). However, some features of our model prevent us from directly invoking these ranking theorems to evaluate the impact of increasing price risk on conservation technology choice. First, from the long-run first-order condition in (III.8), the value of conservation may be increasing or decreasing in p. Second, the range over which the expected marginal value of conservation is defined is endogenous to the choice of a, which reflects the rebound effect. By comparing the expected marginal value of conservation under the two distributions, we derive the conditions under which the shock to the price distribution induces an increase or a decrease in conservation.

Let *F* and *H* be probability distributions of the input price with support $\left[\overline{p}, \overline{p}\right]$ and let $f\left(p\right)$ and $h\left(p\right)$ be the corresponding densities. As a special case, assume that *F* second-order stochastically dominates *H*. Define $v\left(p\right) = -px^{*}$ as the marginal value of conservation for a particular realization of the factor price. Then $E_F\left[v\left(p\right)\right]$ is the expected marginal value of conservation under the distribution *F*, represented as $E_F v_0$ in Figure III.1. $E_H\left[v\left(p\right)\right]$ is the expected marginal value of conservation under the distribution *H*.

To determine conservation technology choice under the two distributions, we compare the expected values of v at the distributions *F* and *H*:

(III.9) $$E_H\left[v\left(p\right)\right] - E_F\left[v\left(p\right)\right] = \int_{\overline{p}}^{\hat{p}(a)} \left[v - \left(p\right)\right] dH - \int_{\overline{p}}^{\hat{p}(a)} \left[v - \left(p\right)\right] dF .$$

Integrating (III.9) by parts yields

(III.10) $$E_H\left[v\left(p\right)\right] - E_F\left[v\left(p\right)\right] = -\int_{\overline{p}}^{\hat{p}(a)} \left[H - F\right] v'\left(p\right) dp$$

where

(III.11) $$v'\left(p\right) = -\left(\boldsymbol{e}_x + 1\right) x^{*} ,$$

and $\boldsymbol{e}_x$ is the input price elasticity of utilization, or

(III.12) $$\boldsymbol{e}_x = \frac{\partial x^{*}}{\partial p} \frac{p}{x^{*}} .$$

Define $\Phi\left(p\right)$ as

(III.13) $$\Phi\left(p\right) = \int_{\overline{p}}^{p} \left[H\left(p\right) - F\left(p\right)\right] dp .$$

We define *H* as “riskier” than $F\left(p\right)$ in the sense that $\Phi(p) \geq 0 \ \forall p$, which is of course equivalent to second-order stochastic dominance.

Integrating equation (III.10) by parts once again, we obtain

(III.14) $$E_H\left[v(p)\right]-E_F\left[v(p)\right]=v'(p)\,\Phi(p)\Big|_{\overline{p}}^{\hat{p}(a)}-\int_{\overline{p}}^{\hat{p}(a)}v''(p)\,\Phi(p)dp\,.$$

Using equation (III.4), equation (III.10) can be rewritten as

(III.15) $$E_H\left[v(p)\right]-E_F\left[v(p)\right]=-\int_{\overline{p}}^{\hat{p}(a)}v''(p)\,\Phi(p)\,dp\,.$$

These results together with the definition of $\boldsymbol{e}_x$ in equation (III.12) indicate that we can evaluate $E_H\left[v(p)\right]-E_F\left[v(p)\right]$ in terms of the input price elasticity of utilization. As $\boldsymbol{e}_x$ becomes large in absolute value, the first term in equation (III.15) dominates, and thus $E_H\left[v(p)\right]>E_F\left[v(p)\right]$. This case corresponds to a shift from $E_F v_0$ to $E_H v_e$ in Figure III.1. In this case, an increase in risk increases the marginal productivity of investment in conservation technology. As $\boldsymbol{e}_x$ approaches 0, the second term in (III.15) dominates and $E_H\left[v(p)\right]<E_F\left[v(p)\right]$. This case corresponds to a shift from $E_F v_0$ to $E_F v_i$ in Figure III.1. We summarize these results as

$$E_H\left[v(p)\right]-E_F\left[v(p)\right]\begin{cases}\geq 0 & \text{if} \quad \boldsymbol{e}_x \ll 0\\ \leq 0 & \text{if} \quad \boldsymbol{e}_x = 0.\end{cases}$$

These conditions imply that as utilization becomes more responsive to changes in input price, adoption of conservation technology increases in response to an increase in input price risk.

To illustrate the results, consider the case of irrigation technology adoption examined in the empirical section. We compare conservation technology adoption under two distributions, where one is characterized as a mean-preserving spread of the other.[2] We compare the effect of a change in the price distribution for two production activities: production of permanent crops and production of annual crops. In the case of annual crop production, which is highly responsive to short-run realizations of water price, the model presented in this section predicts that mean-preserving spread of the input price increases the incentive to adopt conservation technology. In the case of permanent crop production, which is relatively inelastic to changes in water price, our model predicts that a mean preserving spread of input price decreases investment in conservation technology.

This analysis establishes that changes in the distribution of input price, regardless of whether they follow from policy reform or construction of infrastructure, may have an ambiguous effect on the incentives to improve efficiency. We also show that the rebound effect can determine the effect of price risk on adoption of conservation technology. In the following section, we test our

[2] A mean-preserving spread is a special case of second-order stochastic dominance, when the means are equal, thus our results extend to this case.

model predictions using data from the Arvin-Edison Water Storage District in the southern San Joaquin Valley of California.

3. Empirical Analysis

In this section, we test the relationship between investment in conservation technology and the probability distribution of the price of water. The null hypothesis that we test is based on the model in the previous section. In particular, we test whether a mean-preserving spread of the water price distribution affects adoption of water-conserving irrigation technology. Rejecting the null hypothesis would demonstrate that the price distribution has an effect on adoption of water-conserving irrigation technology and support the theory presented in Section 2.

The data set is unique and highly useful in that the unit of observation is an individual field. This characteristic was already exploited in the previous section, which is based on largely the same data set. The data set includes information about the technology, crops produced, and agronomic characteristics of the fields. An ordered probit regression is used to estimate the probability of adopting water-conserving irrigation technology.

1. Empirical Model

Actual input-output coefficients are not directly observed in this data set, however, we observe the type of irrigation technology employed by the producer on each field in the sample. Irrigation technology efficiency is measured in terms of evapotranspiration per unit of applied water, that is, the percent of applied water that the plant utilizes. In general, irrigators can choose among three types of irrigation technologies: gravity, high pressure or low pressure irrigation technologies. Gravity irrigation includes the "traditional" technologies such as furrow or flood irrigation systems. These technologies are the least efficient, with efficiency ranging from 70–85%. High pressure technologies include sprinkler technologies such as center pivot and mechanical-move sprinklers. Sprinklers have a medium level of efficiency, ranging from 75–85%. Low pressure technologies include drip and microsprinkler irrigation systems. These are the most efficient, with efficiency ranging from 85–95%. These technology choices are ordered in terms of efficiency as well as cost. The least efficient systems (gravity) are the least expensive while the most efficient systems (low pressure) are the most expensive.[3]

We can make inferences about the irrigator's preference for conservation by analyzing the choice of technology. Although the technology choice is discrete, ordering the technology choice by efficiency reflects the ranked nature of the choices in terms of conservation. Let T^* represent the unobserved input-output coefficient of conservation technology and assume that it is a linear function of net benefits from investing in conservation technology, that is,

$$T^* = \boldsymbol{b}'x + \boldsymbol{e}$$

[3] See Caswell (1983) for a detailed description of irrigation technology used in California agriculture.

where x is a matrix of the explanatory variables, b is a vector of coefficients and e is the error term, which is assumed to have a standard normal distribution. Technology choice, which can be defined in terms of T^* :

$$T = \begin{cases} 0 & \text{if} \quad T^* \le m_1 \\ 1 & \text{if} \quad m_1 < T^* \le m_2 \\ 2 & \text{if} \quad T^* > m_2 \end{cases}$$

where $T = 0$ indicates gravity technology is observed, $T = 1$ indicates high pressure technology is observed, and $T = 2$ indicates low pressure technology is observed. The m's represent the cut-off points in the distribution for each choice of technology; these parameters are estimated in the model.

We estimate the following probabilities:

(III.16)
$$\begin{aligned} &\text{Prob}(T=0) = \Phi(m_1 - b'x), \\ &\text{Prob}(T=1) = \Phi(m_2 - b'x) - \Phi(m_1 - b'x), \\ &\text{Prob}(T=2) = 1 - \Phi(m_2 - b'x). \end{aligned}$$

Equation (III.16) provides the structural model for the ordered probit estimation of the probability of adopting water-conserving technology.[4] In the following sections we describe our data and estimation results.

2. Data

The data set used in this analysis is a sample of 1,224 agricultural fields serviced by the Arvin Edison Water Storage District. The data set includes information on soil characteristics, irrigation technology and water source for 92,294 acres of land in 1993. It was compiled from customer records maintained by the district. The data set categorizes irrigation technologies used in the district into three categories: gravity, high pressure and low-pressure technologies. We estimate the probability of adopting conservation technologies using this discrete, ordered variable. Next we consider the variables we use on the right hand-side of our estimation model.

Caswell and Zilberman (1986) show that soil quality is an important determinant of irrigation technology adoption. To control for the effect of soil quality on the decision to adopt irrigation technology, we included two soil quality variables in our estimation: soil permeability and field slope. Soil permeability is measured in inches per minute and describes how fast the soil drains, or conversely, how poorly it retains moisture. Because pressurized technologies can distribute water more evenly over time, these technologies may help improve the soil's water storage capacity relative to gravity systems. Thus we expect soil permeability to have a positive effect on adoption. Field slope describes the grade of the field. This variable is measured as a percentage, where a higher percentage indicates a steeper slope. Since gravity irrigation technologies are

[4] The model does not include a constant as a right-hand side variable.

difficult to implement on sloped fields, we would expect slope to have a positive effect on adoption of pressure technologies.

The data also include the size of each field in acres. Field size can be used to control for scale economies in technology adoption. If there are scale economies associated with conservation technology adoption, we would expect the probability of adoption to increase with field size. Summary statistics for field characteristics are given in Table III.1.

Table III.1. Summary Statistics for Field Characteristics.

Variable	Mean	Standard Deviation	Minimum	Maximum
Soil Permeability (in/hr)	2.80	3.00	0.13	13
Slope (%)	1.58	1.32	0.50	10
Field Size (acres)	50.78	52.66	1	490

The crops included in this data set are citrus, deciduous, vine, and truck crops.[5] Because we are interested in the difference in response to a change in the variance of water price by crop types, we categorized crops into permanent and annual crops. Permanent crops in the data set include citrus, deciduous, and vine crops. Truck crops make up the annual crop category.

Arvin-Edison has two service areas, which have the same mean price, but differ in terms of price volatility. Water rates in the District are set so that the mean input price (including lift for ground water users) is the same for both service areas. However, ground water levels are variable, and the price of ground water fluctuates from year to year. Surface water prices and delivery amounts are constant in the District, owing to Arvin-Edison's extensive conjunctive use facilities. Thus with this data set, we can analyze the effect of a mean-preserving spread in water price on conservation choice by considering the effect of switching from the more reliable water service to the more volatile water service area.

The data set denotes the source of water to the field as a binary variable (*Volatile*), which is coded as 1 if the field is in the volatile service area. The conceptual model predicts that the effect of switching from surface water to ground water may decrease the incentive to adopt pressure technology for fields in permanent crops, and may increase the adoption incentive for fields in annual crops. We evaluate the effect of switching to the volatile service areas on technology choice and control for field size and soil quality.

[5] Truck crops include lettuce, processing tomatoes, and carrots.

3. Estimation Results

Following the conceptual model developed above, we consider the impact of a mean-preserving decrease in the variance of the price of water on technology adoption. We estimate the probability of adopting a conservation technology using an ordered probit. Our model includes service area, crop choice, an interaction dummy variable for service area and crop, soil permeability, and slope as regressors.

Table III.2 presents the ordered probit estimate of the probability of adopting water-conserving technology. All the explanatory variables except soil permeability and the dummy for reliability are statistically significant at the one percent level. The interaction dummy (ground* permanent) for service area and crop type is statistically significant. Reliability and the interaction dummy are jointly significant at least at the 1 percent level. Interpreting the coefficients from the ordered probit estimation is more intuitive when we consider the effect of the explanatory variables on the probability of adoption.

Table III.2. Ordered Probit Estimation Results.

Variable	Estimated Coefficient	Standard Error	*p*-value
Volatile (0/1)	0.1297	0.1339	0.333
Volatile* Permanent (0/1)	–0.5112*	0.1546	0.001
Field Size	0.0027*	0.0007	0.000
Permeability	0.0055	0.0120	0.646
Slope	0.3948*	0.0314	0.000
Permanent (0/1)	.1942**	0.1147	0.0900
m_1	.5654	0.1143	
m_2	1.1886	0.1143	
Test	$\hat{b}_{\text{volatility}} = 0 = \hat{b}_{\text{vol*perm}}$ $x^2(2) = 22.77$ $p - \text{value} = .0000$		

* Statistically significant at the 1% level.
** Statistically significant at the 10% level.

Although the volatility variable is not significant, the volatility/permanent interaction variable is highly significant and the two variables are jointly significant. These results provide evidence in support of our model: the type of activity and price distribution matter in the technology choice. To examine how much service area and crop choice matter, consider the discrete effect for permanent and annual crops are computed in Table III.3.

In Table III.3, we consider how the probability of adopting each of the three types of technologies changes when the field switches to the price volatile service area. For fields in annual crops, increasing price volatility *increases* the probability of adopting low pressure technologies by 5 percent. The effect on high pressure technologies is negative but small. This corresponds to the case where elasticity of utilization is relatively high. Looking at the results for fields in permanent crops, we find that a shift to a more volatile price distribution *decreases* the probability of adopting low pressure technologies by nearly 12 percent. These results suggest that input price risk has a large influence on adoption of conservation technology and that these effects depend on the type of economic activity.

Table III.3. Adoption Effects for Annual and Permanent Crops.

	Annual Crop			Permanent Crop		
	Predicted Probability			Predicted Probability		
Technology	Groundwater	Surface Water	Discrete Effect	Groundwater	Surface Water	Discrete Effect*
Furrow	36.74%	41.73%	–4.98%	49.14%	36.33%	12.81%
Sprinkler	24.46%	24.34%	.12%	23.49%	24.45%	–.96%
Drip	38.79%	33.93%	4.86%	27.37%	39.22%	–11.85%

*Change in probability of adopting when switching from surface to groundwater areas.

Now we evaluate the marginal effects on the probability of adopting with respect to the continuous variables. Table III.4 computes the elasticities of the probability of adopting each of the technologies with respect to the continuous variables. All the variables are evaluated at the sample means. The effect of field size is positive. Conserving technology is more likely to be adopted on a larger field. This reflects the possible economies of scale associated with adopting newer technologies. Soil permeability is positive. One would expect better draining soil to be more conducive to pressure technologies, however the coefficient is not significantly different from zero. Slope is positive and significant. More sloped fields are more likely to have pressure technologies since gravity is difficult to implement on slopes.

Table III.4. Elasticities Evaluated at the Sample Means.

	x_i		
Elasticities	Field Size	Soil Permeability	Field Slope
Furrow	–12.75	–1.50	–58.76
Sprinkler	1.20	0.14	5.52
Drip	14.48	1.71	66.74

4. Conclusion

In this section we explore the impact of input price risk on conservation technology adoption and model technology as putty-clay. The theoretical model developed shows that, unlike the option value literature, the impact of increasing price risk can have an ambiguous effect on adoption of conservation technology. We show that the level of activity responsiveness to input price determines the effect of price risk on conservation technology adoption. We also extend the technology adoption literature led by Hausman (1979) and Caswell and Zilberman (1986) by introducing price risk into the adoption decision.

An empirical analysis of irrigation technology adoption in the San Joaquin Valley supports our model. Our empirical analysis predicts that a mean preserving spread of the input price distribution can increase or decrease adoption. When the agent's activity is relatively price elastic, such as production of an annual crop, price risk increases adoption of conservation technology. When the agent's activity is relatively price inelastic, as in permanent crop production, price risk decreases adoption.

The policy implications of our results are two-fold. First policy makers should consider reliability and conservation policy jointly. As our results indicate, response to conservation may differ for different types of activities. Second, policy makers can use results from the model presented in this section to more effectively encourage resource conservation. These issues may become particularly important in energy markets. As deregulation in energy markets continues, increasing price volatility may result, as has been observed in California.

IV. Pricing and Conservation Policies at the Retail Level

1. Introduction

Retail pricing by water agencies is usually based on average cost and is likely to lead to economic inefficiency. The costs associated with this inefficiency are likely to increase as water availability declines. Block rate pricing (Wichelns, 1991a, 1991b) and various water marketing schemes (Howe et al., 1986) have been important components of proposals for water pricing reform.

This section analyzes policy options available to retail water agencies. These policies are (i) average cost pricing with the administration of quota allocation; (ii) block rate pricing; and (iii) a transferable water rights regime.

The main obstacle to efficient water allocation within a water agency is asymmetric information: aggregate available water is known to the central decision maker whereas at farm level the individual farmers know (and tend not to reveal) the efficient amount of water required for each crop (see Zusman, 1991). This analysis shows that reform based water rights that are relatively transferable may lead to welfare improvement with minimal information required, despite the reduction in overall water use. It also shows that tiered pricing does not necessarily lead to an efficient outcome. The properties of these three policy options are compared, and a numerical example is based on data from Israel.

Some of the literature on water pricing (Burness and Quirk, 1979; Gisser and Sanchez, 1980; Gisser and Johnson, 1983; Howe et al., 1986; Zilberman and Shah, 1994) recognizes the sub-optimality of a traditional water pricing system and recommends transition to a more market-like allocation of water, although these papers do not include a revenue constraint relevant to the non-profit nature of water utilities. The water pricing policies considered in this section are subject to the balanced budget constraint of the water agencies. Furthermore, it is assumed that water rights are defined by the water use level prior to a water supply reduction, rights which must be considered by the water agency in response to supply cuts. Historical usage patterns are of crucial importance in allocating water with prior appropriation and other water rights systems. We expand Zusman's (1988) model of cooperative behavior to obtain optimal water pricing and allocation as well as income distribution taking previous water use levels into account. Also new in this section, we explicitly incorporate heterogeneity among farmers in the analysis.

We have these theoretical results. A Hicksian barter market will result in Pareto efficiency if the following conditions exist: information is perfect, trading is costless and the management allocates "initial endowments" of water according to the historical rights of the farmers. When trading is not costless and information is imperfect, an alternative policy option of "passive trading" with internal price quotation by the management achieves Pareto efficiency. It is also shown that under realistic assumptions, tiered pricing results in a second best allocation.

2. Modeling the Existing and Optimal System

Let us assume that a regional water agency consists of N farmers. The supply of water is generated from two origins: local underground water from wells within the area, and surface water imported from outside. The quantity of water used by the region is regulated by the State as follows: maximum amount of local underground water is fixed, while water from outside the region, $Q - Q_L$, can be purchased from other districts in such quantities as required. It is assumed that water from both sources are of the same quality. However, the cost per unit of local water, w_L, is fixed and lower then w_e, the cost per unit of imported water. Thus, the region faces a two-step supply function with the following properties:

$$MC(Q) = \begin{cases} w_L > 0 & 0 < Q < Q_L \\ w_e > 0 & Q_L < Q \end{cases}.$$

The average cost function of generating water to the region decreases at the range $0 < Q < Q_L$ and increases asymptotically towards w_e at the range $Q > Q_L$.

Let $f^n(q_n)$ be the n^{th} individual benefit from water use, measured by the dollar value obtained by application of q units of water. This benefit function may represent gross revenue, if water is the only scarce input, or revenue net of fixed input, assuming that water is the only scarce variable input. The function $f^n(q_n)$ is well behaved with $f_q^n(q) > 0, \quad f_{qq}^n(q) < 0$. Note that the water demand function of the n^{th} individual is given by $f_q^n(q)$.

The aggregate demand curve for water consists of the horizontal summation of the *N* individual water demand curves. For each given price, the aggregate quantity is the sum of the quantities demanded by the individuals.

1. Inefficient Allocation with Average Cost Pricing

Assume that under the initial system, the water agency sets a price for water that will both satisfy farmers' demands and balance the water agency budget. The equilibrium conditions in this case are

(a) $$f_q(q_n^0) = w_0$$

(b) $$w_0 = AC(Q_0),$$

where w_0 is the initial price of water, q_n^0 is the quantity of water used by the n^{th} farmer under the initial system and $Q_0 = \sum_{n=1}^{N} q_n^0$ is the aggregate water use under the initial system. Equation (a) states that water use for the n^{th} individual is where the marginal benefit from water (inverse demand) is equal to the water price. Equation (b) states that under the initial system, average cost pricing is used for the price of water. It is almost trivial to say that such a policy results in inefficient resource allocation, i.e., the quantity Q_0 is greater than the optimal quantity Q_e which results from the intersection between the *MC* curve and the aggregate demand curve, *D*. (It is assumed that the intersection point occurs at the upper segment of the *MC* curve.)

2. Optimal Allocation and Pricing

Suppose that the water agency has central management which aims at developing an optimal pricing policy with the following criteria:[6]

a. Efficient water allocation.
b. Balanced budget.
c. Equity-rent distribution in proportion to historical water use.

Studies of water allocation design suggest that water reform seems more equitable and thus politically acceptable if the reform recognizes historical rights. An efficient resource allocation of water in the region is obtained by maximizing the aggregate welfare function of the farmers in the region.

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[6] Fudenberg and Tirole (1991) identify properties a, b, and c as necessary to obtain an efficient sustainable rate design.

(IV.1) $$\max_{q_1,\ldots,q_n} \quad \sum_{n=1}^{N} f^n(q_n) - C(Q)$$

$$\text{s.t. } Q = \sum_{i=1}^{n} q_n \ .$$

The necessary conditions which ensure the maximization in (IV.1) consist of the *n* equations,

(IV.2) $$f^n_{q_n}\left(q_n\right) = MC\left(Q\right).$$

These equations imply that each farmer equates the value of the marginal product of water to the marginal cost of generating *Q* units of water.

Let $h\left(q_n, q_n^h\right)$ denote the payment function, i.e., the rule which determines the amount of payments by each farmer where q_n is the amount of water delivered to the farmer, and q_n^h is the historical water use right. At the micro level each farmer maximizes quasi-rent,

(IV.3) $$\max_{q_n} \quad f^n\left(q_n\right) - h\left(q_n, q_n^h\right).$$

The necessary conditions for solving the individual farmer's optimization problem imply that each farmer equates the value of the marginal product of water to the marginal payment charged for water,

(IV.4) $$f^n_{q_n}\left(q_n\right) = h_q .$$

Thus, (IV.2) and (IV.4) result in

(IV.5) $$MC(Q) = h_{q_n} .$$

which implies marginal pricing.

Now, for simplicity, assume that the payment function has a linear form and depends on the actual use of water and the historical rights. Thus,

(IV.6) $$h\left(q_n, q_n^h\right) = Aq_n + Bq_n^h .$$

The no-profit constraint implies that the sum of payments of the *N* farmers equals the total costs of generating *Q* units of water, i.e.,

(IV.7) $$\sum_{n=1}^{N} \left[h\left(q_n, q_n^h\right) \right] = C\left(Q\right).$$

Introducing (IV.6) into (IV.7), and using (IV.5), *B* results in, (IV.8) $$B = \frac{C(Q) - MC(Q)Q}{Q^h} = \left[AC(Q) - MC(Q)\right]\frac{Q}{Q^h}.$$

where $Q^h = \sum_{i=1}^{N} q_n^h$ and $AC(Q)$ are the average costs. Since average costs are less than marginal costs $(C' > 0)$, B is negative, and thus under optimal pricing farmers are paid for their historical water use rights. The per unit rent of historical water use rights is $-B$.
Rewriting equation (IV.6),

(IV.9) $$h(q_n, q_n^h) = MC(Q)q_n + \left[\frac{C(Q) - MC(Q)Q}{Q^h}\right]q_n^h.$$

The payment function (IV.9) depicts the two goals of the optimal policy: the first, efficient water allocation, i.e. each farmer pays the marginal costs of water for the actual quantity used by him, and the second, water rent distribution in proportion to the historical water use rights.

The pricing rule (IV.9) can be written differently. Let $s_n = q_n^h / Q^h$ be the share of the n^{th} individual in the historical rights. Then, his "adjusted" water right is obtained by calculating his share in the total quantity used, i.e., $q_n^r = s_n Q$. Thus, the allocation rule can be presented as:

(IV.10) $$h(q_n, q_n^h) = MC(Q)\left[q_n - q_n^r\right] + AC(Q)q_n^r.$$

According to equation (IV.10) the individual pays average costs for his adjusted rights and when $q_n > q_n^r$, he also pays the marginal costs for the difference between actual use and adjusted rights. When $q_n < q_n^r$, he receives this difference. Several payment schemes can be based on equations (IV.9) and (IV.10).

3. Policy Options

Assume that the policy maker knows the aggregate demand and supply, but not the individual demands; two policies are optional. The first option is the "active trading" policy. At the beginning of each time period (e.g., a year or season), the water agency determines the optimal aggregate quantity, Q_e, at the intersection of the aggregate demand and supply and allocates individual annual rights in proportion to the historical rights $q_n^r = s_n Q_e$. Each farmer pays for each unit of his "initial endowment" of water rights the price of $AC(Q_e)$, i.e., the average costs of generating the aggregate quantity Q_e. This ensures a balanced budget. Farmers are allowed to trade their water rights. Assuming a perfect competitive market with costless trading, the market will determine the equilibrium price w_e. At this price each farmer may have an excess demand (supply) according to whether the sign of $f_q^n(q_n^r) - w_e$ is positive (negative). Assuming also, that trading is conducted at a given place and time, the price, w_e, will clear the market with a rent per unit of water rights: $w_e - AC(Q_e) = r$.

The second option is called "passive trading" policy. At the beginning of each time period, the water agency determines and announces the optimal price, w_e, at the intersection of the aggregate demand and supply. Each farmer applies the amount of water, q_n^e according to his individual demand at w_e. The summation of all the quantities, q_n^e, used during the time period, will result in an aggregate quantity Q_e. At the end of the time period, the water agency calculates the imputed price of a unit of water rights that equals $r = w_e - AC(Q_e)$. The water agency also calculates the periodical individual water right as $s_n^r Q_e$. For each period the farmer will be entitled to receive $s_n^r Q_e r$. Thus , the total water expenditure of the n^{th} farmer will be

(IV.11) $$q_n^r AC(Q_e) + r\left(q_n^e - q_n^r\right).$$

Note that *ex-post* (at the end of the period) a farmer is a "buyer" ("seller") of water according to whether the sign of $q_n^e - q_n^r$ is positive (negative), and he pays (receives) the amount $r\left(q_n^e - q_n^r\right)$. Thus, the "passive" market has the characteristic whereby the participant buyer (seller) does not have to pursue a matching seller (buyer).

For the passive trading policy, a unique market place is not needed. Each farmer determines his water use at the price determined by the central management. In both cases, the distribution of the water use rights is predetermined according to historical shares (e.g., riparian rights along a river, see Anderson, 1983). For the active trading policy, the periodical water rights result from the policy maker's *ex-ante* estimation of Q_e, while for the passive trading policy, the periodical water rights result from the *ex-post* summation of the quantities used by the individual farmers at a unique price, w_e, as announced by the water agency.

Water markets exist in some localities, e.g., the water law in New Mexico allows trading in consumptive use of surface water rights. In other localities, institutional water trading is absent. Institutions for active trading would have to be created, including new trading channels, legislative framework and detailed registration of the bilateral transactions. Hence, active trading has substantial transaction costs. Central decision making by water agencies may be less costly, explaining the absence of water markets in some localities. However, the inefficiencies resulting from administrative allocation under asymmetric information may be higher than "active trading" transaction costs.

4. Effects on the Distribution of Income

Income is redistributed by policy reform from average cost pricing to either active or passive trading. We index average cost pricing with a 0 subscript, and policy reform with a subscript of 1. For average cost pricing, the aggregate quantity of water used is Q_0, and its price is equal to

AC_0. Policy reform results in a price increase from AC_0 to w_e with aggregate quantity and the average cost decreasing respectively to Q_1 and AC_1. Also, given the historical shares, each of the *n* individual water use rights decreases from $q^r_{n_0}$ to $q^r_{n_1}$.

Consider the case of two farmers, *i* and *j*, with equal water rights. The demand curves of farmers *i* and *j* are denoted respectively as f^i_q and f^j_q. Farmer *i* obtains a higher income using the same quota and therefore he is considered to be more efficient. Under policy 1, farmer *j* (the seller) will use less than his rights and farmer *i* (the buyer) will use more than his rights. Neither of them will be adversely affected by the reform if the following holds,

(IV.12) $$\left(w_e - AC_0\right) q^r_{n_0} \le \left(w_e - AC_1\right) q^r_{n_1}.$$

Equation (IV.12) implies that the total water rent does not decrease after the implementation of the reform. A necessary condition for (IV.12) is that the arc elasticity of the *AC* curve is equal to 1 (which also implies that the elasticity of the cost curve equals 2).[7] The income impact on each of the two individuals depends on whether or not condition (IV.12) holds.

(*I*) If (IV.12) holds, then it can be verified that farmer *j* benefits more than farmer *i* from the reform.
Proof:
(*a*) The case of equal historical shares of *i* and *j*.
Given that the elasticity of the *AC* curve equals 1, the area of the rectangular *fghd* (which measures the increase in water rent resulting from the reform for both farmers) is equal to the area *cdak*. Since *aed* < *abcd* < *cdak*, although both farmers benefit from the reform, farmer *j* benefits more than *i*.
(*b*) The case of unequal historical shares of *i* and *j*.
In this case farmer *j* benefits from the reform *relatively* more than *i*. It can be easily verified by normalizing the water use rights of both farmers to 1 and using the procedure as in (*a*).

(II) If, however, condition (IV.12) does not hold and the elasticity of the *AC* curve is smaller, some of the farmers are worse off as a result of the reform. The relative reduction in the regional water rent can be measured by $r_1 Q_1 / r_0 Q_0 < 1$. The smaller the elasticity of the *AC*, i.e., the larger the number of farmers that will be disadvantaged.

5. An Alternative Pricing Policy: Tiered Prices

Block pricing, a common pricing method employed in the electricity and natural gas industries, was introduced recently as tiered pricing in some water agencies in California. A two-block rate design[8] consists of a two-step payment function as follows,

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[7] Note that the average cost elasticity equals to $\frac{\partial AC}{\partial Q}\frac{Q}{AC} = \frac{MC}{AC} - 1 = \lambda - 1$ where λ is the cost elasticity.

[8] The implementation of tiered pricing may be much more complex. Here we use a simple general form. Most of the results obtained here are preserved for other forms of tiered pricing.

(IV.13) $$h(q,q^r) = \begin{cases} w\left(q - \boldsymbol{g} q^r\right) + \boldsymbol{d} w \boldsymbol{g} q^r & \text{if } \left[q(w) \geq \boldsymbol{g} q^r\right] \\ \boldsymbol{d} w q & \text{if } \left[q(w) < \boldsymbol{g} q^r\right] \end{cases}$$

where $q^r, w, \boldsymbol{g}$ and $\boldsymbol{d}$ are determined by the water agency. The first two parameters measure the assigned water quota of the n^{th} individual farmer and the price of water, and the two last parameters are between 0 and 1.

This payment function is linear in q in two segments with a discontinuous jump at $\boldsymbol{g} q_n^r$. The farmer pays a reduced price, w, for the first $\boldsymbol{g}$ percent of his water quota q_n^r, and full price, w, for additional water, $\left(q_n - \boldsymbol{g} q_n^r\right)$.[9] This payment function should be compared to the payment function described by equation (IV.9), which is linear over the whole range of q_n. Note that some farmers may not use water efficiently for some parameter ranges. This can be verified by applying the individual optimization conditions (see equations (IV.4) and (IV.5)) to the case of the tiered pricing, deriving three types of behavior by the farmers:

(IV.14a) Type j: $f_q^j\left(\boldsymbol{g} q_j^r\right) < MC(Q)$ where $q_j^e < \boldsymbol{g} q_j^r$,

(IV.14b) Type k: $f_g^k\left(\boldsymbol{g} q_k^r\right) \geq MC(Q) \geq f_g^k\left(q_k^r\right)$ where $\boldsymbol{g} q_k^r < q_k^e < q_k^r$,

(IV.14c) Type i: $f_q^i\left(q_i^r\right) > MC(Q)$. where $q_i^r < q_i^e$,

where q_j^e, q_k^e, q_i^e are the economically efficient quantities for each type of farmer. While the individual farmers in groups of type k and i apply their water efficiently, i.e., $f_q^k\left(q_k^e\right) = MC\left(Q_e\right)$ and $f_q^i\left(q_i^e\right) = MC\left(Q_e\right)$, those in group type j apply their water inefficiently, i.e., $f_q^j\left(q_k^r\right) = \boldsymbol{g} MC\left(Q_e\right)$.

In general, the corresponding losses of water and welfare by the farmers of type j group can be calculated from

(IV.15a) $$\sum_{j=1}^{J}\left(q_j^t - q_j^e\right),$$

and

[9] The payment function may include a third segment where water use in excess of the water quota q_n^* will be charged an extra fine.

(IV.15b) $$\sum_{j=1}^{J}\int_{q_j^e}^{q_j}\left[f_q^j(q) - MC \right] dq \,.$$

As was characterized above, the regional water agency management follows the efficiency rule $w = MC$ which determines the efficient aggregate quantity Q_e, subject to the balanced budget constraint. The water quotas q_n^r of each of the individual farmers are determined exogenously by the management relative to the historical water rights subject to

(IV.16) $$Q_e = \sum_{n=1}^{N} q_n^r \,.$$

The choice of the parameters is subject to the balanced budget constraint in (IV.7), i.e., $0 \le \boldsymbol{d} \le \dfrac{AC(Q_e)}{MC(Q_e)}$ and $\left[1 - \dfrac{AC(Q_e)}{MC(Q_e)}\right] \le \boldsymbol{g} \le 1$.

Maximum reduction of inefficient use of water by type j farmers can be achieved by choosing either:

(a) $\boldsymbol{d}$ and $\boldsymbol{g} = \left[1 - \dfrac{AC(Q_e)}{MC(Q_e)}\right]$.

(b) Allowing trading in water rights.

Note that the effectiveness of condition (a) is reduced as the heterogeneity of water requirements among crops and among farmers is increased. Hall and Hanemann (1996) argued that a policy based on (a) may not be politically feasible due to equity considerations.[10]

In the case of water trading (b), efficient allocation implies

(IV.17) $$\sum_{j=1}^{J}\left(\boldsymbol{g} q_j^r - q_j^e\right) = \sum_{i=1}^{I}\left(q_i^e - q_i^r\right).$$

The quantities scheduled for sale by type *j* farmers must equal the quantities scheduled for purchase by type *i* farmers. Note that for the type *k* farmers the following inequality holds

(IV.18) $$\sum_{k=1}^{K} q_k^r > \sum_{k=1}^{K} q_k^e \,.$$

Therefore, by using (IV.17) and (IV.18), it can be verified that

[10] Under policy (a) the average charge per unit of water for farmers who use small amounts of water is significantly lower than the average for those who use large amounts of water.

(IV.19) $$\sum_{n=1}^{N} q_n^r > \sum_{n=1}^{N} q_n^e ,$$

which contradicts (IV.16). Note that information on the distribution of type j, k and i is needed for complete efficient allocation given the constraint in (IV.19). Thus, more information is needed for efficient implementation of tiered pricing than the information needed for the implementation of a market mechanism.

An alternative policy for reducing the loss caused by the type j farmers is to abandon historical rights and to design a block rate on a crop basis. Such a policy requires detailed information concerning the production functions of each crop and as pointed out by Hall and Hanemann (1996), involves a trade-off between efficiency and transaction costs.

6. Conclusion

This section compares policy options to allocate water in response to reduced water supply. Average cost pricing with quota reductions results in administratively inefficient pricing and allocation.

Economists suggest water markets as a remedy, but the absence of well-defined property rights and high transaction costs remain barriers to this solution. According to Coase (1992), "if the costs of making an exchange are greater than the gains which that exchange would bring, that exchange would not take place, and the greater production that would flow from specialization would not be realized." The "passive trading" policy developed in this section enables a trade of water use rights with low transaction costs. The passive trading enables an efficient allocation with minimal losses by farmers and therefore minimal political resistance by them. This is made possible by increasing the welfare resulting from the use of water and establishing quasi rights related to historical use. The greater the "pie" the easier it is to redistribute it between the farmers. In the long run the increased "pie" enables the diversion to higher value products and water saving technologies.

Water institutions and their laws in many states do not allow trading in water use rights. Tiered prices have recently been suggested as an efficient pricing method. It is shown in this section that under reasonable assumptions tiered prices lead to a "second best" solution. Passive trading results in a Pareto efficient allocation and does not require new water legislation. Such a policy could also be useful in other price pooling systems, such as production and marketing boards.

V. Water Trading and the Cost of Reallocating Water from Agriculture

I. Introduction

Agriculture in the western United States, particularly California, is highly dependent on the diversion of water resources for irrigation. At the same time, population growth, increased industrialization and, most importantly, heightened public awareness of environmental benefits from enhancing instream flows are all exerting tremendous pressure on federal and state agencies to reduce these diversions. This section presents a framework for assessing the costs of reducing agricultural water supplies and applies this method to California agriculture.

The design of this framework recognizes some of the unique features of water resources use and management, in particular:

- Barriers to trade in water resulting from the water rights regime. The analysis will consider alternative implementation procedures for the water supply cuts, varying the extent to which water trading is allowed and the regions affected by their water supply cuts.
- Heterogeneity in terms of cropping patterns and water availability and productivity among regions.
- Multiplicity of responses to water supply reductions including: (a) changes in land allocation among crops, (b) adoption of water conserving practices, (c) use of ground water, and (d) fallowing of lands.

The modeling framework was developed to provide inputs to policy makers in assessing alternative versions of the Central Valley Project Improvement Act (CVPIA) and provides various measures of economic impacts, including impacts of supply cuts on producers' surplus, producers' revenue, state product, employment, and irrigated acreage. Furthermore, recognizing the large uncertainty regarding producers' behavior and water productivity in crop production, differences between responses in the short run and the long run, and data and computational constraints, the empirical analysis does not rely on one comprehensive model that incorporates all aspects of the problem at hand. Instead, this section presents an overall conceptual framework but obtains policy impacts from three empirical models, each emphasizing different aspects of agricultural water use in the Central Valley.

The section is structured as follows. Section 2 below provides background on the economics of agricultural water use in general and the particulars of the California policy problem. Section 3 provides a conceptual model and analysis of the impacts of water supply reduction policies. The particulars of the California policy problem and the three empirical models used to analyze it are presented in Section 4. Section 5 presents the empirical findings, and conclusions and direction for further research are presented in Section 6.

2. A Conceptual Model of the Economic Impacts of Water Supply Reduction

The modeling framework applied here is taken from Sunding et al. (2001), and consists of a microeconomic model of resource allocation by the irrigated agricultural sector. Optimization is conducted subject to water supply reductions and economic relationships that provide additional assessment measures, including estimated impacts of supply response on employment and gross regional product.

The model recognizes the heterogeneity of producers, by assuming that production is carried out by J micro production units of various sizes. Such units may be interpreted as farms, water districts, or counties depending on the application and the data available. The micro unit indicator is j, $j = 1, J$; and the land base of each unit is denoted by L_j. It is assumed that there are no constraints on water movement within the micro units, but there may be barriers to trade and transfer of water between micro units. Indeed, water rights regimes, such as the prior appropriation system and riparian rights systems, restrict trading; and one major features of a policy reform is the extent to which water trading is allowed.

The analysis is conducted for $N + 1$ water policy scenarios, with n a scenario indicator $n = 0, 1, 2, ..., N$. The scenario $n = 0$ corresponds to the pre-regulation or base water allocation. Under each scenario, microunits are aggregated into regions. Water trading is feasible within regions but not between regions. Let K^n be the number of regions under scenario n and k^n be the region indicator, so that $k^n = 1, ..., K^n$. The set of microunits in region k^n is denoted by R_k^n. For example, if we have eight microunits divided into two regions under scenario n, $R_1^n = \{1,2,3,4\}, \quad R_2^n = \{5,6,7,8\}$.

Each microunit has an initial "endowment" of surface or ground water representing annual surface water rights and ground water pumping capacity. Let $\overline{S}_j$ be annual surface water available to district j in the base scenario and $\overline{G}_j$ be annual ground water available to district j. Alternative policy scenarios affect these water availability constraints.

In the base scenario, total water available to region k^n is $\sum_{j \in R_k^0} \left(\overline{S}_j + \overline{G}_j\right)$. However, surface water availability differs among alternative scenarios. Let ΔS_k^n be the reduction of water supply available to region k^n. The overall surface water supply reduction in scenario n is

$$\Delta S_n = \sum_{k^n=1}^{K_n} \Delta S_k^n.$$

This change reflects the total amount of water reallocated from agriculture. Actual use levels of ground and surface water at region j are denoted by G_j and S_j, respectively, with $S_j < \overline{S}_j$ and $G_j \le \overline{G}_j$.

Following theory and empirical evidence, Sunding et al. (2001) suggest that California growers have responded to reductions in water supply by (i) changing land allocation among crops (ii) increasing the amount of ground water pumping, and (iii) modernizing their water application methods (on this point, see also Moreno and Sunding, 2001; Green and Sunding, 1997; Green et al., 1996; and Zilberman et al., 1995). The modeling of production relationships makes these choices feasible here. There are I crops and i is the crop indicator, $i = 1, I$. Let the amount of water applied to crop i in microunit j be denoted by A_{ij} and let L_{ij} be the amount of land allocated to the production of crop i at microunit j. Let Y_{ij} be the output of crop i at microunit j. For modeling convenience, total output is represented as the product of yield per acre, y_{ij}, and acreage of crop i in microunit j is $Y_{ij} = y_{ij} L_{ij}$.

Output is produced by land, labor, irrigation equipment, and other inputs (e.g., chemicals), and is affected by local environmental conditions. The general specification of the per acre production function is

$$y_{ij} = f\,(L_{ij}\,,\, a_{ij}\,,\, z_{ij}\,,\boldsymbol{\theta}_{ij}\,),$$

where

$a_{ij} = A_{ij} \,/\, L_{ij}$ (applied water per acre),

$z_{ij} = Z_{ij} \,/\, L_{ij}$ (annual irrigation equipment cost per acre),

Z_{ij} = total irrigation equipment cost on crop i in microunit j,

and

$\boldsymbol{\theta}_{ij}$ = regional environmental quality parameters.

This specification is consistent with the observations of Dinar and Zilberman (1991a) Specifically, they argue that increased annual irrigation equipment costs increase output by increasing irrigation efficiency, and that both land quality (in particular, water-holding capacity) and water quality (especially salinity) affect the productivity of water. Specific applications may have special functional forms, but all specifications maintain concavity. Yield per acre may decline as land use increases (i.e., $\frac{\partial y_{ij}}{\partial L_{ij}} \leq 0$) because of decreasing marginal productivity of land.

Let the cost of surface water at microunit j be W_j^s and cost of ground water be W_j^g.[11] Generally, $W_j^g > W_j^s$, so that surface water is cheaper than ground water. The cost of inputs other than water and irrigation technology are assumed to be a convex function of crop i acreage in microunit j and is denoted by the function $C_{ij}(L_{ij})$ with

$$\frac{\partial^2 C_{ij}}{\partial L_{ij}^2} \geq 0.$$

This cost function reflects the important empirical observation that land fertility is heterogeneous in California and that increases in acreage lead to increased expenditures on inputs, such as fertilizers, that augment land productivity.[12]

The most general specification of output markets would assume that producers face downward-sloping demand curves and that output prices are determined endogenously. In this case, the optimization problem will maximize the sum of producer and consumer surplus subject to resource constraints. In our model, we assume price-taking behavior and denote the price of

[11] These costs are delivery costs or water costs paid by users. Since we are interested in developing a regional optimization model that will provide competitive outcomes, we do not consider differences between private and public costs of obtaining water.

[12] We distinguish between dimensions of land quality such as water-holding capacity that affect productivity indirectly (for example, through their effect on the productivity of applied water) and other dimensions such as fertility that affect productivity directly.

output i by P_i. This assumption is consistent with the high demand elasticity that California producers face.

Assuming profit-maximizing behavior by growers, the aggregate regional optimization problems under scenario n are

(V.1) $$\Pi^n = \max \sum_{j=1}^{J} \sum_{i=1}^{I} P_i Y_{ij} - W_j^s S_j - W_j^G G_j - Z_{ij} - C(L_{ij}),$$

(V.2) $$\text{s. t.} \sum_{I=1}^{I} A_{ij} = S_j + G_j \quad \forall j,$$

(V.3) $$\sum_{j \in R_k^n} \left(S_j + G_j \right) \leq \sum_{j \in R_k^n} \bar{S}_j + \bar{G}_j - \Delta S_k^n \quad \forall k,$$

(V.4) $$\sum_{i=1}^{I} L_{ij} \leq L_j \quad \forall j.$$

Constraint (V.2) states that total water used in crops is comprised of either surface water or ground water. Condition (V.3) is the most important constraint as it sets a limit on the water available to each region under a given policy scenario. Availability is the sum of water available to districts under initial allocation minus the amount diverted under the specific scenario. Inequality (V.4) is the land availability constraint.

The solution of the regional optimization problem using Kuhn-Tucker conditions requires assigning shadow prices for each of the constraints. The shadow price of equation (V.2) is W_j^d. This is the shadow cost of water delivery and is equal to W_j^s if only surface water is used and W_j^g if ground water is used in district j. The shadow price of the regional water constraint (V.3) is V_k^n. Thus, the marginal cost of a unit of water in district j that belongs to region k under scenario n is $W_j^d + V_k^n$.

If the production function is differentiable, optimal water use per acre with crop i at district j is at the level where the value of marginal product of water is equal to the shadow price of water.

(V.5) $$P_i \frac{\partial f_{ij}}{\partial a_{ij}} = W_j^d + V_k^n \quad \forall_{i,j}.$$

Optimal irrigation cost per acre is determined similarly at the level where the value of marginal product of the expenditure is equal to its price. The next condition is

(V.6) $$P_i \frac{\partial f_{ij}}{\partial z_{ij}} = 1.$$

The shadow price of the land availability constraint in district j is r_j, and under standard assumptions, land is allocated to crop i in district j so that the value of marginal product of land is equal to r_j, i.e.,

$$(V.7) \qquad r_j = P_i f_{ij}(...) - \left(W_j^d + V_k^h\right) a_{ij} - z_{ij} - \frac{\partial C_{ij}}{\partial L_{ij}} + P_i L_{ij} \cdot \frac{\partial f_{ij}}{\partial L_{ij}} \; \forall i, j \;\; L_{ij} > 0.$$

Condition (V.7) states that the optimal acreage of crop i at district j is such that net marginal benefit of land is equal to its shadow price. Marginal net benefits of land are the difference between revenue added by marginal land and the extra cost of water, irrigation technology, and other inputs as well as the extra cost associated with the decline of land productivity. The conditions are more elaborate if there are land availability constraints for individual crops.

In principle, conceptual and empirical analysis requires solving the model under scenario 0, the initial condition, and then under each alternative scenario. The net income effect of a policy under the scenario denoted by $\Delta\Pi^n$ is the change in producer surplus between scenario 0 and scenario n, i.e.,

$$\Delta\Pi^n = \Pi^0 - \Pi^n.$$

It is expected that, for most scenarios, $\Delta\Pi^n > 0$, namely, reduction in water supply reduces overall income. But different scenarios assume different partitions of the regions. Under the initial scenario ($n = 0$), the state is divided into K_0 regions, where water trading is feasible within regions and where water trading is allowed between regions. Two types of scenarios are likely to be associated with a given reduction in overall surface water supply. Under water trade scenarios, trading is allowed throughout the state; under proportional cuts scenarios, the supply reductions to regions are proportional to initial allocations so that the reduction in surface water for regions under such scenarios, ΔS_k^n, is

$$\Delta S_k^n = \Delta\bar{S} \frac{S_k^0}{\sum_{k=1}^{K_o} S_k^0}.$$

By the La Chatelier Principle, given total supply reduction, aggregate profit is higher under the free trade scenario as there are fewer constraints. In some cases, a water reform that reduces surface water supply and allows trading may increase profit $\left(\Delta\Pi^n > 0\right)$ if gains from trading are greater than losses from surface water supply reductions.

Standard welfare analysis considers impacts on consumer and producer surplus, but policy makers may be interested in changes in other variables.[13] Other such variables are gross farm income, regional income, and employment.

[13] These impact measures were requested from us by the U.S. EPA for their use in designing water quality standards.

The gross income effect of scenario n, ΔR^n, is derived by subtracting gross revenues of scenario n from gross revenues of the initial scenario. As with net income, it seems that gross revenues will decline as aggregate water levels decline. However, under some scenarios, the reduced water supply may lead producers to adopt modern irrigation technologies, which tend to increase per acre yields (Caswell and Zilberman, 1986) but also entail higher production costs. Under these scenarios, the higher yield will result in increased revenues in spite of the overall water supply reductions.

The impact of water policy changes on the nonagricultural economy is another useful policy indicator. Let y_i be a regional impact coefficient, denoting an increase in regional product (both direct and indirect effects) associated with a \$1.00 increase in revenues of crop *i*. The reduction in regional impact associated with policy scenario n, ΔRNP^n is

$$\Delta RP^n = \sum_{i=1}^{N} \sum_{j=1}^{J} P_i \left(Y_{ij}^0 - Y_{ij}^n \right) y_i .$$

In most cases one expects regional product to decline as a result of reduction in water supply. However, if supply reduction is associated with increased water trading possibilities and higher water prices, regional income may increase because of adoption of conservation technologies that increase yield or increase water used for production of high value crops. These crops generate more revenue per acre-feet of water than low value crops and have stronger linkages to the non-agricultural regional economy due to their higher labor requirements.

The employment impact of a water policy change can also be calculated using standard multipliers. Typically, job loss is measured based on changes in gross revenues. Of course the scope of water trading should mitigate the total labor market impact of water policy changes, particularly if trading results in less high-value fruits and vegetables going out of production following a supply cut.

4. Alternative Impact Models

The impacts of reducing agricultural water supplies vary with the planning horizon. The immediate impacts of supply reduction may differ from longer run impacts since in the short run growers' flexibility is much more limited. Production function parameters, water availability, and costs are subject to much variability and randomness. Ideally, an impact assessment model should be versatile and comprehensive to generate various types of impact estimates. Unfortunately, a model that accounts for heterogeneity among growing regions and all dimensions of grower response to water supply changes does not exist and would be quite costly to construct. Instead, this section obtains policy impact estimates from three models, each emphasizing a different aspect of Central Valley agriculture. The results of these various models provide a range of impacts within which the actual outcomes are likely to lie.

The three impact models are special cases of the model presented above. They differ in their assumptions regarding production technologies and the set of responses that growers have in adjusting to changes. They also differ in the degree of detail in the data they use, in particular, the type and number of basic units of analysis they assume. A model that includes a response set with a wide variety of options requires a complex nonlinear programming algorithm and a large amount of data for each decision-maker. As the response set becomes smaller, fewer data are required for each unit. This lower data requirement per unit allows larger numbers of decision-making units to be considered. Thus, the models that allow more responses to policy changes have more aggregated basic units.

The models measure the impact of several policy scenarios that have three basic dimensions. The first dimension of the policy change is the level of the supply cut. Two levels of aggregate water supply reduction are considered. The lower level of 0.8 MAF corresponds to a requirement of annual enhancement of instream flows. The higher level of annual reduction is 1.3 MAF, and was derived by U.S. EPA and the U.S. FWS in the context of their work on endangered species protection.

The second dimension of the water allocation policies considered is the allocation of the aggregate cutback among growers. To a large extent, the final allocation of the supply reduction is an open question, depending on what state or federal agency takes responsibility for the decision. If the State of California makes the decision, then all water users in the State whose consumption affects Bay/Delta flows are potential targets for cutbacks. However, if the federal government implements the reduced diversions, then only CVP users are liable for the reductions. Thus, the allocation of the cuts is treated as a choice variable, and a variety of initial allocation schemes are considered.

Third, the extent of water trading is currently a policy choice, particularly for the State of California. Trading is highly active within small units such as water districts, and a large volume of water is traded between neighboring districts within the CVP system. There is, however, controversy about how much water can and should be traded among growers, between growers and urban areas, and between basins. Further, there are physical constraints on conveyance that are, at present, hard to define precisely due to hydrological uncertainties and constantly changing regulatory restrictions on pumping. Thus, the scope of the water market is treated here as a policy variable, and the impact models are used to examine a wide array of trading scenarios.

The following sections describe each of the three impact models in more detail and discuss how each model calculates the economic consequences of agricultural water supply reductions.

1. CARM Model

The California Agriculture and Resource Model (CARM) was developed to predict profit-maximizing farmers' short-run acreage and production responses to changing market conditions or resource constraints (Howitt, 1995; California Air Resources Board, 1987; Goodman and Howitt, 1986). The model divides California into fourteen regions that are homogenous in terms of their agronomic conditions, microclimate and resource costs. Each region has a set of cropping activities defined that are drawn from a set of thirty-four crop types, and correspond to the observed annual crop data recorded by the county agricultural commissioners. Each crop has an average yield function, a calibrated quadratic cost function and Leontieff input requirement coefficients for land, irrigation water, nitrogen, fuel and labor. The resulting model is a calibrated quadratic programming model with quadratic functions for both the regional crop supplies, and the statewide output prices.

The CARM model objective function can be shown to maximize the sum of producer and consumer surplus from California agricultural crop production. The model has regional constraints on land and water availability and some crops that are sold through predetermined contracts. The shadow values on these constraints enable the model to generate estimates of the regional opportunity costs of land and water resources in excess of the fixed charges for these inputs. By changing the regional availability of surface irrigation water, and restricting the farmer's ability to substitute ground water, the effects of alternative implementation methods for the CVPIA can be modeled and compared with other analysis methods.

The CARM model differs from the two other models presented by having a formal and explicit calibration procedure for the crop acreages produced in a given year. The approach is termed Positive Mathematical Programming (PMP) (Howitt, 1995). The essential difference between PMP and other calibration methods based on constraints is in the quadratic costs that are a function of regional crop acres. The cost functions are derived from the shadow values of constraints that calibrate the cropping pattern in the model to that observed in the base data. The calibration is performed by changing the linear average cost function to a quadratic specification that equates the reduced gradient to the calibration shadow value at the observed level of crop production. However, the average cost and shadow values of the binding resource constraints are not changed by this modification of the crop production cost function. The resulting calibrated model is therefore able to respond to changes in physical quantities of available resources or their prices, and reflect these changes in terms of changes in acreage, production, consumer surplus or producer surplus.

The combination of the fourteen growing regions and thirty-four potential crops yields three hundred and five regional cropping activities. The quadratic crop cost calibration results in a precise calibration to the base year data, but allows the model to respond to changes in comparative advantage due to policy changes. The model responds to changes in surface irrigation water by adjustments on three margins. The first margin is the total statewide production of crops. Second, the balance of crops grown in particular regions changes in response to changes in water supply. Given the reductions in water availability from the CVPIA, crops with lower marginal product values from water will be reduced in the affected areas. Third, the balance between surface water, ground water and limited dry-land production will change within the limits of the agricultural and water infrastructure in a given region. The model is not restricted by rotational constraints as empirical tests of correlation between the rates of change of crop acres in a region do not show any relationship.

2. The Agroeconomic Model

This model has the least detail in terms of number of crops and regions but has the most advanced specification of water productivity. This specification allows investigation of the impacts of water supply reductions on irrigation technology choices under alternative scenarios, and also enables adjustment of predicted water use and technology choices to variations in weather and land quality. The model was constructed initially to analyze water and drainage policies and is described in detail in Dinar et al. (1991).

The agroeconomic model is applied to three policy scenarios. The "Proportional" scenario assumes that the cuts in surface water deliveries are allocated proportional to water use among growers in both the Sacramento and San Joaquin Valleys and that there are only markets for water within each of the four regions. The "San Joaquin" scenario assumes that all reductions in diversions are borne by growers in the San Joaquin Valley, and that there is trading among the basic units in this area only. Finally, the "Efficient" scenario assumes that there is a market for surface water encompassing all four regions so that water is allocated according to its marginal value across all four regions.

3. Rationing Model

The rationing model measures immediate impacts from changes in water supply policy and relies on the most detailed micro level data. The basic unit of the rationing model is the individual water district. The water districts are grouped into five regions according to their proximity to various CVP facilities and have similar water rights and growing conditions. The model also captures the largest number of crops among the three impact models and is the only model to include both annuals and perennials.

Growers in the rationing model respond to reductions in surface water availability by ceasing production of the crops with the lowest marginal value of applied water. This approach is motivated by the fact that growers have a large degree of flexibility when they make long-term decisions regarding irrigation technology and cropping patterns but have only limited flexibility in the short run. In this respect, the model is based on the "putty-clay" approach to water policy modeling of Hochman and Zilberman (1978) and Green and Sunding (2000).

Another fact motivating the rationing analysis is the large degree of heterogeneity in California agriculture. The Central Valley consists of many production regions that vary both in terms of weather and land quality. Existing crop allocation patterns have evolved over time to maximize the overall benefits from agricultural production. At each location, farmers have invested substantial resources in production infrastructure, including equipment for harvesting, packing, and irrigation. As a result, crop mix choices are largely predetermined in the short run and appropriate for individual locations. Agronomic evidence suggests that, within a given production technology, a crop should either be irrigated with a certain amount of water, the "water requirement," or not irrigated at all (Letey et al., 1985; Letey and Dinar, 1986). As a result of these considerations, water supply reductions that change the preconditions for a successful crop mix are likely to be met in the short run with the only response available to growers: reducing the amount of land cultivated while retaining the existing production technology on the land remaining in production.

The rationing model calculates the impacts of water policy changes on farm revenue, fallowing, state product, and employment. The latter measures are computed with revenue multipliers. Two policy scenarios are simulated by the rationing model: the "Proportional" scenario in which the supply reduction is allocated pro rata among all CVP contractors in the Central Valley with no trading among regions, and the "Efficient" scenario in which there is an interregional market for surface water incorporating both the Sacramento and San Joaquin Valleys. In this latter scenario, as discussed earlier, the total impacts of the supply reduction are independent of the initial allocation of the cutbacks.

5. Benefits to Agriculture of Water Trading

Table V.1 summarizes the impacts measured by the three models. The estimated impacts are quite consistent between models. This consistency is apparent by comparing the results of the agroeconomic model, which computes profit, with the results of the rationing model, which has impacts on revenue, and comparing them to the CARM model, which has impacts on both profit and revenue.

All of the models suggest that the incremental costs of removing water from the Central Valley increase sharply as the quantity reallocated increases. Increasing the amount of water devoted to environmental protection from 0.8 MAF to 1.3 MAF more than doubles the cost of the regulation to growers. Experimental runs with higher levels of water supply reduction show that this tendency continues and incremental costs of water supply reduction increase as water scarcity increases. This result is attributable to the fact that profit-maximizing farmers will first reduce or cease production of low-value crops in response to reductions in water supply, and will only cease producing high-value crops if the reductions are drastic.

The results of Table V.1 further suggest that the overall level of the water supply cut is not the most important factor affecting the social cost of protecting Bay/Delta water quality. Rather, the impacts depend more importantly on the extent of a water market and, when trading is limited, on how supply cuts are distributed among regions. If a market mechanism is used to allocate an annual reduction of 0.8 MAF among a large body of growers in the Central Valley, both the CARM model and the agroeconomic model estimate the annual reduction as around $10 million, and the CARM model suggests that the revenue reduction is approximately $19 million. Using a proportional allocation for the same region, the agroeconomic and CARM models both suggest that the annual reduction of profits is nearly $45 million, and the CARM model suggests that annual revenue reductions are around $85 million. The rationing model suggests that if the 0.8 MAF reduction applies to CVP contractors alone, under the market solution, revenue reductions are close to $40 million, and under the proportional solution, reductions total about $100 million. If the cuts are restricted to the Delta-Mendota Canal area, the most water-efficient region in the San Joaquin Valley, the CARM model suggests that with a market allocation, the revenue losses are around $110 million, and with proportional allocation, losses are close to $165 million.

When the overall water supply reduction is 1.3 MAF, then according to both the agronomic and CARM models, profit loss is close to $30 million if the cut applies to a large group of farmers in the San Joaquin Valley, and the revenue effect is about $52 million annually. If the allocation is proportional for a large region, both the CARM and agronomic models predict annual profit reductions of around $77 million and revenue reductions of around $145 million. When the cuts are targeted to the CVP contractors, revenue losses with a water market are around $100 million, and with a proportional allocation, about $224 million. When the cuts are aimed at growers in the Delta-Mendota Canal area, revenue losses can reach $276 million annually.

Table V.1. Summary of Impacts on California Agriculture

Cuts in CVP Deliveries	Model	Decrease in Revenue	Decrease in Profit	Decrease in Gross State Product	Decrease in Labor	Acres Fallowed
acre-feet		----------$ million----------			000 person yrs	000 acres
800,000						
	CARM					
	Proportional Allocation					
	San Joaquin	85.96	45.50	90.26	2.15	
	Local Market Allocation					
	San Joaquin	18.88	9.82	19.82	.47	
	Agroeconomic					
	Proportional		53.05			127
	South of Delta		36.87			14
	Rationing					
	Proportional	97.38		102.86	4.49	243
	Efficient	40.21		46.25	2.02	132
1,300,000						
	CARM					
	Proportional Allocation					
	San Joaquin	145.83	76.95	153.12	3.65	
	Local Market Allocation					
	San Joaquin	52.43	26.69	55.05	1.31	
	Agroeconomic					
	Proportional			118.44		239
	South of Delta			59.14		39
	Rationing					
	Proportional	224.88		226.63	10.80	373
	Efficient	96.62		111.90	4.87	321

6. Concluding Comments

There is increasing pressure in the western United States to protect natural resources by enhancing instream flows. Such policies inevitably mean reducing diversions to irrigated agriculture. This section presents a method for measuring the impacts on agriculture of such reductions. The fundamental tension to be addressed in constructing an agricultural impact model is between the detail necessary to permit examination of the distributional consequences impacts, and the fact that growers have a multidimensional response to policy changes. Rather than constructing a highly complex model incorporating all growing regions and all responses, this section argues that the results of existing, smaller models can be compared to accurately measure policy impacts in a cost-effective way.

With regard to the Bay/Delta problem, the three impact analyses considered here suggest that the overall cost of improved water quality in the estuary can be reduced dramatically by allowing broad-scale water trading among growers. In particular, the costs are much lower if most of the reduction is borne by growers in the Sacramento Valley instead of the west side of the San Joaquin Valley, including the Delta-Mendota Canal region. Reducing the scale of agricultural production in the Sacramento Valley effectively diminishes the acreage planted to irrigated pasture and field crops including alfalfa, wheat, beans, rice and feed corn.

This least-cost solution may face political and physical feasibility constraints because local concerns may well resist large-scale, out-of-area trades. Policies that entail either limiting water supply reductions to one region or proportional cuts represent higher cost alternatives than the least cost alternative. These are likely to be the solutions for the short run without extensive transfers. These will cost about $100 million for the 0.8 MAF cut and about $225 million for the 1.3 MAF cut. Direct costs per acre-foot in lost farm returns range from $50 to $80/AF depending on location and quantity of water removed.

One of the implications of the analysis is that if the lack of conveyance infrastructure is a physical barrier to trade, then enhanced conveyance facilities such as the Peripheral Canal can lower the costs of water quality regulations by reducing the transaction costs associated with water trading. The buildup of water storage reservoirs can further reduce the impact of supply reductions. Increased storage facilities south of the Delta may enhance the ability of growers to trade water between the Sacramento and San Joaquin Valleys and with urban areas. Future economic analysis should measure the costs and benefits of these facilities.

VI. Water Trading within Agriculture: Current Patterns and Ideas for Improvement

1. Water Trading within California Agriculture

Water is not currently allocated by price in most areas of California. As a result, farmers face wide disparities in price and availability. Markets are emerging in California and at other locations throughout the west in response to these factors, and also in response to increasing scarcity.

Challenge Grant researchers have argued that increased flexibility in water trading would help farmers cope with supply cutbacks needed to improve instream quality. This result follows from the observation that markets allocate the burden of a supply reduction to the party most able to bear it. In the case of water, a water market would allocate the cut to the grower making the least productive use of his water.

Economic research of California agriculture suggests that the benefits of a market are large. For example, Sunding and others have shown that the most productive 25% of the water used in California agriculture accounts for 50% of the sector’s revenue. Conversely, the least productive 20% of the water used in California agriculture produces less than 5% of its revenue.

A number of regional water markets have emerged in California in response to the scarcity of water resources in the region. These markets are local, as opposed to statewide or otherwise, due to legal, economic and conveyance constraints on transfers. However, despite their limited geographic scope, trading can be quite active within these cells. One such regional market occurs within California's Westlands Water District.

Every year, farms in Westlands complete thousands of water trades involving hundreds of thousands of acre-feet. Given that the size of a local water market is constrained by the size of the water district, there is more "market potential" in Westlands than in other water districts. It is the largest district in the Central Valley Project, covering nearly 600,000 acres and including approximately 800 farms.

The volume of water traded in Westlands was greater in the wet years of 1995 and 1996 than in the dry years of 1993 and 1994. However, the volume traded as a share of the annual CVP water supply, and the number of trades made were greater in 1993 and 1994.

Table VI.1. Westlands Water Market

Year	Trades	Acre-Feet	AF/Trade	Share
1993–94	2,519	382,964	152	51%
1994–95	2,580	284,540	110	45%
1995–96	1,839	410,493	223	27%
1996–97	1,673	394,449	236	28%

Small farms participated in the market less frequently than large farms. Looking at the 1993 data, 61.1 percent of the small farms made at least one market trade; 48.0 percent of the medium farms and 36.2 percent of the large farms made at least one market trade.

Table VI.2. Percent Participation

	1993–94	1994–95	1995–96	1996–97
small	61.1	49.6	50.3	45.7
medium	76.0	79.2	86.2	64.4
large	93.9	84.8	81.3	87.5

Generally, large farms are net buyers and small farms are net sellers. Large growers thus appear to benefit from trading more than small growers. This finding reflects the fact that large growers are able to afford the high transactions costs present in an informal market. This is one of the reasons behind the creation of *WaterLink* – providing water market information is fundamentally democratic and extends the benefits of trading to small growers.

Table VI.3. Average Annual Supply Change (Acre Feet /Year)

Size	1993–94	1994–95	1995–96	1996–97
small	–73	–14	–120	–309
medium	222	–35	–103	69
large	–197	152	703	744

The amount and nature of water trading within Westlands is not typical, but is still of interest to irrigators throughout the Reclamation service area. Westlands should be viewed as a glimpse into the future rather than simply as an aberration. Farmers in Westlands have achieved remarkable levels of productivity and efficiency while owning some of the most junior water rights in the CVP system. Water trading has helped them cope with scarcity, and even thrive, in the face of highly unreliable water supplies. As pressure on agricultural water use mounts throughout the western United States, agricultural interests would be wise to study the lessons of the Westlands experience with water markets, and consider how they can be applied to other settings.

2. Reducing Transaction Costs with the *WaterLink* System

The *WaterLink* electronic marketing system, introduced by the Challenge Grant team in Westlands in 1996, has begun to reduce market transaction costs. *WaterLink* consists of a server (located in the main district office in Fresno), a bank of phone lines and modems, and communications software. The major features of the system are the following:

- Water Trading
  Growers have the opportunity to post bids and asks in a central location. These are then made available to other growers, either to find a trading partner or simply to keep tabs on water trading activity. Information included in a posting: the amount of water, delivery time frame, the type of water to be traded, a bid/ask price (optional), and a contact person. Growers can then negotiate electronically over the *WaterLink* system, or can talk off-line by phone or in person.

- Water Market Summary
  WaterLink makes available the following market summary information: volume traded in the previous month, annual trading volume, price in the previous month. This information is useful to market participants and to growers who are considering making a purchase or sale.

- Transfer Approval
  Significant cost savings have been realized by the *WaterLink* system's ability to facilitate the transfer approval process. Once growers have agreed on the terms of a transfer, they notify the district staff via-e-mail about the terms of their proposed trade. The district can then complete the transfer process.

- Water Ordering

  Perhaps the most commonly used feature of the *WaterLink* system in Westlands is the water ordering program. Growers can fill out and send the district an electronic form to order water deliveries to their farm. Well over half of all the irrigated acres in the district order their water via *WaterLink*. The district also reports cost savings from this feature.

- District and USBR Information

  The Westlands newsletter is available via the *WaterLink* system, as is USBR supply and storage information.

- Links to Irrigation-Related Sites

  WaterLink identifies other irrigation-related sites, including the California Irrigation Management Information System (CIMIS) that gives reference ET data for numerous weather stations in the Westlands service area, as well as weather forecasts.

- Bulletin Board

  Growers can post information on this site. The bulletin board has been used to sell farm machinery, for example.

In 1998, *WaterLink* was expanded to include 10 additional water districts in the San Luis & Delta-Mendota Water Authority. Users of the system include staff of the participating districts, authority personnel and USBR staff. The features of the system are similar to the intra-district system used in Westlands, with one notable exception: the inter-district version of *WaterLink* allows district managers to receive on-line approval for proposed inter-district transfers. This feature of the system is quite popular since delay in receiving USBR approval for proposed transfers retarded development of a more active spot water market in this area.

Response to the *WaterLink* system has been positive. The Westlands version of *WaterLink* is currently used by most of the largest growers in the district. Water ordering is the most commonly used feature of the program, but then water is ordered more often than it is traded. With regard to trading, at any given time during the growing season there are several current bids and asks listed on *WaterLink*. The electronic market has not proven to be "thin." Also, the district sometimes procures water via the *WaterLink* system, mostly to meet operational needs.

The inter-district version of *WaterLink* has only operated for part of one growing year, so it has a more limited track record. Yet the on-line approval feature has caught the attention of district staff. The first two transfers submitted to the Bureau's office were approved in a single afternoon. Like the rest of the economy, water users in California are beginning to take advantage of improvements in information technology to minimize production costs and improve the efficiency of resource use decisions.

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