Economic Valuation of Increased Water Supply Reliability and Trading Opportunities in Westside Agriculture

David Sunding, David Zilberman,
Georgina Moreno, and Daniel Osgood

Department of Agricultural and Resource Economics
University of California at Berkeley

June 30, 2000

Final Report:

Economic Valuation of Increased Water Supply Reliability and Trading Opportunities in Westside Agriculture

(Contract #B-81588)

Prepared for:
CALFED Bay-Delta Program
1416 Ninth Street, Suite 1148
Sacramento, CA 95814

Prepared by:
David Sunding* and David Zilberman, Principal Investigators
Georgina Moreno and Daniel Osgood, Graduate Student Researchers
Department of Agricultural and Resource Economics
UC Berkeley

June 30, 2000

* Contact information: 510-642-8229; email: sunding@are.berkeley.edu

D-054037

Table of Contents

Final Report:
Economic Valuation of Increased Water Supply Reliability and Trading Opportunities in Westside Agriculture

(Contract #B-81588)

Executive Summary

This report measures the value of water supply reliability to farming interests in California's Central Valley, particularly the San Luis and Delta-Mendota Water Authority (SLDMWA). Value is defined as increase in expected, or long run, farm profit; equivalently, value is defined as willingness to pay. The analysis is important because it feeds into a larger cost-benefit analysis of proposed infrastructure projects (e.g., surface reservoirs or groundwater banking projects) designed to change the distribution of agricultural water supplies in the Central Valley.

The study begins by characterizing water supply reliability. Although the term is widely used in water policy debates, it is actually quite ambiguous. Consider just two alternative and, to some extent, extreme definitions:

- Reliability I: A Mean-Preserving Reduction in the Variance of Water Deliveries

  Example: Consider two distributions: A and B. Under distribution A, the grower receives 1 acre foot in half of all years and 3 acre feet in half of all years. Under distribution B, the grower always receives 2 acre feet. Under this definition, Distribution B is "more reliable" than Distribution A.

- Reliability II: Reducing the Probability of Receiving Less than <u>Any</u> Arbitrary Amount of Water

  Example: Suppose that Distribution A is as above. Consider a second distribution, C, such that the grower receives 2 acre feet half the time and 3 acre feet half the time. Under this definition, C is more reliable than A.

Reliability I is a minimal definition of reliability. Offering growers the same amount every year would be absolutely reliable, but not desirable by the agricultural sector if the level of supply were too low. Reliability II is a more expansive definition. Note, however, that this definition of reliability entails an increase in mean deliveries. This change would also be undesirable to some stakeholders. The economic valuation models developed in the study are general enough that they incorporate a variety of alternative definitions of reliability. Hopefully, the definitional discussion in the first chapter will lead to more precision in policy discussions of water supply reliability.

The report consists of three chapters, each of which presents a conceptual model of water supply reliability together with numerical results. The models have varying degrees of generality, but all have a common structure: they recognize that farmers make both short- and long-run decisions that are influenced by the distribution of surface water supplies. In the long run, farmers make capital investments that are not easily altered from year to year. Investments in perennial crops, specialized farm machinery, and irrigation systems are all examples. Growers make other decisions that are more temporary in nature, and that are influenced by annual project water allocations. The amount of groundwater pumped, the acres planted to annual crops, and the amount of water bought and sold on local water markets are all short-run decisions. These decisions are also influenced by prior capital investments.

We consider the impact of changes in the distribution of surface water allocation on both short- and long-run farm decisions. The first chapter of the report presents the basic framework of the valuation model, and develops many of the basic theoretical results. Among the conceptual results are the following:

- An increase in the reliability of surface water deliveries (by either definition above) increases expected farm profits.

- When surface water is supplemented by water from other sources, the value of small changes in the surface water distribution is related to the avoided cost of supplemental water. This conclusion is especially important for empirical analysis since the cost of groundwater (or water purchased on local water markets) is usually easy to measure.

- An improvement in surface water reliability can increase or decrease the amount of long-run capital investment. The direction of the change depends on whether the investment increases or decreases the productivity of water. For example, under normal conditions, an increase in reliability is expected to increase the amount of perennial crops grown. Conversely, the same shift can decrease the incentive to invest in water-conserving irrigation technologies.

- Changes in the distribution of surface water can increase or decrease the amount of supplemental water procured. In part, the direction of the response depends on how capital investment changes. Stabilization of surface supplies that increases the amount of capital investment and increases the marginal productivity of water application will actually increase the amount of supplemental water used by farmers. In this way, stabilization of project water deliveries can increase the expected amount of groundwater pumping.

In a case study described in the first chapter, the general model is applied to the SLDMWA to measure the willingness of growers to pay for arbitrary changes in the distribution of Central Valley Project (CVP) water supplies. We show that the following relationship describes willingness to pay:

$$Value = 144.5767(\Delta Mean) - 73.9620(\Delta Var),$$

where $\Delta Mean$ is a change in the mean and ΔVar is a change in the variance of CVP deliveries. Thus, keeping variance constant, the value to growers of a one acre foot

D-054041

increase in mean deliveries is $145, ignoring the cost of the water. An increase in the variance of deliveries decreases expected per acre profits.

One finding of the case study is that expanding the scope of water trading within the Authority significantly lowers the value of increases in water supply reliability. The basic reason for the result is that there are large differences in access to CVP water supplies among growers in the area. The value to junior rights holders of increases in water supply reliability is relatively high. However, if an expansion of the regional water market reduces the cost of supplemental water to junior rights holders, then their valuation of the increase in reliability is also lower.

The second and third chapters consider the impact of changes in reliability on specific types of capital investments. Chapter 2 presents a detailed conceptual model of the influence of reliability on land allocation among permanent and annual crops. Theoretical results show that the influence of reliability depends on the marginal cost of obtaining non-project water supplies. Cases are identified where increasing the reliability of project water supplies increases or decreases investment in permanent crops. In a prior appropriation system, reliability is associated with seniority, and we exploit cross-section differences in seniority within the Authority to assess the impact of reliability on investment in permanent crops. An empirical test is presented wherein land allocation is compared between exchange and service contractors in the SLDMWA. Statistical results show that the influence of the seniority of water rights on land allocation and water productivity is statistically significant and large. Thus, increasing the reliability of CVP water supply would be expected to increase the acreage of permanent crops in the Authority.

The final chapter considers the effect of changes in the distribution of water price on the incentives to adopt water-conserving irrigation technologies. A two-stage decision model is developed wherein agents make long-term decisions about irrigation technology investments and decide production levels based on short-term realizations of water price. Comparative statics results show that the impact of changes in the distribution of water price hinge on the responsiveness of cultivated acreage to fluctuations in the price of water. The model is tested using a unique data set on irrigation technology investment from the Arvin-Edison Water Storage District in Kern County. Econometric results strongly support the conceptual model, and show that changes in the distribution of water price have systematically different impacts on permanent and annual crops. Thus, increasing water supply reliability is expected to have an ambiguous effect on farm-level water-use efficiency in the SLDMWA.

D-054043

Chapter 1:

Capital Investment and The Value of Changes in Agricultural Water Supply Reliability

Abstract

The chapter presents a general model of the impact of changes in the distribution of surface water supplies on farm-level water use and profitability. The framework allows that farmers have access to non-project water supplies such as groundwater or imported water purchased on a water market. The model distinguishes between long-run capital investments that are not changeable in the short run, and temporary decisions. Short-run decisions depend on the current level of project water allocation and on prior capital investments; capital investments are heavily influenced by the distribution of surface water supplies. Theoretical results define conditions under which changes in the distribution of project water supplies increase expected profits, provide incentives for increased capital investment and increase the amount of supplemental water procured. In a case study, the model is applied to the San Luis & Delta-Mendota Water Authority to measure the willingness of growers to pay for arbitrary changes in the distribution of Central Valley Project water supplies.

Introduction

A fundamental aspect of agricultural water use in the western United States is that the supply of water from government projects is variable. Annual water availability depends on natural fluctuations in precipitation, and also on features of the supply and conveyance infrastructure. While it is impossible to influence weather, governments still have the capacity to alter the distribution of water availability, for example by making infrastructure investments. This study develops a method for measuring the value of changes in the distribution of surface water supplies.

The model captures some important aspects of water use in the western United States. In particular, we allow for the possibility that growers have access to non-

D-054044

project sources of water. Examples include groundwater and water purchased on local water markets. These sources of water are typically more expensive than water from federal and state reclamation projects. Hence, agricultural customers typically take all of the project water to which they are entitled and then supplement with pumping and water market purchases as they desire. This two-tiered structure is somewhat unique to water, although economists have also explored the possibility of bypass in the telecommunications, electric and natural gas industries (Laffont and Tirole).

The valuation model also distinguishes between long-run capital investments that are not changeable in the short run, and temporary decisions. Short-run decisions such as production levels for annual crops and the amount of groundwater pumping depend on the current level of project water allocation and on prior capital investments. Capital investments such as the establishment of trees and vines and investment in specialized farm equipment can be altered in the long run but, once selected, cannot be changed from year to year. In this respect, the model exhibits the "putty-clay" property (Johansen; Solow; Calvo; Sheshinski; Cass and Stiglitz; Atkeson and Kehoe; Green and Sunding). Because they are both long-run phenomena, capital investment decisions are heavily influenced by the distribution of surface water supplies.

Theoretical results developed here show how changes in the distribution of project water supplies affect farm-level water use decisions and, ultimately, long-run farm profits. For example, we consider how change in the distribution of surface water supplies affects the level of capital investment. We develop theoretical conditions under which changes in the distribution of surface water supplies will increase or decrease various types of capital investments. We also develop predictions about the impact of the surface water supply distribution on the amount of supplemental water procured by farmers. This result is important because it is essential that water managers know how changes in the surface water supply infrastructure will impact the amount of groundwater extraction.

With respect to changes in farm profits (or, alternatively the willingness of agricultural water users to pay for changes in the distribution of project water), we derive some fundamental theoretical and empirical results. When growers supplement project supplies with non-project water, we show that the value of a change in the distribution of surface water deliveries is a function of how it impacts the procurement of supplemental water. In particular, if surface water is used first since it is cheapest, then the value to farmers of providing small amounts of additional surface water is the avoided cost of the supplemental water. This result has important empirical implications, since in most regions, there is readily available and accurate information about the cost of supplemental water.

An important implication of the analysis is presented graphically in Figure 1. Consider the case where the water supply can take one of two values, and an increase in reliability is reflected by an increase in the lower support.[1] In the baseline case where these values are equally likely, the expected value of farm profit is given by $E\pi^A$. If growers make capital investments that affect the marginal productivity of water, and the level of investment is a function of the water supply distribution, then

[1] This formulation is consistent with the first-order stochastic dominance assumption made earlier.

an increase in seniority alters the *ex post* value of water. This productivity shift is captured in Figure 1 as a shift in the profit function from $\pi(A)^0$ to $\pi(A)^1$. Altering the water supply distribution thus has a value of $E\pi^C - E\pi^A$, which is the value as calculated in our model. Ignoring the impact of changes in the supply distribution on long-run capital investment, one would underestimate the expected profit gain from the increase in seniority as $E\pi^B - E\pi^A$. Similarly, treating long-run capital as completely malleable also biases the valuation of changes in water supply reliability.

In a case study, the conceptual model is applied to the San Luis & Delta-Mendota Water Authority to measure the willingness of growers to pay for arbitrary changes in the distribution of Central Valley Project water supplies. We parameterize the distribution of surface water supplies and measure the willingness of growers to pay for changes in the moments of the distribution. These values can then be compared to the cost of altering the distribution, usually through capital investments in water storage and conveyance infrastructure.

As an alternative to these types of investments, we also consider the impact of expanded water trading on the value of water supply reliability. One finding of the case study is that expanding the scope of water trading in the western San Joaquin Valley can significantly lower the value of increases in water supply reliability. The basic reason for this result is that there are large differences in access to surface water supplies among growers in the area. The value to junior rights holders of increases in water supply reliability is relatively high. However, if an expansion of the regional water market reduces the cost of supplemental water to junior rights holders, then their valuation of the increase in reliability is also lower. Empirical results show that

D-054047

expanded water trading reduces the value of an increase in mean project deliveries by more than 30 percent. Thus, water trading is, to some degree, a substitute for investments in new water supplies for west side agriculture.

The Model

The farmer receives a stochastic allocation of surface water from a government water project. Let A represent this allocation, and assume that there is no charge for A. A has a known distribution $f(A;\theta)$ with support $[\underline{A},\overline{A}]$ so that $F(\underline{A};\theta)=0$ and $F(\overline{A};\theta)=1$. The parameter θ indexes the distribution, and is a function of public policy choices.

Net farm returns are given by $\pi(W,z)-C(I)$, where W is total water use and I is the amount of non-project (or incremental) water obtained. Total water use is the sum of project water and incremental water, or $W=A+I$. Net returns are also influenced by capital investment, denoted by z.[2] At this stage, we will be general in the treatment of these expenditures, and will work out special cases later. For now, it is sufficient to assume that $\pi_W>0$, $\pi_{WW}<0$, $\pi_z>0$, $\pi_{zz}<0$, and that $C_I>0$ and $C_{II}>0$.

The optimization problem consists of two stages. In the first stage, the farmer chooses the level of capital investment. These expenditures have the "putty-clay" property of being malleable *ex ante*, but fixed in the short run. For example, z could

[2] Alternatively, z could denote physical units of capital measured in such a way as to normalize the price at 1.

denote investment in perennial crops or irrigation technology. In the second stage of the optimization problem, once the level of project water supply is realized the farmer decides the amount of total water use by selecting an amount of incremental water to procure, if any.

As usual, we solve the model by working backwards. The second stage, or short-run maximization problem is

$$(1) \qquad \max_{I} \quad \pi(A+I,\bar{z})-C(I),$$

where capital is denoted as $z=\bar{z}$ since it is fixed in the short run. The first order condition is the following:

$$(2) \qquad \pi_W - C_I = 0 \ \forall A.$$

The second order condition for this problem is $\pi_{WW} - C_{II} < 0$, which is ensured by the assumptions on second derivatives above. The short-run optimality condition states that the farmer will procure supplemental water until the point at which its marginal benefit equals marginal cost, conditional on the current realization of project water supply and past capital investments. Denote the short-run optimal level of incremental water as $I(A,\bar{z})$.

The first stage, or long-run maximization problem is

$$(3) \qquad \max_{z} \quad \int_{\underline{A}}^{\bar{A}} [\pi(A+I(A,z),z)-C(I(A,z))]f(A)dA - z,$$

which has the following first order condition:

$$\int_{\underline{A}}^{\bar{A}} \left[\pi_W \frac{dI}{dz} + \pi_z - C_I \frac{dI}{dz}\right] f(A)dA - 1 = 0.$$

By the short-run first order condition (2), this expression reduces to

(4) $$\int_{\underline{A}}^{\overline{A}} \pi_z f(A)dA - 1 = 0.$$

Thus, the level of capital investment is such that the expected marginal productivity of capital equals its marginal price. At this point, we allow for the possibility that capital is either complementary to or a substitute for applied water.

Comparative Statics

The central question of the chapter is to value changes in the distribution of project water supplies. That is, we wish to measure the change in expected farm profit resulting from a change in the parameter θ. Define expected profit as

(5) $$E\Pi = \int_{\underline{A}}^{\overline{A}} \left[\pi\left(A + I(A,z^*), z^*\right) - C\left(I(A,z^*)\right)\right] f(A)dA - z^*.$$

Taking the derivative of (5) with respect to θ, it follows that

$$\frac{dE\Pi}{d\theta} = \int_{\underline{A}}^{\overline{A}} \left[\pi_W \frac{dW}{dz}\frac{dz}{d\theta} + \pi_z \frac{dz}{d\theta} - C_I \frac{dI}{dz}\frac{dz}{d\theta}\right] f(A)dA - \frac{dz}{d\theta} + \int_{\underline{A}}^{\overline{A}} [\pi - C] f_\theta dA,$$

assuming that the supports of the water supply distribution are invariant with respect to the policy parameter. Using equations (2) and (5), this expression reduces to

(6) $$\frac{dE\Pi}{d\theta} = \int_{\underline{A}}^{\overline{A}} [\pi - C] f_\theta dA.$$

We now consider general conditions under which (6) can be signed, that is, we wish to uncover cases in which changes in the project water distribution will increase expected profit. Fortunately, the ranking theorems of Rothschild and Stiglitz provide some useful tools in this regard. To apply these theorems, it is necessary to understand how long-run profits, Π, respond to changes in A. First, it is straightforward to show that Π is increasing in A. Formally,

$$\begin{aligned}\frac{d\Pi}{dA} &= \pi_W\left(1+\frac{dI}{dA}\right) - C_I\frac{dI}{dA} \\ &= \pi_W > 0,\end{aligned}$$

It is also necessary to establish whether Π is concave. Differentiating again, we see that

$$\begin{aligned}\frac{d^2\Pi}{dA^2} &= \pi_{WW}\left(1+\frac{dI}{dA}\right) \\ &= \pi_{WW}\left(\frac{-C_{II}}{\pi_{WW} - C_{II}}\right) < 0.\end{aligned}$$

The inequality results from the assumptions that $\pi_{WW} < 0$ and $C_{II} > 0$, and from the short-run second order condition ($\pi_{WW} - C_{II} < 0$). Thus, Π is increasing and concave in A.

To see how the ranking theorems can be applied to this model, consider a special case of (6) that arises when considering the notion of water right seniority. In the western United States, surface water is allocated by a priority-based queuing system in which some users are allocated water before others. Under this "prior appropriation" rule, a marginal increase in seniority (indexed by θ) decreases the probability that the water right holder receives less than any arbitrary amount of water from the project. That is, seniority is synonymous with first order stochastic dominance as defined by Rothschild and Stiglitz: if θ' is senior to θ, then

$F(A;\theta') \le F(A;\theta) \; \forall \, A$, with the inequality being strict in some region (i.e., $F_\theta \le 0$).[3] Thus, in a prior appropriation system where users make durable capital investments in water use, an increase in seniority increases expected profits so long as Π is increasing in A, which was verified above.

One benefit of using the stochastic dominance ranking theorems is that they permit consideration of less restrictive changes in the distribution of project water supplies. For example, if the proposed project water distribution only second order dominates the status quo distribution, then the fact that Π is increasing and concave in A is sufficient to ensure that this change also increases expected profits. Further, if the proposed change in project deliveries simply reduces the variance of project supplies but leaves the mean unchanged (as with a simple water banking project that reallocates water from year to year), then expected profits still increase. These conclusions are quite general as they follow from unrestrictive assumptions about the diminishing marginal productivity of applied water and the increasing marginal cost of obtaining non-project water.

Before moving on to other parts of the analysis, it is important to spell out how the analysis can be applied for empirical work; doing so also provides intuition for the results obtained thus far. Equation (6) can be manipulated as follows to yield a convenient expression:

$$\frac{dE\Pi}{d\theta} = \int_{\underline{A}}^{\bar{A}} [\pi - C] f_\theta \, dA$$

---

[3] This formulation is consistent with the seminal analysis of Burness and Quirk.

$$= [\pi - C]F_\theta \Big|_{\underline{A}}^{\bar{A}} - \int_{\underline{A}}^{\bar{A}} \left[\pi_W \left(1 + \frac{dI}{dA}\right) - C_I \frac{dI}{dA} \right] F_\theta dA$$

$$= -\int_{\underline{A}}^{\bar{A}} \pi_W F_\theta dA$$

(7) $$= -\int_{\underline{A}}^{\bar{A}} C_I F_\theta dA,$$

where the last two steps use the short-run first order condition (2). Equation (7) indicates that the marginal value of changes in the distribution of project water is related to its impact on the purchase of supplemental water. Information on the marginal cost of supplemental water is usually easy to come by since pumping depth and hence the cost of groundwater is easily known in most areas, and information on water market prices is also fairly simple to obtain (in the worst case through interviews with farmers). This data provides information about the function C_I. As in the case study section of this chapter, some parametric assumptions will typically be made about the water supply distribution F. For example, we assume that this distribution is lognormal. Working with a parametric specification, it is possible to value changes in the moments of the distribution directly by using equation (7).

There is another nonparametric approach to valuation. Equation (7) indicates that the marginal value of changes in the distribution of project water is related to its impact on the purchase of supplemental water. This equation is most convenient if the researcher has specified a parametric distribution and knows how the policy change will alter the moments of the distribution. Often, however, in water policy work one only knows how a policy change will alter deliveries in various types of water years. That is, the researcher only has a comparison of deliveries before and after some policy change such as construction of a canal or reservoir. In this case, (7) is not convenient to work with. Fortunately, (7) expression can be rewritten to yield the following:

$$(8) \qquad \frac{dE\Pi}{d\theta} = -\int_{\underline{A}}^{\bar{A}} C_l F_\theta dA = \int_{\underline{A}}^{\bar{A}} C_l \Delta A f(A) dA,$$

where ΔA is the change in the amount of water available to growers at each previous level of A, holding F constant. Intuitively, both expression (7) and (8) indicate that the marginal value of a change in the surface water distribution is the change in expected expenditures on supplemental water. It is significant that both (7) and (8) hold current water use patterns constant, in particular current land use patterns and levels of investment in water use capital. This result is also important for empirical applications of the model.[4]

Returning now to the theoretical analysis, it is of interest to know how farm-level decisions are affected by changes in the distribution of project water supplies. First consider how changes in θ affect capital investments, z. Totally differentiating equation (4), we see that

$$(9) \qquad \frac{dz}{d\theta} = \frac{-\int_{\underline{A}}^{\bar{A}} \pi_z f_\theta dA}{\int_{\underline{A}}^{\bar{A}} \pi_{zz} f(A) dA}.$$

The denominator is the long-run second order condition, which is negative. Further examination of the numerator is required to sign (9). Integrating this expression by parts, the numerator becomes

[4] It is worth repeating, however, that this result holds only for marginal changes in f.

$$(10) \quad \int_{\underline{A}}^{\bar{A}} \pi_z f_\theta dA = \int_{\underline{A}}^{\bar{A}} \pi_{zw}\left(1+\frac{dI}{dA}\right)F_\theta dA,$$

where $dI/_{dA} = {-\pi_{ww}}/_{SRSOC}$ is found by total differentiation of the short-run first order condition. Substituting this expression in (10), it follows that

$$(11) \quad \frac{dz}{d\theta} = \frac{-\int_{\underline{A}}^{\bar{A}} \pi_{zw}\left(1-\frac{\pi_{WW}}{SRSOC}\right)F_\theta dA}{LRSOC}.$$

The effect of changes in the project water supply distribution on water use investments depends on the interplay of two factors. First, it depends on whether these investments are complementary to or a substitute for applied water, that is, on the sign of π_{zW}. Second, the sign of (11) depends on the concavity of π with respect to water application, or on the magnitude of π_{WW}.

Finally, we would also like to determine how supplemental water purchases vary with changes in the distribution of project water supplies. Taking a long-run perspective,

$$\frac{dEI}{d\theta} = \frac{d}{d\theta}\int_{\underline{A}}^{\bar{A}} I(A,z)f(A;\theta)dA.$$

Differentiating and then integrating by parts, it follows that

$$(12) \quad \frac{dEI}{d\theta} = \int_{\underline{A}}^{\bar{A}} \frac{\pi_{zW}}{SRSOC}\frac{dz}{d\theta}f(A)dA + \int_{\underline{A}}^{\bar{A}} \frac{\pi_{WW}}{SRSOC}F_\theta dA.$$

This last expression uses the fact that the short-run first order condition implies that $dI/_{dz} = {-\pi_{zw}}/_{SRSOC}$. This expression is also of ambiguous sign, depending on the relative magnitudes of π_{zw}, π_{WW} and $dz/_{d\theta}$. Despite this result, equation (11) does raise the interesting possibility that a stochastically dominant increase in surface water deliveries (i.e., $F_\theta \leq 0 \; \forall \; A$) may actually increase the amount of groundwater pumping or water market purchases. This result may occur through the effect of the water supply distribution on capital investments. If the shift in the project water distribution induces enough investment of the type that increases the marginal productivity of water application, then even a stochastically dominant shift in project water deliveries can increase the expected amount of supplemental water purchased.

Case Study: San Luis & Delta-Mendota Water Authority

In this section the conceptual model is quantified using data from the San Luis & Delta-Mendota Water Authority in California's San Joaquin Valley. We utilize the parametric approach implicit in equation (7) since our analysis does not assume any particular change in the water storage and conveyance infrastructure. That is, we wish to know how growers value general changes in the moments of the surface water supply distribution. It is most convenient to use a parametric approach to obtain closed-form solutions to the main theoretical relationships, and to measure the marginal values derived in the previous section. Suppose that $f(A;\theta)$ is lognormal; this specification is reasonable since it constrains per-acre deliveries to be non-negative and fits the observed distribution of deliveries well.[5] That is,

$$f(A;\theta) = \frac{1}{\sqrt{2\pi}\sigma(\theta)A} \exp\left[\frac{-(\ln A - \mu(\theta))^2}{2\sigma(\theta)^2} \right],$$

[5] A qq-plot of normalized log deliveries against lognormal scores is approximately linear.

where the moments are written as functions of policy choices. Eliminating these arguments for presentation purposes only, the moments of the distribution are

$$\mu_n' = \exp\left(n\mu + \frac{n^2\mu^2}{2}\right),$$

so that

$$\bar{A} = \exp\left(\mu + \frac{\sigma^2}{2}\right), \text{ and}$$

$$Var(A) = \exp(2\mu + \sigma^2)(\exp(\sigma^2) - 1).$$

The density *f* is parameterized using historical per-acre deliveries to service contractors in the SLDMWA. The U.S. Bureau of Reclamation provided these data. Using historical deliveries, we find that $\mu = 0.5286$ and $\sigma^2 = 0.1682$; these parameters imply that $\bar{A} = 1.8454$ and $Var(A) = 0.6238$.

The other function that must be parameterized is the marginal cost of supplemental water as a function of per-acre deliveries and prior investments in water-use capital. This function is measured by considering the spatial distribution of the cost of groundwater in the Authority.[6] The theory behind this assumption is that there is a competitive water market within the Authority's service contract area. This market equates the marginal price of supplemental water across all microunits (farms or water districts) within the region. Groundwater depths and pumping costs are taken from the inventory of groundwater wells in the central Western San Joaquin Valley compiled by Gronberg et al., and analyzed in Gronberg and Belitz, Belitz and

---

[6] This technique of using spatial microparameter distributions for environmental analysis was developed by Green and Sunding (1999).

Phillips, and Belitz et al. An exponential function was fit through the data given in these studies to obtain the per-acre cost of supplemental water. The regression results are given in Table 1, along with basic measures of goodness of fit. The estimated relationship between the per-acre cost of supplemental water as a function of per-acre project deliveries is as follows:

$$\ln C = 4.6990 + 1.5515 \ln A.$$

For example, if project deliveries are 1.8 acre feet per acre, then the estimated function implies that growers spend $78 per acre on supplemental water; if deliveries are only 1.0 acre foot, then supplemental water cost is $228.

With this information in hand, it is possible to calculate marginal value according to equation (7).[7] Since we have selected a parametric representation of the density function *f*, we will consider the marginal valuation of changes in the moments of the density (i.e., the mean and the variance, since the lognormal is a two-parameter distribution). These figures are somewhat difficult to interpret directly because if we vary only one parameter of the distribution of ln*A*, both moments of the distribution of *A* change. Thus, we calculate the slope of the hyperplane in the $\Delta\bar{A}, \Delta VarA$ space

---

[7] The form of (7) that is most convenient to estimate empirically is derived by integration by parts and cancellation:

$$\frac{dE\Pi}{d\theta} = \int_{\underline{A}}^{\bar{A}} C(I(A)) \left(\frac{dI}{dA}\right)^{-1} f_{\theta}(A;\theta) dA.$$

to measure the marginal value of changing the mean and variance of A itself.[8] This hyperplane has the following form:

$$(13) \quad Value = 144.5767(\overline{A}' - \overline{A}) - 73.9620(VarA' - VarA).$$

Thus, the per-acre value to service contractors of changing the mean of project deliveries by one acre foot per acre is $145. Equation (13) also defines an indifference relationship for the service contractors, and indicates that for a one-unit increase in the variance of deliveries, service contractors need to be compensated by increasing mean deliveries by about one-half of an acre foot per acre.

It is of interest to know how water trading would alter the value of changes in the distribution of surface water supplies. Broadly, the study area is comprised of growers with two different types of water rights. The service contractors described above have relatively junior rights, and thus have low mean deliveries. The so-called exchange contractors have much more senior rights. Not surprisingly, exchange contractors usually have cheaper supplemental water than service contractors. In part, this fact results from the large amount of deep percolation in exchange contracting areas. Another factor that influences relative groundwater costs in the study area is the fact that a higher fraction of exchange contractors can pump groundwater from an unconfined aquifer, whereas most service contractors must pump from a deeper, confined aquifer. With an active regional water market, the cost to service contractors of supplemental water is

$$\ln C = 4.7159 + 1.0047 \ln A.$$

[8] Note that "Value" is the value of a change in the distribution, so the value of the status quo mean and

D-054059

These results are derived by the same procedure used to define the water cost relationship for service contractors alone, and regression results are shown in Table 1. The relationship implies that if project deliveries are 1.0 acre foot, then supplemental water cost is $179, compared to $228 per acre with no trading between exchange and service contractors.

If service and exchange contractors can trade freely, the marginal cost of supplemental water to service contractors is reduced. This, in turn, lowers service contractors' valuation of additional surface water supply. Performing the same exercise as described in the preceding paragraph, but this time using the supplemental water cost function that results from regional trading, we find that the value hyperplane becomes the following:

$$(14) \qquad Value = 93.7453\left(\bar{A}' - \bar{A}\right) - 43.5448\left(VarA' - VarA\right).$$

Thus, trading between exchange and service contractors reduces the value of a unit change in mean deliveries from $145 per acre to $94 per acre – a drop of over 34 percent. This analysis suggests that, to some degree, water trading within agriculture is a substitute for additional investment in water supply reliability.

Conclusions

The chapter begins by characterizing water supply reliability. Although the term is widely used in water policy debates, it is actually quite ambiguous. In this study, reliability is couched in terms of changes in the probability of receiving various

---

variance of lnA is 0.

D-054060

amounts of surface water. As commonly used in a policy context, the term reliability is most synonymous with the following definition: one distribution is more reliable than another if it increases (or leaves unchanged) the probability of receiving from the project more than any arbitrary amount of water. That is, the grower never receives less water. By this definition, reliability increases mean deliveries, perhaps substantially, and may increase or decrease the variance of deliveries. But this is not the only possible definition of reliability. In common usage, reliability implies assurance. Thus, a decrease in the variance of deliveries can also be said to increase reliability. In the context of west side agriculture, a distribution that assured growers they would always receive 1 acre foot per year would certainly be more "reliable" than the present water supply distribution, but this increase in reliability would not be desirable. As the term is used by agricultural interests, what is usually meant by reliability assumes an increase in expected deliveries.

The chapter presents a general model of the impact of changes in the distribution of surface water supplies on farm-level water use decisions and on farm profitability. The model recognizes that farmers make both short- and long-run decisions that are influenced by the distribution of surface water supplies. In the long run, farmers make capital investments that are not easily altered from year to year. Investments in perennial crops, specialized farm machinery, and irrigation systems are all examples. Growers make other decisions that are more temporary in nature, and that are influenced by annual project water allocations. The amount of groundwater pumped, the acres planted to annual crops, and the amount of water

D-054061

bought and sold on local water markets are all short-run decisions. These decisions are also influenced by prior capital investments.

We consider the impact of changes in the distribution of surface water on both short- and long-run farm decisions. The first chapter of the report presents the basic framework of the valuation model, and develops many of the basic theoretical results. Among the conceptual results are the following:

- A first order stochastically dominant increase in the reliability of surface water deliveries increases expected farm profits. A mean-preserving decrease in the variance of deliveries also increases expected profits.
- When surface water is supplemented with water from other sources, the value of small changes in the surface water distribution is related to the avoided cost of supplemental water. This conclusion is especially important for empirical analysis since the cost of groundwater (or water purchased on local water markets) is usually easy to measure.
- Changes in the distribution of surface water can increase or decrease the amount of long-run capital investment. The direction of the change depends on whether the investment increases or decreases the productivity of applied water. For example, under normal conditions an increase in reliability is expected to increase the amount of perennial crops grown. However, the same shift can decrease the incentive to invest in water-conserving irrigation technologies.

- Changes in the distribution of surface water can increase or decrease the amount of supplemental water procured. In part, the direction of the response depends on how capital investment changes. Stabilization of surface supplies that increases the amount of capital investment and thereby increases the marginal productivity of water application increases the amount of supplemental water used by farmers. In this way, stabilization of surface water deliveries can increase the expected amount of groundwater pumping.

In a case study, the model is applied to the San Luis & Delta-Mendota Water Authority to measure the willingness of growers to pay for arbitrary changes in the distribution of Central Valley Project water supplies. Using a previous inventory of the cost of groundwater in the region, we show that the gross per acre value of a one acre foot change in mean surface deliveries is $145. A one-unit increase in the variance of deliveries decreases expected profit by $74 per acre.

An important finding of the case study is that expanding the scope of water trading in the west side of the San Joaquin Valley can significantly lower the value of increases in water supply reliability. The basic reason for the result is that there are large differences in access to surface water supplies among growers in the area. The value to junior rights holders of increases in water supply reliability is relatively high. However, if an expansion of the regional water market reduces the cost of supplemental water to junior rights holders, then their valuation of the increase in reliability is also lower. In the case study, if a regional water market is established in

D-054063

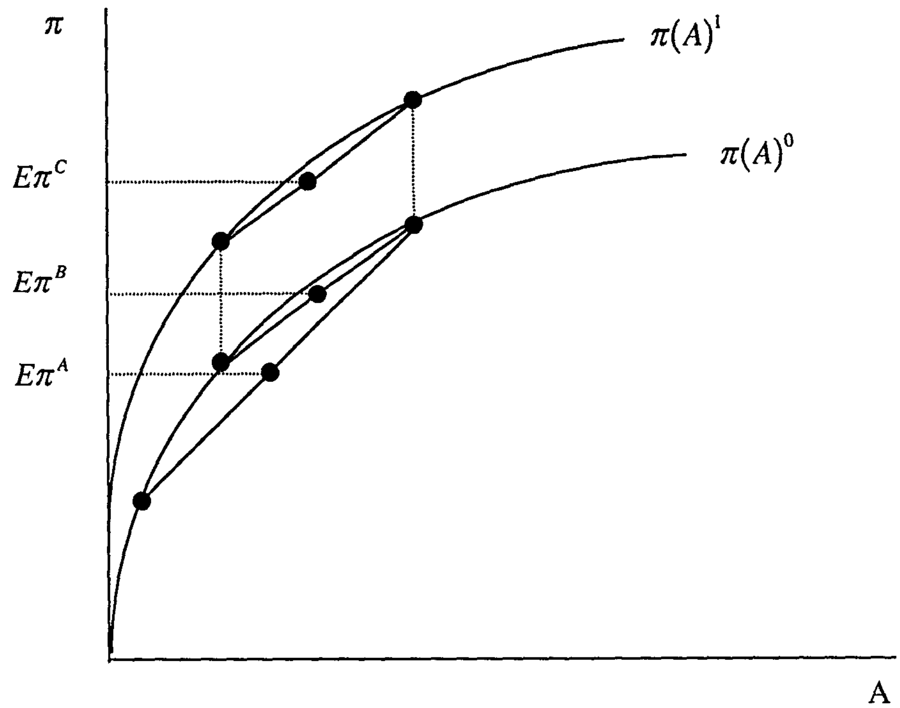
which junior rights holders can trade freely with senior rights holders, the value of a one acre foot increase in mean deliveries is $94, or a drop of over 34 percent.

Table 1: Estimated Cost of Supplemental Water

	Dependent Variable: ln C	
	Service	*Aggregate*
Constant	4.6990	4.7159
	(55.3625)	(46.6810)
ln A	1.5515	1.0047
	(20.6838)	12.4994)
R^2	0.9839	0.9398

*t-statistics in parentheses.

Figure 1: Effect of a Change in Reliability on *Ex Post* and *Ex Ante* Profits



Chapter 2:

Reliability, Land Allocation and Water Productivity

Abstract

The chapter presents a conceptual model of the influence of reliability on land allocation among permanent and annual crops. Theoretical results show that the influence of reliability depends on the marginal cost of obtaining non-project water supplies. Cases are identified where increasing the reliability of project water supplies increases or decreases investment in permanent crops. An empirical test is presented wherein land allocation is compared between two groups of agricultural water districts in California who have different levels of project water supply reliability. Statistical results show that the influence of the reliability of water rights on land allocation and water productivity is statistically significant and large.

Introduction

This chapter addresses the relation between water supply reliability and patterns of agricultural water use. In particular, the chapter examines how land allocation and the productivity of surface water used in irrigated agriculture are influenced by the distribution of surface water supplies. A fundamental decision about land allocation is between permanent and annual crops. Permanent crops typically generate higher profits per unit of water applied, but also consume more water per acre. In the event that project-provided surface supplies are insufficient to meet permanent crop irrigation needs, growers must obtain high-priced water from other sources. By contrast, annual crops generate lower levels of profit per acre foot of water applied, but are also more flexible in that they can be produced at levels that are responsive to annual water supply conditions. A long-run equilibrium land allocation is achieved when the expected marginal cost of producing the perennial crop, including expected

D-054067

supplemental water costs, equals the marginal benefit of producing these crops.

By differentiating between permanent and annual crops, this chapter endogenizes water productivity as a function of the known distribution of surface water deliveries. A goal of the analysis is to show how water productivity in irrigated agriculture is influenced by the moments of the water supply distribution. Senior water rights holders have supplies that are more reliable (in the sense of first order stochastic dominance) than the supplies of junior rights holders, and have an enhanced incentive to devote more land to permanent activities that harden water demand.

By accounting for the influence of property rights on land allocation, the chapter extends the literature on efficient water allocation and the valuation of water rights originating with Burness and Quirk. They consider the effect of water supply distributions on investments in water use, emphasizing the implications of the requirement that irrigators make investments in conveyance and water use infrastructure before receiving project supplies. Their analysis does not examine the land allocation effects of the seniority of water rights, and does not quantify the investment effects they do consider.

Our conceptual model goes further than Burness and Quirk in that it can also be used to assess the equilibrium impacts of changes in the moments of the surface water supply distribution. For example, a straightforward groundwater-banking project may achieve inter-year reallocation and hence stabilize water supplies, but leave mean supplies virtually unchanged. This type of project alters the distribution of available water supplies, but does not correspond to the first order stochastic

D-054068

dominance concept relevant to an analysis of water right seniority.

The conceptual model is tested using data on land allocation and water project deliveries taken from the San Luis & Delta-Mendota Water Authority. The Authority is an ideal location to test the hypotheses generated in this chapter. The Authority is comprised of two basic types of water districts that differ according to their entitlement to CVP water. One type of district has more senior rights than the other, and the water supply of this group stochastically dominates the distribution of the other group. We test the hypothesis that there are differences in land allocation between these two types of districts, controlling for variations in environmental conditions such as soil quality and elevation, and economic factors such as the cost of supplemental water. The data used to test the hypothesis are taken from a Geographic Information System (GIS) database developed by the authors; the empirical section describes the procedures used to compile them. The econometric results show that the growers holding senior water rights are 39% more likely to produce perennial crops; this result is also highly significant.

The Model

Consider a situation in which land is allocated between permanent and annual crops. Surface water is provided from a public irrigation project at subsidized rates (free, without loss of generality), but delivered in random amounts. Figure 1 is a timeline that shows the basic sequence of events. In the short run, after surface water supplies are realized, land is allocated to annual crops conditional on past investments in the permanent crop (which translates into the "firm" portion of water demand) and

D-054069

current surface water availability. The model allows for procurement of supplemental water supplies, say from groundwater pumping or a local water market, and this procurement decision is also made after current-year project supplies are realized. It is possible that in some types of water years no annual crop will be produced at all; this equilibrium occurs when the marginal cost of procuring additional water exceeds the marginal return from the annual crop. It is also possible that no additional water will be procured. The second type of land allocation decision is the long-run choice of permanent crop production capacity. This decision is made to maximize expected profit given the known distribution of surface water supplies. This distribution is conditional on the seniority of the underlying water right.[1]

Short Run Behavior

In the short run, the farmer maximizes current-year profit by choosing the amount of land allocated to the annual crop, given prior plantings of the perennial crop and the current year's allocation of project water. The farmer's short-run optimization problem is as follows:

$$\max_{L} \quad \Pi = \pi_{\overline{H}}(\overline{H})a_{\overline{H}}\overline{H} + \pi_L(L)a_L L - C(a_{\overline{H}}\overline{H} + a_L L - A) \ ,$$

where H denotes acres devoted to the perennial crop, L is acres of the annual crop, π_H and π_L are net returns per acre foot of applied water (excluding expenditures on supplemental water), a_H and a_L are crop water requirements per acre, A is the per-

[1] This formulation is stylized, and the treatment of annual and permanent crops is fairly general. In particular, "permanent" crops need not be only perennials, but rather any type of activity where there is a pre-commitment to a particular level of production. Production of fresh vegetables fits this description, especially when production takes place under a distribution contract.

acre allocation of project water, and $C(I)$ is the cost of supplemental water.[2] Land allocated to the permanent crop is denoted $\overline{H}$ to indicate that it is fixed in the short run.

The solution to the short-run problem is straightforward: land is allocated to the annual crop to equalize the net return per unit of water applied and the marginal cost of supplemental water. The equilibrium condition is

$$\pi_L'(L)L + \pi_L(L) - C'(a_H\overline{H} + a_L L - A) = 0,$$

which implicitly defines the short-run production of the annual crop as a function of permanent crop capacity and project water allocation, or $L^* = L(\overline{H}, A)$.

This equilibrium condition is illustrated in Figure 2. The horizontal axis in the figure is supplemental water, and land allocated to the permanent crop (and hence, the amount of water needed by the permanent crop) is fixed. The marginal revenue from irrigating the annual crop is MR_L/a_L; note that this figure works with marginal revenue of water application to the annual crop, which is a simple transformation of the marginal revenue of land allocation. To determine the optimal amount of water used on the annual crop, the farmer simply finds the point in the right-hand quadrant where the marginal cost of water is equal to the marginal revenue of water applied to the annual crop.

For example, suppose that the project water supply is A_1, the permanent crop water requirement is $a_H\overline{H}$, and $a_H\overline{H} > A_1$. Then the farmer will procure $a_H\overline{H} - A_1$ units of supplemental water to produce the permanent crop. This implies that the first unit of supplemental water that can be purchased for use on the annual crop has a cost

[2] $I = a_H\overline{H} + a_L L - A$. Net returns and the cost of supplemental water are assumed to be twice

of M, and that the short-run equilibrium occurs at the point where $MC_1 = MR_L/a_L$. The level of permanent crop plantings and the amount of water from the project jointly determine the amount of water and land allocated to the annual crop. Suppose that project water supply is A_1 as before, but the farmer has pre-committed to produce a larger amount of the permanent crop, $\overline{H}' > \overline{H}$. In this case, the first unit of supplemental water available to the farmer for production of the annual crop has a cost of M', which is above marginal revenue. Thus, the farmer does not produce the annual crop.

Figure 2 also helps derive some threshold levels of project water supply that define classes of short-run equilibria. There is a threshold level of project water allocation, denoted $\hat{A}(\overline{H})$, such that

$$\hat{A}(\overline{H}) = \left\{A \mid \pi_L'(0)\cdot 0 + \pi_L(0) - C'(a_{\overline{H}}\overline{H} - A) = 0\right\}.$$

Above $\hat{A}(\overline{H})$, the low value crop is produced, and below this level, the water requirements of maintaining the permanent crop production capacity pushes the marginal cost of water to levels where production of the low value crop is uneconomic. Given a pre-existing choice of permanent crop production capacity, $\hat{A}(\overline{H})$ is the level of project water supplies that leaves the farmer just indifferent between producing the annual crop and not.

Figure 2 illustrates how $\hat{\hat{A}}(\overline{H})$ is determined. If marginal returns from producing the annual crop decline, in general there exists a saturation level of land allocated to the annual crop, denoted L_s. The saturation level is the acreage allocated

---

continuously differentiable.

to the annual crop above which marginal revenue of the annual crop is negative. Formally,

$$L_S = \{L \mid \pi_L'(L)L + \pi_L(L) = 0\}.$$

Now define $\hat{\hat{A}}(\overline{H})$ as the project water allocation above which the grower will not increase land allocated to the annual crop; this level of project water supply is also defined graphically in Figure 2. Above the point of saturation, that is,

$$\hat{\hat{A}}(\overline{H}) = \{A \mid a_H \overline{H} + a_L L_S = A\},$$

it is uneconomic for the farmer to purchase supplemental water.

Long Run Behavior: The Capacity Choice Problem

We now turn to the problem of how land is allocated to the permanent crop when future project water supply, or the long-run marginal cost of water, is uncertain. The water supply delivered by the irrigation project has a known, continuous density $g(A;\theta)$ with support $[\underline{A}, \overline{A}]$. The parameter θ indexes the distribution of water supply, and we assume that $G(\overline{A};\theta) = 1$ and $G(\underline{A};\theta) = 0$.

There are four possible production scenarios in the short run that the farmer must consider when choosing the amount of land to devote to the permanent activity:

Case 1: The farmer produces the permanent crop only and procures supplemental water.

Case 2: The farmer produces the permanent crop only but does not procure supplemental water.

Case 3: The farmer produces the permanent crop and the annual crop and procures supplemental water.

Case 4: The farmer produces the permanent crop and the annual crop but does not procure supplemental water.

D-054073

Table 1 describes the conditions under which each scenario occurs.

Case 1 occurs when the project allocation is less than $\hat{A}$ and the marginal cost of supplemental water is above marginal revenue for the annual crop. Case 2 occurs when the farmer's project allocation is greater than the water required to produce the permanent crop, but the farmer does not purchase supplemental water. However, this scenario is inconsistent with profit maximizing behavior. As long as the marginal revenue from the annual crop is positive, the profit-maximizing farmer would use the remaining project water for the annual crop, hence producing both crops. Furthermore, the farmer would purchase supplemental water to produce the annual crop until marginal revenue from the annual crop equals marginal cost of supplemental water. Thus Case 2 is eliminated. Case 3 occurs when the project allocation is between $\hat{A}(\overline{H})$ and $\hat{\hat{A}}(\overline{H})$. Finally, Case 4 occurs for any project allocation above the saturation level of project allocation, $\hat{\hat{A}}$.

The long-run maximization problem is the following:

$$
\begin{aligned}
&\max_{\overline{H}} \int_{\underline{A}}^{\hat{A}(\overline{H})} \left[\pi_{\overline{H}}(\overline{H})a_{\overline{H}}\overline{H} - C(a_{\overline{H}}\overline{H} - A)\right]g(A;\theta)dA \\
(1)\qquad &+ \int_{\hat{A}(\overline{H})}^{\hat{\hat{A}}} \left[\pi_{\overline{H}}(\overline{H})a_{\overline{H}}\overline{H} + \pi_L(L^*)a_L L^* - C(a_{\overline{H}}\overline{H} + a_L L^* - A)\right]g(A;\theta)dA \\
&+ \int_{\hat{\hat{A}}(\overline{H})}^{\overline{A}} \left[\pi_{\overline{H}}(\overline{H})a_{\overline{H}}\overline{H} + \pi_L(L_s)a_L L_s\right]g(A;\theta)dA,
\end{aligned}
$$

where $L^* = L(\overline{H}, A)$ is the short-run optimal level of land allocated to the annual crop, which is conditional on prior investments in the perennial crop and the current amount of project water supply. The first term is expected profit when Case 1 occurs.

The second integral is expected profit when Case 3 occurs. The last integral is expected profit when Case 4 occurs.

Net returns per unit of land can vary with the amount of land allocated to the crop. This specification is quite general, and reflects both market demand considerations as well as variations in land quality that affect yields and costs per acre. The first order condition for this problem is

(2)

$$MR_H - \left[\int_{\underline{A}}^{\hat{A}(\overline{H})} C'(a_{\overline{H}}\overline{H} - A)g(A;\theta)dA + \int_{\hat{A}(\overline{H})}^{\hat{\hat{A}}(\overline{H})} C'(a_{\overline{H}}\overline{H} + a_{\underline{L}}L^{*} - A)g(A;\theta)dA \right] = 0,$$

where $MR_{\overline{H}} = \pi'_{\overline{H}}\overline{H} + \pi_{\overline{H}}$. The bracketed term in equation (2) is the expected marginal cost of water, henceforth denoted EMC.

Equation (2) is highly intuitive, and illuminates how land is allocated in irrigated agriculture to maximize the long-run value of scarce and uncertain project water supplies. Allocating land to the permanent crop is advantageous in that net returns per acre (and per acre foot) are higher for this crop than for the annual crop. However, in equilibrium this extra return is balanced against cost of incremental water. Allocating more land to the permanent crop increases the expected marginal cost of water by increasing the expected marginal cost of non-project water. When project deliveries fall below water requirements for the perennial crop, more water will be procured from non-project sources. Equation (2) shows that land will be allocated to the permanent crop until the net return equals the expected marginal cost of supplemental water. The second order condition for this problem is

(3) $$MR'_{\overline{H}} - \frac{\partial EMC}{\partial \overline{H}} < 0.$$

This expression is assumed to be less than zero to ensure an interior solution.

Marginal Impact of Reliability on Land Allocation

It is now possible to determine the effect of changes in the reliability of water supply on land allocation decisions. Consider first how the amount of land allocated to the perennial crop changes in response to marginal perturbations of the distribution of project water deliveries. Totally differentiating (3), the marginal impact of altering θ is

$$(4) \qquad \frac{d\overline{H}}{d\theta} = \frac{\partial EMC / \partial\theta}{SOC},$$

where SOC is the second order condition in equation (3), making the denominator in (4) negative. The impact of reliability on investment in the permanent crop thus depends on the curvature of the cost function for incremental water supply. This is made clear by the following argument. Recall that the expression for a change in expected marginal cost with respect to a change in seniority is

$$(5) \qquad \frac{\partial EMC}{\partial\theta} = \int_{\underline{A}}^{\hat{A}(\overline{H})} C'(a_{\overline{H}}\overline{H} - A)\frac{\partial g(A;\theta)}{\partial\theta}dA + \int_{\hat{A}(\overline{H})}^{\overline{A}} C'(a_{\overline{H}}\overline{H} + a_L L^* - A)\frac{\partial g(A;\theta)}{\partial\theta}dA.$$

Integrating by parts the terms in (5), we can rewrite the derivative as follows

$$(6) \qquad \frac{\partial EMC}{\partial\theta} = \int_{\underline{A}}^{\hat{A}(\overline{H})} C''(a_{\overline{H}}\overline{H} - A)\frac{\partial G(A;\theta)}{\partial\theta}dA - \int_{\hat{A}(\overline{H})}^{\overline{A}} \left(a_L\frac{\partial L^*}{\partial A} - 1\right)C''(a_{\overline{H}}\overline{H} + a_L L^* - A)\frac{\partial G(A;\theta)}{\partial\theta}dA$$

For now, assume that $\frac{\partial G}{\partial\theta} \le 0 \ \forall\, A$, which implies that reliability is synonymous with first order stochastic dominance.[3]

Table 2 summarizes the comparative static results. When the cost function is concave, that is the cost of incremental water is increasing at a decreasing rate, investment in the permanent crop decreases with an increase in reliability. When the cost function is convex, an increase in reliability may increase or decrease investment in the permanent crop, depending on the impact of water allocation on annual crop plantings. If a change in the annual water allocation, A, has a less than proportional impact on land allocation to the annual crop, which is the most likely case, then investment in the permanent crop increases with reliability. If the impact of A on L^* is more than proportional than the impact of reliability on investment in the permanent is ambiguous.

It is also of interest to assess how the amount of land allocated to the annual crop is influenced by the distribution of surface water availability. Taking a long-run perspective, the expected amount of land allocated to the annual crop is

$$(8) \qquad E[L(\overline{H},A)] = \int_{\hat{A}(\overline{H})}^{\overline{A}} L(\overline{H},A)g(A;\theta)dA.$$

Integrating (8) by parts, it follows that

$$(9) \qquad \begin{aligned} &\int_{\hat{A}(\overline{H})}^{\overline{A}} L(\overline{H},A)g(A;\theta)dA \\ &= L(\overline{H},A)G(A;\theta)\Big|_{\hat{A}(\overline{H})}^{\overline{A}} - \int_{\hat{A}(\overline{H})}^{\overline{A}} \frac{\partial L(\overline{H},A)}{\partial A} G(A;\theta)\, dA. \end{aligned}$$

Using the short-run optimality condition, we obtain

[3] This formulation is consistent with Burness and Quirk.

$$\frac{dL(\overline{H},A)}{dA} = \frac{-C''(a_{\overline{H}}\overline{H} + a_L L - A)}{\pi''(L) + 2\pi' - C''(a_{\overline{H}}\overline{H} + a_L L - A)}.$$

Thus,

$$(7) \qquad E\left[L(\overline{H},A)\right] = L(\overline{H},\overline{A}) + \int_{\hat{A}(\overline{H})}^{\overline{A}} \left[\frac{C''(a_{\overline{H}}\overline{H} + a_L L - A)}{SOC_{SR}}\right] G(A;\theta)\, dA,$$

where SOC_{SR} is the short-run optimality condition, which is negative for a maximum. Differentiating (7) with respect to the policy parameter, we have

$$\frac{\partial E\left[L(\overline{H},A)\right]}{\partial\theta} = \int_{\hat{A}(\overline{H})}^{\overline{A}} \frac{C''}{SOC_{SR}} \frac{\partial G(A;\theta)}{\partial\theta}\, dA.$$

The sign of this derivative depends on the curvature of the cost function. The first term in the integral is negative. The second term is positive if $C'' < 0$ and negative if $C'' > 0$. Thus increasing reliability increases production in the annual crop when marginal cost of incremental water is increasing. However, increasing seniority decreases production in the low value crop when the marginal cost of supplemental water is decreasing.

Empirical Test: San Luis & Delta-Mendota Water Authority

In this section, we test the relationship between water supply reliability and land allocation, and measure its significance. The data used to test the results of the previous section are taken from the San Luis & Delta-Mendota Water Authority. The exogenous physical and environmental characteristics that influence investment choices are described, as well as the process through which the data was integrated into a GIS database. A binomial logistic regression is performed and the results are presented and discussed.

The analysis in the previous sections gives rise to the following null hypothesis: a change in water supply reliability does not affect the choice of investment in permanent crops. Refuting this hypothesis would demonstrate that there is a connection between water supply reliability and investment decisions and would therefore support the theory presented in earlier sections.

Data

Data on land allocation were provided by the California Department of Water Resources (DWR). The data describe crop choice for each individual parcel (field) in the study area. The data cover 1,069,657 acres in five counties (Merced, Kern, Madera, Kings, and Fresno) spanning the SLDMWA service area. The basic unit of analysis is an individual field or parcel. The DWR crop categories are aggregated into a binary variable representing whether the field is planted to a permanent or annual crop. Permanent crops grown in the Authority service area include citrus, deciduous fruits and nuts and vineyards, while annual crops include field crops, grain, hay, irrigated pasture, and rice.

Of primary interest is a grower's choice of whether to allocate land to a permanent crop or an annual crop. The primary exogenous variable is the water supply distribution. Water rights are measured as a binary variable since there are two types of water rights in the study area. The so-called "exchange contractors" have senior water rights and therefore highly reliable water; "delivery contractors" have

D-054079

junior rights and an unreliable surface water supply.[4] This difference in the supply distributions can be seen in Table 3, which displays the historical deliveries to water districts with each right's type from 1981 to 1997 as reported by the United States Bureau of Reclamation (USBR). For the exchange contracting districts, the standard deviation of surface water delivered per acre was 0.356, while the junior rights holding delivery contractors faced a much higher per-acre standard deviation of 0.596.

The geographically referenced polygons representing the water district locations were provided by the USBR. The total acreage of cropping data in delivery contracting districts is 836,860 while the exchange contracting districts contain 232,797 acres.

Other exogenous variables are included to account for agroeconomic factors influencing land allocation. The United States Department of Agriculture's STATSGO project provided spatially explicit polygon coverage of soil water storage. Each polygon was classified as one of four intervals, with type A having the fastest drainage (or lowest water storage measured in inches of percolation per hour) and type D having the slowest drainage (highest water storage). For the parcels in the SLDMWA, Type A was not represented, B covered 17% of the land base, C covered 55%, and D covered 28%.

In many settings, elevation provides an effective proxy for the highly correlated variables of weather and slope (Green et al. and Green and Sunding). As

[4] This terminology arises from the fact that growers in exchange contracting districts drew water from the San Joaquin River before the CVP was built. In exchange for relinquishing the use of river water, they agreed to take delivery of CVP water. Owing to their firm supplies prior to the exchange, they have the first call on the CVP system.

elevation up the side of the San Joaquin Valley increases, slope also increases. Weather conditions are also influenced by elevation, especially the number of frost-free days. Cold air tends to concentrate on the valley floor, the locations higher up the western slope are warmer and drier. Within the SLDMWA service area, the mean elevation is 73 meters, ranging from a maximum of 298, to a minimum of 14, and a standard deviation of 38. Elevation data were provided from the United States Geological Survey as a continuous, geo-referenced grid.

Because groundwater is the primary supply of non-project water in the study region, depth to groundwater reflects the marginal price of supplemental water. The California Department of Water Resources provided data on well depth in the survey area. Although each well did not have an explicit spatial reference, the name of each well did contain the township/range cell within which the well exists. The average depth of all of the wells in each square on the township/range grid was then calculated. Next, a coverage provided by the USGS with the spatial coordinates of the township and range grid was used to link the average well depths to a spatial reference. The grid was finally krieged to interpolate for cells with no test wells. The average depth to groundwater was 70.75 feet with a standard deviation of 85.9 feet.

These spatially referenced data sets were integrated into a single Geographical Information Systems database. The parcel was taken as the unit of observation. The DWR crop cover data set was layered over the other geo-referenced data to link the crop cover to the soil drainage, elevation, and groundwater depth that it enclosed. Although the soil drainage rate polygons were much larger than the crop parcels, some parcels did bridge polygons with two separate soil drainage rates. In these cases the parcel was split and each sub-parcel was weighted by its share of the area of the entire parcel. For the water supply seniority variable, the water district rights type was linked to the parcels that fell within the district. The USBR water district boundaries were used to perform this operation.

Estimation Results and Discussion

Having linked the exogenous variables to the parcel, a tabular data set was generated in order to perform the statistical analysis. A binomial logit was performed and the results are presented in Table 4 below. The null hypothesis is strongly rejected with the water rights type variable being significant past the 0.1 percent level. In fact, all of the variables are significant beyond that level. This finding demonstrates the effectiveness of using comprehensive GIS data sets containing both economic and biophysical explanatory variables.

The sign of the explanatory variable for exchange contracting districts is positive, showing that the growers with the more reliable water rights are indeed more likely to invest in permanent crops, supporting the theory proposed in this chapter. The magnitude of the pseudo-elasticity is also important: senior rights holders are 39 percent more likely to invest in perennial crops. This finding indicates that accounting for the land allocating impacts of water supply seniority will have significant implications for welfare analysis of water supply development.

Now consider the influence of environmental conditions on land allocation. As soil water storage capability increases, the probability of permanent crop investment decreases because fast draining soils are more beneficial to trees and

D-054082

vines. The elevation variable has a positive sign. Perhaps the most likely reason for this finding is that freezes that damage fruits and vegetables occur more often in the valley floor where cold air settles.

The negative sign on the groundwater depth strongly supports the theoretical model since groundwater depth influences the cost of supplemental water. The higher water requirements of perennial crops mean that these crops are impacted more by a higher price of supplemental water. The findings on the well depth, elevation and soil quality variables are supportive of the approach taken in Caswell and Zilberman, who consider the influence of environmental conditions and water price on water-use investments. In fact, our spatial database provides even stronger confirmation of their hypotheses than they were able to obtain with a more conventional analysis.

Discussion

The conceptual and empirical analyses have demonstrated that changing water supply reliability has an impact on land allocation. In this section, we demonstrate how significantly this phenomenon can impact the valuation of new water supply projects. In particular, we show the bias that results from analysts treating land allocation as exogenous.

Consider two stylized crops, with values chosen to correspond to conditions in the service contracting areas of the western San Joaquin Valley. Suppose that the annual crop generates net returns of $300 per acre, not counting supplemental water costs, and requires 2.5 acre feet of water per acre. A perennial crop generates net returns of $1,850 per acre, again net of water costs, and requires 3.75 acre feet of irrigation water per acre.[5] Suppose that in the baseline scenario, 11 percent of land in service contracting areas is allocated to the perennial crop and the remainder to the annual crop. At a price of $100 per acre foot, supplemental water expenditures amount to $82.80 per acre, so that profits are $387.70 per acre.

Now suppose that water rights change so that service contractors face the project water distribution of exchange contractors given in Table 3. The econometric analysis suggests that this change implies that 15 percent of land would be allocated to the perennial crop. In this case, profits per acre, including expenditures on supplemental water, amount to $531.30. For comparison, consider the bias resulting from treating land allocation as fixed. Under this erroneous assumption, profits per acre are $469.32 per acre, which underestimates the true value of the change in the water supply distribution by over 40 percent. Thus, the impact of the water supply distribution on land allocation can have a large effect on the valuation of new water supply projects.

Conclusion

This chapter addresses the impact of a change in the distribution of project water supply on land allocation among permanent and annual crops. The theoretical model developed in the chapter provides insights into the relationship between crop choice and the cost of supplemental (non-project) water. At the margin, the impact of an increase in reliability in water supply, or equivalently an improvement in seniority of a farmer's water right, may increase or decrease the land allocated to permanent

---

[5] These numbers are taken from University of California.

crops, depending on the cost of supplemental water. Despite the fact that the general result is ambiguous, it is possible to determine the marginal impact of an increase in reliability in a number of special cases. In the most likely case, where the marginal cost of supplemental water is increasing and production of the annual crop is sensitive to the current year's water supply, an increase in reliability increases the amount of land dedicated to production of perennial crops.

Using a GIS data set of crop production in the SLDMWA, the model is tested empirically. The data support the hypothesis that water supply reliability has a significant impact on the farmer's decision to invest in permanent crops. The data show that a farmer with exchange contract rights is 39 percent more likely to invest in permanent crops than a farmer with service contracting rights. The estimation controls for soil type, elevation, and price of the alternative water sources. All the estimates are statistically significant at the 0.1 percent level.

Given the significant impact of a change in the water supply distribution on land allocation, this effect should be factored into economic valuation of water rights. Furthermore this impact should also be considered in cost-benefit analysis of proposed infrastructure projects. Typically, ignoring the effects of water supply reliability on land allocation will underestimate the value of new water supply and lead to incorrect project evaluation.

Figure 1: Sequence of Events

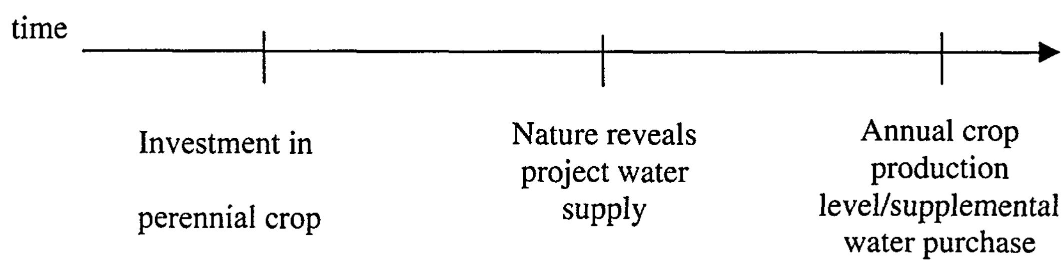


Figure 2: Annual Crop Marginal Revenue and Marginal Costs

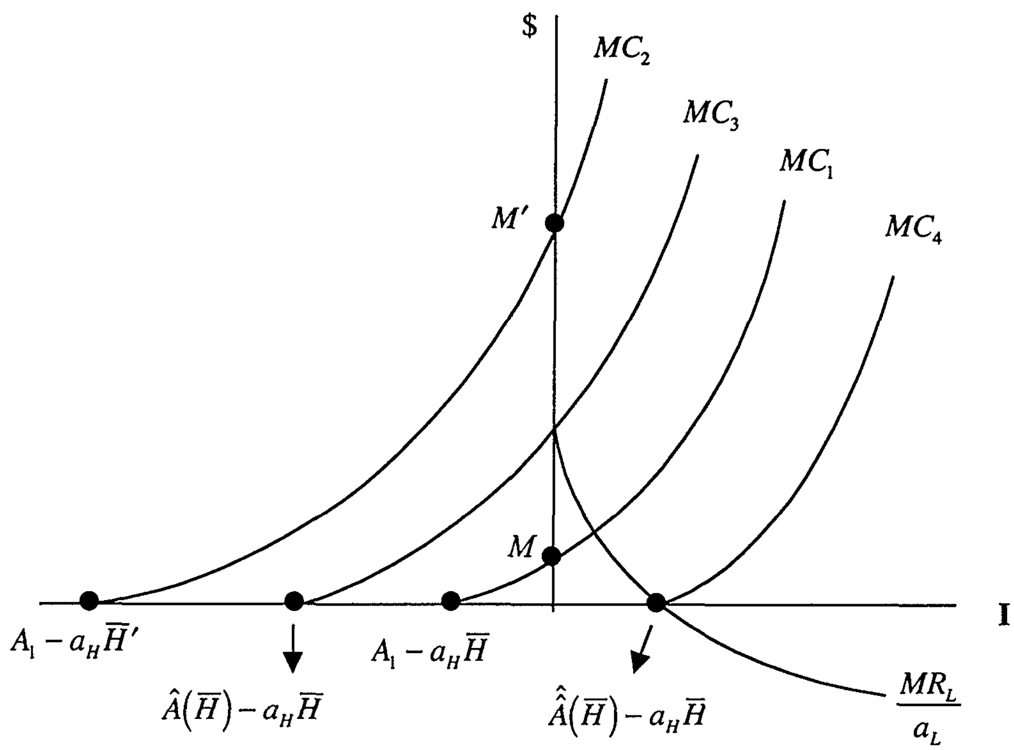


Table 1: Possible Short Run Equilibria

	Farmer Procures Supplemental Water	*Farmer Does Not Procure Supplemental Water*
Farmer Produces Permanent Crop Only	$A < \hat{A}$	Not possible if $MR_L(\varepsilon) > 0$
Farmer Produces Permanent and Annual Crops	$\hat{A} < A < \hat{\hat{A}}$	$A > \hat{\hat{A}}$

Table 2: Comparative Statics

Curvature of the Cost Function	*Sign of* $\frac{fL^*}{fA}$	*Sign of* $\frac{fEMC}{f\theta}$	*Sign of* $\frac{f\overline{H}}{f\theta}$
$C''(I) < 0$	-	+	-
$C''(I) > 0$	+	- if $a_L \frac{fL^*}{fA} < 1$ -/+ if $a_L \frac{fL^*}{fA} > 1$	+ -

Table 3: Moments of the Water Supply Distributions

Contract Type	*Mean Deliveries (AF/acre)*	*Standard Deviation*
Service	1.82	0.60
Exchange	3.11	0.36

Source: U.S. Bureau of Reclamation, 1998.

Table 4: Estimation Results

Variable	*λ*	*Std. Error*	*P-Value*	*Mean of X*	*dPy/dX*	*Elasticity*
Intercept	–3.165	1.221e-1	0.000	1.000	–1.364e-1	–3.017
Soil Water Storage	–1.161	4.386e-2	0.000	1.221	5.005e-2	–1.352
Elevation	–1.940e-2	1.400e-3	0.000	6.578e+1	8.371e-4	1.218
Groundwater Depth	–2.099e-3	5.094e-4	0.000	5.044e+1	–9.056e-5	–1.011e-1
Exchange	9.288e-1	8.735e-2	0.000	3.884e-1	4.101e-2	3.88e-1

Table 5: Impact of Changes in Water Supply Distribution

	Baseline	*Increased Seniority: Land Allocation Endogenous*	*Increased Seniority: Land Allocation Constant*
Perennial Share	0.11	0.15	0.11
Annual Share	0.89	0.85	0.89
Water Use	2.86	2.90	2.86
Profit	387.70	531.30	469.32

Chapter 3:

Irrigation Technology Investment and the Distribution of Water Price

Abstract

This chapter considers the effect of changes in the distribution of water price on the incentives to adopt water-conserving irrigation technologies. A two-stage decision model is developed wherein agents make long-term decisions about irrigation technology investments and decide production levels based on short-term realizations of water price. Comparative statics results show that the impact of changes in the distribution of water price hinge on the responsiveness of cultivated acreage to fluctuations in the price of water. The model is tested using data on irrigation technology investment from the Arvin-Edison Water Storage District. Econometric results strongly support the conceptual model, and show that changes in the distribution of water price have systematically different impacts on permanent and annual crops.

Introduction

Investment in irrigation technology is an important feature of agriculture in the western United States, where crop production is dependent on irrigation. Previous analyses of irrigation technology adoption have considered the effect of changes in the price of water on the incentives to adopt modern irrigation technology, and have also spelled out the important role of environmental conditions. Examples include Green and Sunding, Green et al., Caswell and Zilberman (1985 and 1986), Caswell, et al. While these studies established the importance of water price and other factors on irrigation technology investments, they ignore two important aspects of water use. First, the models assume that price of water is deterministic. Second, they make the neoclassical assumption that technology is malleable in the short run. The model developed in this paper makes the more realistic assumption that the price of water is stochastic, and that, once chosen, irrigation efficiency cannot be altered in response to periodic realizations of water price.

Our model also distinguishes between long-term investments in conservation technology and short-term decisions about the level of production. One of our main conceptual results is that the responsiveness of acreage to changes in the price of water has an important impact on investment behavior. For example, we show that the impact of a mean-preserving decrease in the variance of water price on irrigation technology choice depends on whether the elasticity of acreage with respect to the price of water is greater or less than -1. One implication of this and other findings is that changes in the distribution of water price have different effects on permanent and annual crops.

The Model

The farmer makes a two-stage decision. In the short run, the farmer chooses the level of crop production. In the long run, the farmer chooses the level of investment in conservation technology. While we focus on conservation technology adoption in irrigated agriculture, but this model can be applied to other conservation decisions where there is input price uncertainty, for example in the decision to invest in energy-conserving capital or the choice to purchase a fuel-efficient automobile.

The farmer can improve irrigation efficiency by investing in water conserving practices. In general, farmers can chose two types of irrigation technologies: gravity (traditional) technology such as furrow or flood irrigation, or pressure technologies such as sprinkler or drip irrigation. Traditional technology is the least efficient and

D-054094

requires the smallest investment. Pressure technology is the most efficient and requires a large investment to establish.

The farmer's investment in conservation technology is represented as z in the model. This investment includes the fixed costs of equipment and installation as well as the cost of learning to use the technology and learning new conservation practices with existing equipment. For each field in production, the farmer chooses what to produce and how to produce it; the farmer's land allocation and technology choices are interdependent. In the long run, the farmer chooses the level of investment in irrigation technology, which is assumed to be durable. The farmer chooses investment in technology to maximize long-run expected profits. In the short run, the farmer chooses the level of production in the crop, given her long-run investment in irrigation technology.

In Chapters 1 and 2, we worked with changes in the distribution of water supply. In this chapter, it is more convenient to work with changes in the marginal price of water. The farmer faces a stochastic price of water, C_w.[1] C_w has a known distribution $F(C_w;\theta)$, where θ is the policy parameter, representing reliability in water supply. The support of $F(C_w;\theta)$ is $[\underline{C}_w,\overline{C}_w]$. Water supply reliability is defined in terms of θ; an increase in θ implies an increase in reliability, which can be interpreted as an improvement in stability of the price of water.

Short-Run Equilibrium: The Choice of Activity Level

The farmer's short-run optimization problem is given by

(1) $\max_{L} \Pi^{SR} = L\pi(L) - a(\bar{z})LC_w,$

where L is acres in production (the activity level) and $\pi(L)$ are net returns per acre foot of applied water (excluding expenditures on water and conservation technology). The function $a(\bar{z})$ represents the water input coefficient, in terms of acre feet of applied water per acre in production. Increasing expenditures on technology improves efficiency, thus $a(\bar{z})$ is decreasing in $\bar{z}$, that is, $a'(\bar{z}) < 0$. Expenditure on conservation technology is denoted $\bar{z}$ to indicate that it is fixed in the short-run.

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

(2) $\pi(L) + L\pi'(L) - a(\bar{z})C_w = 0.$

This optimality condition implicitly defines the optimal level of L as a function of $\bar{z}$

(3) $L^* = L(\bar{z}, C_w).$

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

(4) $\frac{dL}{d\bar{z}} = \frac{a'(\bar{z})C_w}{SOC_{SR}} > 0,$

and

(5) $\frac{dL}{d\hat{C}_w} = \frac{a(\bar{z})}{SOC_{SR}} < 0,$

where SOC_{SR} is the short-run second order condition, which is negative for an interior maximum. Equation (4) implies that crop production increases with expenditure on irrigation technology. Equation (5) is negative, as expected for an input demand.

[1] The price of water is assumed constant but it can be generalized to include more complicated pricing structures.

Using the optimality condition in (2), define the threshold price of water, $\hat{C}_w$, such that the farmer produces the crop for all prices of water below the threshold. The threshold level can be expressed as

$$\text{(6)} \qquad \hat{C}_w = \left\{ C_w \middle| \pi(L) + L\pi'(L) - a(\bar{z})C_w = 0 \right\}.$$

Long-Run Equilibrium: Technology Investment

Now we turn to the long-run investment choice, which is expressed as

$$\text{(7)} \qquad \max_{\bar{z}} \Pi^{LR} = \int_{\underline{C}_w}^{\hat{C}_w(\bar{z})} \left[L^*\pi(L^*) - a(\bar{z})L^*C_w \right] f(C_w;\theta)dC_w - (\bar{z}),$$

where L^* is the short-run optimal production of the crop given in equation (3). The first term in equation (7) is profit in the state of nature when it is profitable to produce the annual crop.

The optimality condition for the long-run problem is

$$\text{(8)} \qquad -a'(\bar{z}) \int_{\underline{C}_w}^{\hat{C}_w(\bar{z})} L^*C_w f(C_w;\theta)dC_w - 1 = 0,$$

which implicitly defines the long-run optimal investment in conservation technology. This condition says that at the optimal level of investment in conservation technology, the expected *VMP* of technology investment equals the marginal cost.

Marginal Impact of Changes in the Distribution of Water Price

Using this model, we analyze how changes in the distribution of the input price affects expenditure on conservation technology. Totally differentiating the long-run optimality condition in (8), yields the comparative static

$$(9) \qquad \frac{d\bar{z}}{d\theta} = \frac{-a'(\bar{z}) \int_{\underline{C}_w}^{\hat{C}_w(\bar{z})} L^* C_w \frac{\partial F(C_w;\theta)}{\partial \theta} dC_w}{SOC_{LR}},$$

where SOC_{LR} is the second order condition, which is negative to insure an interior maximum.

We cannot sign equation (8) directly using the standard stochastic dominance ranking theorems because the expected marginal productivity of technology investment may increase or decrease with C_w. This follows from the fact that L^* and C_w move in opposite directions as C_w increases. However, manipulation of equation (9) will uncover cases in which we can determine the direction of changes in conservation technology investment.

Integrating equation (9) by parts yields,

$$(10) \qquad \frac{d\bar{z}}{d\theta} = \frac{-a'(\bar{z}) \int_{\underline{C}_w}^{\hat{C}_w(\bar{z})} \left(\frac{\partial L^*}{\partial C_w} C_w + L^* \right) \frac{\partial F(C_w;\theta)}{\partial \theta} dC_w}{SOC_{LR}}.$$

Define the acreage elasticity with respect to price of water as

$$(11) \qquad \varepsilon_L = \frac{\partial L^*}{\partial C_w} \frac{C_w}{L^*}.$$

Substituting ε_L into (10) yields

$$(12)\quad \frac{d\bar{z}}{d\theta} = \frac{-a'(\bar{z}) \int_{\underline{C}_w}^{\hat{C}_w(\bar{z})} (\varepsilon_L + 1) \frac{\partial F(C_w;\theta)}{\partial \theta} dC_w}{SOC_{LR}}.$$

Suppose $\frac{\partial F(C_w;\theta)}{\partial \theta} \geq 0 \forall C_w$, with the inequality being strict in some region. If acreage is elastic with respect to water price $(\varepsilon_L < -1)$, investment in irrigation technology increases. The opposite is true in the case where acreage is inelastic with respect to the price of water.

This result is consistent with the stochastic dominance ranking theorems of Rothschild and Stiglitz. If $\varepsilon_L < -1$, then expected *VMP* is decreasing in C_w. Formally,

$$(13)\quad \frac{\partial EVMP}{\partial C_w} = a'(\bar{z}) \int_{\underline{C}_w}^{\hat{C}_w(\bar{z})} (\varepsilon_L + 1) f(C_w;\theta) dC_w < 0.$$

When the price of water increases, there are two effects on expected *VMP*. The increase in C_w directly increases the marginal productivity of *z* by increasing the value of water savings. There is also an indirect effect on productivity that works in the opposite direction: an increase in C_w decreases L^*, which decreases marginal productivity. In the case where acreage is highly responsive to short-run realizations of water price, the indirect effect dominates the direct effect and expected *VMP* is decreasing in C_w. Since the assumed change in the distribution of water price corresponds to first order stochastic dominance, it follows that an upward shift of *F* decreases expected *VMP* and reduces the incentive to invest in conservation technology. The opposite result holds for the case where $\varepsilon_L > -1$.

D-054099

Of course, the assumption of first order stochastic dominance is quite restrictive, although useful as a place to start the analysis. To sign the effect of other types of changes in the distribution of water price, it is helpful to establish whether *VMP* is concave or convex with respect to C_w. Consider first the case where $\varepsilon_L > -1$. We have already established that *VMP* is increasing in C_w when the acreage elasticity is small in absolute value. Taking the second derivative of *VMP* with respect to the price of water yields

$$(14) \quad \frac{\partial^2 VMP}{\partial C_w} = a'(z)\left(\frac{\partial^2 L^*}{\partial C_w^2} C_w + 2\frac{\partial L}{\partial C_w}\right).$$

From equation (4) and the short-run second order condition, it follows that $\frac{\partial^2 L^*}{\partial C_w^2} = 0$.

Thus, *VMP* is increasing and concave in C_w when ε_L is smaller than unity in absolute value. Similar reasoning shows that *VMP* is decreasing and convex in C_w when $\varepsilon_L < -1$.

With these intermediate results in hand, we can consider the marginal impacts of changes in the distribution of water price that are less extreme than first order stochastic dominance. In particular, we can sign the impacts of a mean preserving decrease in the variance of water price. This case is especially interesting as it captures the effect on technology investment of a water infrastructure project that stabilizes deliveries. It also corresponds to the real-world situation we examine in the empirical section of this paper. In the case where acreage is relatively unresponsive in the short run with respect to changes in the price of water, a mean preserving decrease in the variance of water price increases the expected *VMP* of technology investment, and increases investment in conservation technology. This result follows from the ranking theorem of Rothschild and Stiglitz since we have established that *VMP* is increasing and concave in C_w in this case. When acreage is highly responsive to short-run realizations of water price, a mean preserving decrease in the variance of water price decreases the investment in irrigation technology improvements. Again, this result follows from Rothschild and Stiglitz.

This analysis establishes that changes in the distribution of water price, regardless of whether they follow from water policy reform or construction of water projects, have an ambiguous effect on the incentives to improve irrigation efficiency. In particular, we have shown that the direction of the effect depends to a large extent on the acreage response to short-run fluctuations in the price of water. If a grower produces a permanent crop, such as trees or vines (or even an annual crop that is grown under a long term production contract), then a first order stochastic dominant decrease in the price of water will reduce the incentive to invest in irrigation technology. A mean preserving decrease in the variance of water price will increase the incentive to invest in efficiency improvements. When the farmer produces an annual crop, by contrast, the opposite results hold. In the following section, we test these predictions using data from the Arvin-Edison Water Storage District in the southern San Joaquin Valley.

Empirical Analysis

In this section, we test the relationship between investment in conservation technology and water price distribution. The data used in this section is from a

D-054101

unique survey of farmers in Arvin-Edison Water Storage District conducted by Green and Sunding. The data set includes information about the technology used and crops grown by farmers in Arvin-Edison. It also includes information about the physical characteristics of the parcels in the district. A binomial logit regression is used to estimate the probability of adopting low-pressure irrigation technology.

The null hypothesis that we test is based on the model in the previous section. The null hypothesis states that a mean-preserving decrease in the variance of water price does not affect irrigation technology choice. Rejection of the null hypothesis would demonstrate that the price distribution has an effect on adoption of water-conserving irrigation technology and supports the theory presented in the previous section.

Data

The survey collected data on irrigation technology and crop patterns from 1993. The data set includes 1,717 quarter sections of farmland. The data cover 92,294 acres of land. Summary statistics for the continuous variables are shown in Table 1.

In addition to these continuous variables, we have data for binary variables. The data set distinguished the types of crops grown on each quarter section. The data reported crops in six categories: (1) citrus, (2) deciduous, (3)vine, (4) truck, (5) cotton, and (6) potato. We created a new variable re-categorizing the crop types into permanent and annual crops. Citrus, deciduous, and vine crops were included in the permanent crops. Truck, cotton and potato were included in the annual crop category.

Table 2 summarizes the acres covered by each type of crop. The acreage in Arvin-Edison is about evenly divided between permanent and annual crops.

In the data set there were three types of irrigation technology: gravity, high pressure and low pressure. For our analysis, we recategorized the technologies into two categories: gravity and pressure, where pressure includes both high and low pressure technologies. About 75 percent of the acreage in the district use pressure technologies, about 25 percent use gravity.

We use the variable for service area type to index the water price distribution. In Arvin-Edison, farmers receive either surface water or groundwater. Water rates in the district are set so that the mean price of water (including lift for groundwater users) is the same for both service areas. However, groundwater levels are variable, and the price of groundwater 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.[2] Thus, relative to the groundwater service area, the distribution of water price in the surface water service area has the same mean and a lower variance. The conceptual model of the previous section predicts that the effect of switching from groundwater to surface water in this district should increase the incentive to adopt pressure technology for permanent crop growers, and decrease the adoption incentive for annual crop growers.

[2] In the past two decades, water prices and water availability have not changed at all in the surface water service area.

Estimation Results

Using the data described above a binomial logit was performed for each type of crop. The results are presented in Tables 3 and 4. The null hypothesis that the water price distribution does not affect conservation technology adoption is strongly rejected for both the permanent and annual crops with the service area variable significant above the one percent level. The coefficients on service area are also of the sign predicted by the conceptual model. Except for soil permeability in the case of permanent crops and slope in the case of annual crops, all of the environmental quality variables are significant at the 10 percent level.

Conclusions

This chapter considers the effect of changes in the distribution of water price on the incentives to adopt water-conserving irrigation technologies. A two-stage decision model is developed wherein agents make long-term decisions about irrigation technology investments and decide production levels based on short-term realizations of water price. Comparative statics results show that the impact of changes in the distribution of water price hinge on the responsiveness of cultivated acreage to fluctuations in the price of water. One implication of this theoretical result is that changes in surface water deliveries should have a different impact on annual and perennial crop irrigation methods.

The model is tested using data on irrigation technology adoption from the Arvin-Edison Water Storage District in Kern County. Econometric results strongly support the conceptual model, and show that changes in the distribution of water price have systematically different impacts on permanent and annual crops. In particular, the results show that an increase in the variance of surface water deliveries gives incentives for perennial crop producers to adopt conservation technology, while it has the opposite effect on producers of annual crops. Thus, the impact of an increase in supply reliability on farm-level water-use efficiency is ambiguous.

Table 1: Summary Statistics

Variable	*Mean*	*Maximum*	*Minimum*	*Standard Deviation*
Soil Permeability	2.91	13.00	0.13	2.99
Slope	1.42	10.00	0.50	1.16
Acres	53.75	490.00	1.00	49.9

Table 2: Land Allocation in Arvin-Edison

Crop	*Acres*	*Percent*
Permanent		
Citrus	12,605	13%
Deciduous	11,700	13%
Vine	23,666	26%
All Permanent Crops	47,431	51%
Annual		
Truck	14,721	16%
Potato	17,286	19%
Cotton	12,856	14%
All Annual Crops	44,863	49%

Table 3: Estimation Results for Permanent Crops

Variable	*Coefficient*	*Standard Error*	*P-Value*	*Mean*	*Marginal Effect*
Soil Permeability (in./hr)	–0.0308	0.0246	0.210	2.96	–0.0077
Slope (%)	0.7172	.0758	0.000	1.70	0.1784
Acres	0.0059	0.0014	0.000	49.41	0.0015
Surface (0/1)	0.5699	0.1471	0.000	--	0.1417
Constant	–1.553	0.1782	0.000	--	--

Table 4: Estimation Results for Annual Crops

Variable	*Coefficient*	*Standard Error*	*P-Value*	*Mean*	*Marginal Effect*
Soil Permeability (in./hr)	0.1143	0.0613	0.062	2.84	0.0083
Slope (%)	0.2164	0.2652	0.415	1.07	0.0157
Acres	0.0071	0.0036	0.055	59.26	0.0051
Surface (0/1)	–0.7335	0.2725	0.007	--	–0.0533
Constant	1.7653	0.4143	0.000	--	--

References

Atkeson, A. and P. Kehoe, "Models of Energy Use: Putty-Putty Versus Putty-Clay," *American Economic Review* 89(1999): 1028–1043.

Belitz, K. and S. Phillips, *Simulation of Water Table Response to Management Alternatives, Central Part of the Western San Joaquin Valley, California*, U.S. Geological Survey Water Resources Investigations Report 91-4193, 1994.

Belitz, K., S. Phillips and J. Gronberg, *Numerical Simulation of Ground-Water Flow in the Central Part of the Western San Joaquin Valley, California*, U.S. Geological Survey Water Resources Investigations Report 91-535, 1992.

Burness, H. and J. Quirk, "Appropriative Water Rights and the Efficient Allocation of Resources," *American Economic Review* 69(1979): 25–37.

California Department of Water Resources, *Bulletin 160-98*, Sacramento: State Printing Office, 1998.

CalFed Bay-Delta Program, *Economic Evaluation of Water Management Alternatives*, Sacramento: California Department of Water Resources, 1999.

Calvo, G., "Optimal Growth in a Putty-Clay Model," *Econometrica* 44(September 1976): 867–878.

Cass, D. and J. Stiglitz, "The Implications of Alternative Saving and Expectations Hypotheses for Choices of Technique and Patterns of Growth," *Journal of Political Economy* 77(July/August 1969): 586–627.

Caswell, M. and D. Zilberman, "The Effects of Well Depth and Land Quality on the Choice of Irrigation Technology," *American Journal of Agricultural Economics* 68(1986): 798–811.

_____, "The Choices of Irrigation Technologies in California," *American Journal of Agricultural Economics* 67(1985): 224–232.

Caswell, M., E. Lichtenberg and D. Zilberman, "The Effects of Pricing Policies on Water Conservation and Drainage," *American Journal of Agricultural Economics* 72(1990): 883–890.

Green, G. and D. Sunding, "Designing Environmental Regulations with Empirical Microparameter Distributions: The Case of Seawater Intrusion," *Resource and Energy Economics* 22(2000): 63–78.

Green, G. and D. Sunding, "Land Allocation, Soil Quality and Irrigation Technology Choice," *Journal of Agricultural and Resource Economics* 22(November 1998): 367–375.

Green, G., D. Sunding, D. Zilberman and D. Parker, "Explaining Irrigation Technology Choice: A Microparameter Approach," *American Journal of Agricultural Economics* 78(1996): 1064–1072.

Gronberg, J. and K. Belitz, *Estimation of a Water Budget for the Central Part of the Western San Joaquin Valley, California*, U.S. Geological Survey Water Resources Investigations Report 91-4192, 1992.

Gronberg, J., K. Belitz and S. Phillips, *Distribution of Wells in the Central Part of the Western San Joaquin Valley, California*, U.S. Geological Survey Water Resources Investigations Report 89-4158, 1990.

Johansen, L., "Substitution versus Fixed Production Coefficients in the Theory of Economic Growth: A Synthesis," *Econometrica* 27(April 1959): 157–176.

Laffont, J.-J. and J. Tirole, *A Theory of Incentives in Procurement and Regulation*, Cambridge: MIT Press, 1993.

Rothschild, M. and J. Stiglitz, "Increasing Risk I: A Definition," *Journal of Economic Theory* 2(1970): 225–243.

Sheshinski, E., "Balanced Growth and Stability in the Johansen Vintage Model," *Review of Economic Studies* 34(April 1967): 239–248.

U.S. Bureau of Reclamation, CVP Operations Office, Facsimile Communication, 1998.