The Economics of Agricultural Water Use and the Role of Prices

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Prof. David Sunding
Department of Agricultural and Resource Economics
207 Giannini Hall
UC Berkeley
Berkeley, CA 94720

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I. Choice of Irrigation Technology

Agricultural production is heavily dependent on the nature of the local environment. Factors such as soil permeability, slope, and microclimate have a large effect on yield and water use. It is important to explicitly incorporate the influence of these “microparameters” when assessing agricultural water demand.

The farmer’s choice of irrigation technology can have a large influence on the demand for applied water, so it is sensible to begin with a description of how farmers select irrigation methods. Following Caswell and Zilberman (1986), let

\[
\begin{align*}
    y &= \text{output/acre} \\
    e &= \text{effective input/acre} \\
    a &= \text{applied input/acre} \\
    i &= \text{technology indicator} \\
        &\begin{cases}
                i = 0 & \text{for traditional} \\
                i = 1 & \text{for modern}
        \end{cases} \\
    \alpha &= \text{land quality} \\
    p &= \text{output price} \\
    w &= \text{input price} \\
    k_i &= \text{per acre cost of technology } i, k_1 > k_0
\end{align*}
\]

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

\[
\begin{align*}
    0 &\leq h_0(\alpha) = \alpha \leq h_1(\alpha) \leq 1 \\
    h_i'(\alpha) &> 0 \quad \text{and} \quad h_i''(\alpha) < 0.
\end{align*}
\]

The farmer’s irrigation technology choice problem is as follows:

\[
\begin{align*}
    \max_{\delta, a} & \sum_{i=0}^{1} \delta_i \left[ pf(h_i(\alpha) a_i) - wa_i - k_i \right] \\
    \text{s.t.} & \quad \delta_i \in \{0,1\} \\
        & \quad 0 \leq \sum_{i=0}^{1} \delta_i \leq 1.
\end{align*}
\]
The search for a maximum consists of two stages. First, the optimal amount of applied water (a continuous choice) is determined conditional on each technology. Then, working backwards, the highest-profit technology is identified.

The applied input choice is determined by the following:

\[
\pi_i = \max_{a_i} pf(h_i(\alpha)a_i) - wa_i - k_i.
\]

The FOC is

(I.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

\[
\delta_1 = 1 \quad \text{if} \quad \pi_1 > \pi_0 \quad \text{and} \quad \pi_1 > 0.
\]

\[
\delta_0 = 1 \quad \text{if} \quad \pi_0 > \pi_1 \quad \text{and} \quad \pi_0 > 0.
\]

\[
\delta_1 = \delta_0 = 0 \quad \text{if} \quad \pi_1, \pi_2 < 0.
\]

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 \(\alpha\) is as follows:

\[
\frac{d\Pi_i}{d\alpha} = pf' h_i'(\alpha)a_i = \frac{w\eta_i a_i}{\alpha} > 0,
\]

where \(\eta_i = h_i'(\alpha)\alpha/h_i(\alpha)\). It follows that the difference in profits between the two technologies is equal to

\[
\frac{d\Delta\Pi}{d\alpha} = w\left[\frac{\eta_1 a_1 - \eta_0 a_0}{\alpha}\right].
\]

Now, this expression can be signed by taking a Taylor’s series approximation of \(a\) as follows:

\[
a_i = a_0 + \frac{\partial a}{\partial \alpha} (h_i(\alpha) - \alpha),
\]

recognizing that adoption of the precision technology is equivalent to a shift in land quality from \(\alpha\) to \(h_i(\alpha)\). Substituting the elasticity expressions above, it follows that

\[
a_i = a_0 \left(1 - \frac{1}{\alpha} \phi\right),
\]

where \(\phi = -f''e/f'\). Substituting this equation into (2), it follows that
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 possible 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 $\Delta \Pi(1) = k_{0} - k_{1} < 0$.

At some level of land quality, all else being equal, the identity of the highest-profit technology will change. This level of land quality is called the switch point. Modern technology is adopted for levels of land quality below $\alpha = \hat{\alpha}^{*}$ and the traditional technology elsewhere. Note that the modern irrigation 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., $\hat{\alpha}_{1} < \hat{\alpha}_{0}$, where $\hat{\alpha}_{i} = \{\alpha | \Pi_{i}(\alpha) = 0\}$ is the shut-down level of land quality under technology $i$).

**Figure I.1 Adoption of Precision Technology**

Figure I.1 shows that it is not profitable to operate on land of quality $\alpha < \hat{\alpha}_{1}^{*}$ regardless of the type of irrigation technology chosen. On the other hand, with high-quality land, either technology is profitable, although the traditional technology is more profitable. This is because on high quality land, the increase in yield with the modern technology is not worth the fixed cost of installing it. Where the modern technology makes a difference is on land of moderate quality,
i.e., the land between $\hat{\alpha}_i$ and $\alpha^s$. The modern technology increases profits on land between $\hat{\alpha}_0$ and $\alpha^s$ and $\alpha^i$, and enables production to be profitable on land between $\hat{\alpha}_i$ and $\hat{\alpha}_0$.

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

$$
\frac{d\alpha^s}{dW} = \frac{(a_i - a_0)\alpha^s}{W[\eta a_i - a_0]} > 0 \text{ if } \phi > 1 \text{ and }
$$

$$
\frac{d\alpha^s}{dP} = \frac{(y_1 - y_0)\alpha^s}{W[\eta a_i - a_0]} > 0.
$$

**Other Farm-Level Effects of Precision Technology Adoption**

Recall that profit maximization requires

$$
\frac{w}{h_i} = Pf_e
$$

at the optimum. Since $f'(e) > 0$, it follows that

$$
h_0 < h_i \Rightarrow f'_0 > f'_i \Rightarrow e_0 < e_i.
$$

Thus, modern technology increases the optimal level of effective water use. But note that a higher level of effective water use does not imply a higher level of applied water use. This is because the ratio of applied to effective water is smaller with modern technology, so that greater effective water can be utilized with lower applied water. In most cases, modern technology reduces the optimal level of applied water use, and is therefore water-saving. If $e_0 < e_1$, then $q_0 < q_1$. Thus, use of the modern technology increases crop output.

If land quality is high, water quality is high and the weather is mild, then $h_i$ and $h_0$ are not very different and the adoption of modern irrigation technology will have only a small effect on the optimal levels of crop output and applied water.

If land quality is low, water quality is low or the weather is hot, then adoption of modern irrigation technology may affect optimal crop output and applied water use significantly. When land quality is low and temperature is high, the effect of adopting new technology depends on water price.
II. Empirical Analysis of Irrigation Technology Choice

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.

Empirical Model

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

\[
\pi_{ij} = \beta_i' \chi_j + \varepsilon_{ij}
\]

where \( \beta_i \) is a vector of estimable parameters, \( \chi_j \) is a vector of observed field characteristics (including crop choice), and \( \varepsilon_{ij} \) 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

\[
\beta_i' \chi_j - \beta_0' \chi_j > \varepsilon_{0j} - \varepsilon_{ij}.
\]

To estimate the model parameters, it is necessary to choose a distribution for the \( \varepsilon_{ij} \)'s and, thus, the distribution of the difference of the error terms. Two common assumptions are either the normal or the Weibull distributions (Domencich and McFadden, 1975). Normal random

\(^1\) 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.
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 \( \varepsilon_{ij} \)'s follow a low Weibull distribution. Given this assumption, the probability that the \( i \)th technology is adopted on the \( j \)th field is

\[
P_{ij} = \frac{e^{\beta x_{ij}}}{\sum_i e^{\beta x_{ij}}}; \quad i = 0, I; \quad j = 1, J.
\]

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 \( \beta \). 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.

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.
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.

Estimation

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

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Table II.1. Irrigation and Acreage by Crop.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Acreage</th>
<th>Percentage of Acreage by Irrigation Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Furrow</td>
</tr>
<tr>
<td>Citrus</td>
<td>12,065</td>
<td>15%</td>
</tr>
<tr>
<td>Deciduous</td>
<td>11,700</td>
<td>27%</td>
</tr>
<tr>
<td>Grapes</td>
<td>23,665</td>
<td>61%</td>
</tr>
<tr>
<td>Truck Crops</td>
<td>27,283</td>
<td>11%</td>
</tr>
<tr>
<td>Total</td>
<td>74,713</td>
<td>30%</td>
</tr>
</tbody>
</table>
to assume that $\beta_0$ 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

$$\ln \frac{P_{ij}}{P_{0j}} = \beta_i' X_j,$$ \hspace{1cm} \text{for } i = 1, 2, \text{ and } j = 1, 2, \ldots, 1,493. \hspace{1cm} (II.3)$$

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.

**Estimation 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 $R^2 = 1 - L_{\omega}/L_\Omega$, where $L_{\omega}$ is the restricted maximum log-likelihood and $L_\Omega$ is the restricted maximum log-likelihood with all slope coefficients set equal to zero (Amemiya, 1981). The log-likelihood ratio test is given by $2(L_{\Omega} - L_{\omega})$ 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.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Estimation Results*</th>
<th>Elasticities**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sprinkler</td>
<td>Drip</td>
</tr>
<tr>
<td>Constant</td>
<td>1.9855</td>
<td>-4.5480</td>
</tr>
<tr>
<td>Water price ($/acre-foot)</td>
<td>-0.0130</td>
<td>0.0257</td>
</tr>
<tr>
<td>Surface water (0/1)</td>
<td>-0.5099</td>
<td>0.9706</td>
</tr>
<tr>
<td>Soil permeability (in/hr)</td>
<td>0.0002</td>
<td>0.0529</td>
</tr>
<tr>
<td>Field slope (%)</td>
<td>0.2210</td>
<td>0.6277</td>
</tr>
<tr>
<td>Field size (acres)</td>
<td>0.0101</td>
<td>0.0065</td>
</tr>
<tr>
<td>Crops</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Citrus (0/1)</td>
<td>-5.1537</td>
<td>2.1117</td>
</tr>
<tr>
<td>Deciduous (0/1)</td>
<td>-2.3600</td>
<td>1.3872</td>
</tr>
<tr>
<td>Grapes (0/1)</td>
<td>-6.3777</td>
<td>0.6760</td>
</tr>
<tr>
<td>Probability of adoption evaluated at variable means</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Observations | 1,493 |
McFadden $R^2$ | 0.44 |
Likelihood ratio test: $x^2_{16} = 1.441.16$ |
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.

![Graph showing probability of adoption by marginal water price](image)

**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.](image)

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.

**Discussion and 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.

III. Water Allocation Mechanisms and Agricultural Water Use

In many regions of the United States, water allocation has been based on queuing systems rather than on markets. Queuing systems are sets of laws defining property rights regarding who has priority to use water, when water may be used, how water may be used, and how much water may be used. Although queuing systems are still the norm in many parts of the world, they are undergoing change. A typical queuing system is a use-it-or-lose-it system of water property rights based on the principle “first come first serve.”

Queuing systems for water were established in the western United States to encourage settlement of land and the economic use of water resources. In early periods, water was abundant, governments were poor and they wanted to encourage people to develop water resources. As a result, government gave individuals the right to the water that they divert, so long as they use it in a way that generates economic benefits. Note that markets are the best allocation mechanisms when there is scarcity, but queuing can be very effective when scarcity doesn't exist. The biggest problem with queuing is that demands for water can increase and suddenly scarcity emerges. In this situation, water reforms are needed.

As water scarcity increases there is a tendency to allow trading in water. In California, for example, water trading was introduced during drought periods. The transition from queuing to markets may involve redesign of the water allocation system, building a system for the monitoring of water use, and protection against theft, and all this entails high transaction costs. If the gains from transition are smaller than these transaction costs, reform will not and should not occur.

The queuing system is not an efficient means of allocating water resources if scarcity exists, that is, if junior rights holders do not receive enough water. In particular, if a unit of water provided to junior rights holders has positive MVP, then we know queuing is inefficient since senior rights holders apply water to the point where their MVP = 0.

A simple figure illustrates this argument.
Figure III.1. Queuing vs. Markets

(a) Water supply projects (dams, canals, etc.) often have high initial fixed costs associated with construction and low marginal costs of supplying water up to the capacity of the project. At full capacity, the marginal cost of water supply rises steeply because additional projects or procurement strategies are required in order to supply additional water. Thus, the marginal cost of water supply curve is OIS.

(b) Assume that senior water demand is given by curve BD.

(c) Assume that junior water demand is given by curve AC.

(d) Aggregate demand for water is given by curve AEF, if water markets exist. Under water markets, the equilibrium level of water consumed is $W^*$ and the equilibrium price is $P^*$.

(e) Water rights allocate water to different users at different times. Demand is not aggregated, but discriminated by time in the residual demand curves BD and AC. Senior rights holders purchase an amount of water equal to $W^A$, which is where their water demand equals the marginal cost of water. The price of water used by senior rights holders is $P^A$. 
(f) Once the $W^A$ units of water have been consumed by senior users, junior users face residual water supply $S^R$, and therefore consume $W^U$ units of water and pay a price of $P^U$. The price of water in junior rights areas is higher than in senior rights regions.

Because the prices facing senior and junior users are unequal, the corresponding marginal benefits of water use are unequal. Since the marginal cost to supply each type of user is essentially the same, social welfare may be increased by reallocating water from senior users to junior users. Thus, allocation by queuing is inefficient. Allowing water to be freely traded would lead to water transfers from senior rights holders to junior rights holders.

Notice also that the total level of water consumed is inefficiently high under a queuing system, or that $W^A + W^U > W^*$. Thus, moving to a market oriented system of water allocation can lead to greater water conservation.

**Queuing system**

We now return to the analysis in Section 1 and demonstrate some economic implications of the transition from queuing to markets. Water trading is disallowed under a queuing system. In this case, there is no incentive for senior rights holders to adopt modern technology since water has no price. Water is simply diverted, as needed, according to a farmer’s place in the queue.

Suppose that $L$ is the total amount of water available in a region and that $A$ is the total amount of land available for cultivation. Also, let $y_m = f(e_m)$ denote maximum output per acre, where $e_m$ is defined by $e_m = \{e \mid f'(e) = 0\}$ is the effective water associated with maximum yield.

Senior rights owners use water until the VMP of water = 0, which is the level that will maximize yields. Settlement occurs until water resources are exhausted, so water becomes the limiting factor on development. Applied water use is $a_m = e_m h_0$ per acre, the amount of applied water associated with the maximum effective water absorbed by the crop.

Under a queuing system of water rights, the water price is equal to 0, and the per-acre fee for water use is $\mu$. Settlement will occur until all water is appropriated and the total acres under cultivation is $A a_m = Ah_0 e_m < L$. Total output under a water rights system is $Ah_0 y_m e_m$ and producer surplus is $P A h_0 y_m e_m - \mu A h_0 e_m$.

**Market System**

When all land quality is the same, the efficient solution involves applying water uniformly across all land to equate the MVP. Thus, under a market system, all land is utilized and each owner faces the choice of technology $i$.

Under a market, water use per acre is $A/L$, yield per acre under technology $i$ is $y_i = f(h_i A/L)$ and the price of water = VMP of applied water = $P f_c h_i$. 

15
Producers' annual profits per acre are

$$\Pi_i = Py_i - \frac{A}{L} Pf_i h_i - k_i - \mu - t$$

so that

$$\Pi_1 - \Pi_0 = P(y_1 - y_0) - \frac{A}{L} Pf_e (h_1 - h_0) - (k_1 - k_0)$$

Technology 1 is selected if $$\Pi_1 - \Pi_0 > 0$$.

Both technologies require the same water per acre, because water is evenly distributed across all acres as a result of equating the MVP. When each farmer is a small unit, the farmer does not believe that her choice of technology will affect the market price of water, then the market price of water is taken as a constant in the problem. Then the choice of technology can be expressed as follows:

Select technology 1 when $$p(y_1 - y_0) > k_1 - k_0$$.

Both technologies result in the same water use per acre, but the modern technology increases the yield by raising the amount of effective water received by the crop. If the market value of the increase in yield is greater than the extra capital costs involved with investing in the new technology, then the farmer should invest.

Comparing Market and Queuing Outcomes

Assume that, under market conditions, technology $$i$$ is optimal and adopted by all farmers. Under a market system all arable land is utilized. The transition to market will increase irrigated land from $$Ah_o/e_m$$ to $$L$$. Output will increase by

$$\Delta Y = Lf\left(h_0 \frac{A}{L}\right) - \frac{Ah_e}{e_m} f(e_m) > 0$$

as water is shifted from low MP land to the high MP lands now under cultivation. Output per acre will decrease from $$f(e_m)$$ to $$f(A/L e_i)$$. The reduction in water use per acre is from $$e_m \cdot h_0$$ to $$A/L$$. 
In the transition to the market, \((e_m - h_i A/L)h_i A e_m\) units of water which were used to produce the output associated with area B in the figure are allocated to irrigate new lands. Overall, output increases because the water that was used under queuing to produce output associated with region B of the figure is used under markets to produce output in region A on new land that is brought into production. Obviously, the marginal productivity of this water increases.

If the senior rights owners who appropriated water under the queuing system have to buy water after the transition to a market, their profits will decrease. Under water markets, they now have lower yields, they now have to pay for water, and they also must pay to adopt the new technology, since doing so is now optimal. Their loss per acre is

\[ Pf(e_m) - Pf\left(\frac{h_i A}{L}\right) + Pf h_i A = k_i + u. \]

But if the senior rights are given the property rights to the water, they may gain. These users still have lower output than under queuing, but the gain from selling water may overcome this output loss. Their income per acre will be

\[ Pf\left(\frac{h_i A}{L}\right) + (e_m - h_i A) Pf h_i A - t - k_i \]

If the transaction costs are high, there may be no reason to switch to a system of water markets. Namely, if

\[ t > \frac{P\Delta Y + k_i L - k_o A / (h_o \cdot e_m)}{L}, \]
then transaction costs per acre exceed the per acre change in output plus the cost of adopting the optimal modern technology less the cost savings of senior owners not adopting the conventional technology. In this case, water markets are inefficient.

Because markets for final products have negatively sloped demand, the transition from queuing to markets will also reduce the market price of agricultural commodities. Senior rights owners may thus lose, even if they sell water because of the price decline of their output. Producers as a whole may actually lose, but consumer surplus will increase.

**IV. Water Pricing in a Conjunctive Use System**

The economics of agricultural water use and pricing become more complicated when the possibility of groundwater use is considered. Let \( y_t \) = pumping in year \( t \) and \( x_t \) = the level of the groundwater stock in year \( t \). The level of the stock increases in year \( t \) by \( g(y_t) \), where \( \frac{\partial g}{\partial y_t} \geq 0 \). For example, \( g(y_t) = A + \Theta y \), where \( A \) is rainfall plus imported surface water (which is influenced by the price of water charged by the government) and \( \Theta \) is percent of irrigation water that is return flow. Thus, the growth equation for the stock of groundwater is

\[
(IV.1) \quad x_{t+1} = x_t + g(y_t) - y_t
\]

Let \( B(y_t) \) = benefits from groundwater use and \( C(x_t, y_t) \) = total cost of pumping, where \( \frac{\partial c}{\partial x_t} = 0 \) and \( \frac{\partial c}{\partial y_t} \geq 0 \).

Groundwater is managed optimally when pumping and the stock are chosen each year to

\[
\max \sum_{t=0}^{\infty} (1 + r)^{-t} [B(y_t) - C(x_t, y_t)] \quad t = 0, 1, 2, \ldots
\]

subject to \( x_{t+1} = x_t + g(y_t) - y_t \). To solve this problem, convert the constrained problem into an unconstrained one using Lagrange multipliers as follows:

\[
\max \sum_{t=0}^{\infty} (1 + r)^{-t} [B(y_t) - C(x_t, y_t)] + \mu_t [x_t + g(y_t) - y_t - x_{t+1}]
\]

The first order conditions are

\[
(IV.2) \quad \frac{\partial L}{\partial y_t} = (1 + r)^{-t} \left[ \frac{dB}{dy_t} - \frac{\partial c}{\partial y_t} \right] + \mu_t \left[ \frac{ds}{dy_t} - 1 \right] = 0
\]
\[
\frac{\partial L}{\partial x_t} = (1 + r)^{-t} \frac{\partial c}{\partial x_t} + (\mu_t - \mu_{t-1}) = 0
\]

(IV.4) \[
\frac{\partial L}{\partial M_t} = x_t + g(y_t) - y_t - x_t - x_{t+1} = 0
\]

(IV.5) Define \( \lambda_t = (1 + r)^t \mu_t \). \( \lambda_t \) is the value in period \( t \) of an extra unit of groundwater stock in period \( t \). \( \mu_t \) is the value in period 0 of an extra unit of groundwater in period \( t \).

We can rewrite (2) as

\[
\frac{dB}{dy_t} - \frac{\partial c}{\partial y_t} - \lambda_t \left[1 - \frac{dg}{dy_t}\right] = 0
\]

(IV.6) So optimal pumping equates the marginal benefit of pumping with its marginal cost plus user cost of pumping adjusted for return flows to the aquifer.

Now, from (IV.5) it follows that

\[\mu_{t-1} = (1 + r)^{-t} \lambda_{t-1} = (1 + r)^{-t} (1 + r) \lambda_{t-1} .\]

Substituting into (IV.3) we get

\[(1 + r)^{-t} \lambda_t - (1 + r)^{-t} (1 + r) \lambda_{t-1} - (1 + r)^{-t} \frac{\partial c}{\partial x_t} = 0 .\]

Multiplying by \( (1 + r)^t \) and rearranging yields

\[
r \lambda_t = (\lambda_t - \lambda_{t-1}) - \frac{\partial c}{\partial x_t} = 0
\]

(IV.7) This condition says that the optimal stock of groundwater occurs when the opportunity cost of keeping a unit of water in the ground \((r \lambda_t)\) equals the capital gain when water is kept in the ground \((\lambda_t - \lambda_{t-1})\) minus the reduction in pumping cost from having more water in the ground.

In a steady-state,
In this case, optimality conditions (IV.1), (IV.6) and (IV.7) reduce to the following:

(IV.1’) \( y^* = g(y^*) \)

(IV.6’) \[
\frac{dB}{dy} - \frac{\partial c}{\partial y} - \hat{\lambda}^* \left[ 1 - \frac{dg}{dy} \right] = 0
\]

(IV.7’) \( \hat{\lambda}^* = -\frac{\partial c/\partial x}{r} \)

I will consider the effect of changes in surface water prices in the context of a steady-state.

When \( g(y_t) = A + \Theta y \), and \( A \) is influenced by the price of surface water, it is clear first of all that raising the price of surface water reduces \( A \), reduces the amount of groundwater pumping, and reduces total water use. The shadow price of groundwater, \( \hat{\lambda}^* \), decreases (from equation (IV.7’), and the stock of groundwater decreases (from (IV.6’)). All of these effects must be considered when evaluating the optimality of water price reforms in a conjunctive use setting.

V. Agriculture as a Supplier of Last Resort: An Example from California

Agriculture in the western United States 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.

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.

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 feature 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 $R^n_{k^n}$. For example, if we have eight microunits divided into two regions under scenario $n$, $R^n_1 = \{1, 2, 3, 4\}, \ R^n_2 = \{5, 6, 7, 8\}$.

Each microunit has an initial “endowment” of surface or ground water representing annual surface water rights and ground water pumping capacity. Let $S_j^n$ be annual surface water available to district $j$ in the base scenario and $G_j^n$ 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 $\sum_{j \in R^n_{k^n}} (S_j^n + G_j^n)$. However, surface water availability differs among alternative scenarios. Let $\Delta S^n_{k^n}$ be the reduction of water supply available to region $k^n$. The overall surface water supply reduction in scenario $n$ is
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 $S_j < \bar{S}_j$ and $G_j \leq \bar{G}_j$.

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

$$y_{ij} = f(L_{ij}, a_{ij}, z_{ij}, \theta_{ij}),$$

where

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

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

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

and

$$\theta_{ij} = \text{ regional environmental quality parameters}.$$ 

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 $W_j^g$. Generally, $W_j^s > W_j^g$, 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.\(^3\)

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 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

\begin{align*}
(V.1) & \quad \Pi^n = \max \sum_{j=1}^{J} \sum_{i=1}^{I} P_{ij} - W_j^s S_j - W_j^g G_j - Z_{ij} - C(L_{ij}), \\
(V.2) & \quad \text{s. t. } \sum_{i=1}^{I} A_{ij} = S_j + G_j \quad \forall j, \\
(V.3) & \quad \sum_{j \in R^z} (S_j + G_j) \leq \sum_{j \in R^z} \bar{S}_j + \bar{G}_j - \Delta S''_k \quad \forall k, \\
(V.4) & \quad \sum_{i=1}^{I} L_{ij} \leq L_j \quad \forall j.
\end{align*}

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.

\(^2\) 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.

\(^3\) 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.
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.

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

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

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

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.,

\[(V.7)\quad r_j = P_i f_{ij}(...)-(W_j^d + V_k^n) a_{ij} - z_{ij} - \frac{\partial C_{ij}}{\partial L_{ij}} + P_i L_{ij} \cdot \frac{\partial f_{ij}}{\partial L_{ij}} \quad \forall i, j \quad L_{ij} > 0.\]

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, $\Delta S_k^n$, is

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

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 ($\Delta \Pi^n > 0$) 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.\(^4\) Other such variables are gross farm income, regional income, and employment.

The gross income effect of scenario $n$, $\Delta R^n$, 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 $\psi_i$ 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 $n$, $\Delta RNP^n$ is

$$\Delta RNP^n = \sum_{i=1}^N \sum_{j=1}^I P_i (Y_{ij}^0 - Y_{ij}^n) \psi_i.$$  

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

\(^4\) These impact measures were requested from us by the U.S. EPA for their use in designing water quality standards.
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.

**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.

**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.

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.

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.

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 IV.1. Summary of Impacts on California Agriculture

<table>
<thead>
<tr>
<th>Cuts in CVP Deliveries</th>
<th>Model</th>
<th>Decrease in Revenue</th>
<th>Decrease in Profit</th>
<th>Decrease in Gross State Product</th>
<th>Decrease in Labor</th>
<th>Acre-feet</th>
<th>$ million</th>
<th>000 person yrs</th>
<th>000 acres</th>
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<td></td>
<td>CARM</td>
<td>85.9</td>
<td>45.5</td>
<td>90.2</td>
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<td>6</td>
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<td></td>
<td>San Joaquin Local Market Allocation</td>
<td>18.8</td>
<td>9.8</td>
<td>19.8</td>
<td>.</td>
<td>8</td>
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<td>127</td>
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<td></td>
<td>South of Delta Rationing</td>
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<td>7</td>
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<td>Pro</td>
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<td>4.</td>
<td>243</td>
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</table>
**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.
References


