

# Microeconomics of Irrigation with Saline Water

Iddo Kan, Kurt A. Schwabe, and Keith C. Knapp

Water management and reuse at the field level are analyzed under saline, limited drainage conditions. A function relating crop yield and deep percolation flows to applied water and salinity concentration is developed. This function fits simulated data well and is tractable for theoretical and empirical analysis of irrigation economics. With a single irrigation source, irrigation water for cotton and tomatoes at first increases and then decreases with salt concentration. Drain-water reuse is found to be an efficient strategy in events of high surface-water prices and costly solutions to drainage-related environmental problems. However, blending freshwater and drainage appears plausible only under surface water scarcity.

*Keywords:* drainage disposal, economics, irrigation, nonpoint source pollution, salinity

## Introduction

Intensively irrigated agriculture, while providing one-third of the world's agricultural output, is frequently associated with problems such as high water tables, freshwater source shortages, and pollutant-laden drainage water high in salinity and other substances. Finding attractive solutions to adequately address these problems is both difficult and important. It is difficult in that many of these problems are intricately linked to one another, and it is important because the conflicts surrounding the competing uses for surface water and other natural resources that may serve as mediums or sinks for drainage disposal are intensifying.<sup>1</sup> Assessing the relationships among factors such as the quality and quantity of irrigation water, yield, and drainage disposal is critical in developing adequate solutions to these scarcity problems. Furthermore, an understanding of both the qualitative and quantitative interactions among these factors, and changes in particular price or input parameters, is essential for discerning the potential trade-offs associated with various policy decisions.

This research explores, both theoretically and empirically, the relationships among profits, saline water use, and drainage disposal within the framework of a microeconomic field-level analysis. Three distinct applications are examined which differ with respect to the type and quantity of water available for irrigation. These applications are

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Review coordinated by Gary D. Thompson.

<sup>1</sup>For instance, installing drainage systems to reduce the high water table leads to more drainage water, water known not only to be high in salinity content, but also to contain toxic trace elements such as selenium, boron, and arsenic (Gilliom). Furthermore, current water allocation controversies surrounding the Klamath River along the California-Oregon boundary or the San Francisco Bay Delta in California both include competing demands by urban/business, environmental/fishing, and farming interests (see, e.g., *Western Water*, May/June, July/August 2000).

intended to mimic real-world scenarios in which growers confront varying prices and constraints. Within each of these applications, the responses in application rates, drainage volume, and profits to changes in a variety of parameters, including the price of drainage disposal, and the quantity and quality (i.e., salinity) of irrigation water are considered.

The first application evaluates the profit-maximizing behavior of a grower confronting a single source of irrigation water. A real-world counterpart to this application might be found in the Imperial or Coachella valleys in southern California where the only source of irrigation water for growers is from the Colorado River.

In the second application, profit-maximizing behavior is analyzed when the grower confronts two sources of irrigation water—a low saline surface water source and a more saline groundwater source. Of particular interest are the conditions under which blending high-quality surface water with low-quality groundwater is optimal. The San Joaquin Valley (SJV) is a 4.8 million-acre area of irrigated farmland where such irrigation options are readily available, used, and debated.

The final application examines constraints on application rates. One constraint consists of a limit on surface water supplies. Growers in the SJV often confront limitations on the amount of surface water they are entitled to purchase (Kanazawa 1994). Another constraint consists of a limit on the water application allowed. Such a constraint might capture limits on application rates associated with soil structure or infiltration ability (Shennan et al.).

This research, which focuses on four separate crop-irrigation system combinations, attempts to extend and contribute to the literature along several lines. First, a theoretical analysis of the impacts of changes in salinity of the irrigation water and the price of drainage on water use is presented. Several studies have provided theoretical investigations of the impacts of pricing policies and water markets on water use (Dinar, Knapp, and Letey; Caswell, Lichtenberg, and Zilberman; Dinar and Letey; Dinar, Campbell, and Zilberman; Weinberg, Kling, and Wilen), yet none have analyzed the theoretical impacts of changes in salinity on water use. Additionally, we investigate the efficiency of blending two water sources that differ with respect to quality, an issue analyzed by Yaron and Bresler, and Parkinson et al.

The outcome of our analysis, given no constraints on application rates, reinforces conclusions drawn from previous empirical research by Knapp and Dinar, and by Dinar, Letey, and Vaux. Specifically, given no constraints on the availability of water, we conclude blending is an unlikely outcome from a profit-maximizing perspective. Yet when specific constraints are imposed, such as a binding limit on allowable surface water applications, we do observe profit-maximizing outcomes involving blending, as did Feinerman and Yaron.

Second, we estimate a unique crop-water-salinity production function which deviates from the traditional linear or quadratic crop-water production functions found in much of the literature (e.g., Letey and Dinar; Dinar and Knapp; Dinar, Letey, and Vaux; Caswell, Lichtenberg, and Zilberman; Dinar et al.; Dinar, Aillery, and Moore). Finally, we investigate the sensitivity of field-level profits to changes in the price of drainage, the salinity of the irrigation water, and a restriction on the supply of surface water for irrigation. Similar empirical investigations within a static model framework include Dinar, Knapp, and Letey; Dinar and Letey; and Posnikoff and Knapp for changes in the price of drainage, and Dinar, Letey, and Knapp for changes in irrigation water salinity. Dinar, Aillery, and Moore, while using a dynamic model and a farm-level analysis,

provide one of the few empirical investigations of the impact of surface water restrictions on grower profits in a saline soil environment. For a summary of research related to the economics of irrigation with saline water, see Knapp (1999).

### Model and Data

The profits,  $\pi$ , of growing a given crop with a given irrigation system on a single acre of land are calculated as:

$$(1) \quad \pi = p^y y - \gamma - p^s w^s - p^g w^g - p^d d,$$

where  $p^y$  is the market price,  $\gamma$  is nonwater production and harvest costs, and  $y$  is crop yield. Additional revenue may come from price support payments and other credits (e.g., seed credit for cotton), while additional harvest-related costs may include a variety of crop assessment fees. Water prices are denoted by  $p^s$  for surface water ( $w^s$ ),  $p^g$  for groundwater ( $w^g$ ), and  $p^d$  for deep percolation flows ( $d$ ). The groundwater and deep percolation prices are determined as follows:

$$(2) \quad p^g = \gamma_p + \gamma_g - \lambda,$$

$$(3) \quad p^d = \lambda,$$

where  $\gamma_p$  is pumping costs,  $\gamma_g$  is the cost of gypsum amendments, and  $\lambda$  is the shadow value of additions or subtractions to the underlying water table. Gypsum is added to the water to counter the potential crusting and water penetration problems of irrigating with saline water. The latter term in equation (3) is the shadow value of a constraint on maintaining hydrologic balance at the regional level.

Yield and deep percolation flows are given by:

$$(4) \quad y = f(w, c),$$

$$(5) \quad d = g(w, c),$$

where  $w$  and  $c$  are the depth and salinity concentration of the applied water, respectively, and are calculated as:

$$(6) \quad w = w^s + w^g,$$

$$(7) \quad c = \frac{w^s c^s + w^g c^g}{w^s + w^g},$$

where  $c^s$  and  $c^g$  are the salt concentrations of surface water and groundwater, respectively. Because the unconfined aquifer is extremely large relative to any deep percolation flows, it is assumed groundwater salinity is not changed with additions of deep percolation flows.

#### *Crop-Water-Salinity Production Function*

Critical factors influencing the amount of saline irrigation water applied by a profit-maximizing farmer include a plant's response to both alternative application rates and

salinity levels as well as the resulting deep percolation flows associated with those responses. To model the yield-drainage response to changes in the quantity and quality (i.e., salinity) of applied irrigation water, two approaches from the agro-economic literature are combined. Following Letey, Dinar, and Knapp, and Letey and Dinar, the relationships between yield and seasonal evapotranspiration,  $e(w, c)$ , and between deep percolation and evapotranspiration are specified as:

$$(8) \quad y = \psi_1[e(w, c) - \underline{e}] + \psi_2[e(w, c) - \underline{e}]^2$$

$$(9) \quad d = w - e(w, c),$$

where the  $\psi$  terms are scalars and  $\underline{e}$  represents the minimum evapotranspiration level required for yield production. Implicit in equation (8) is the relationship between marketable yield, represented by  $y$ , and vegetative growth. For a few crops, such as cotton, excessive vegetative growth reduces marketable yield, and this is captured by the quadratic function. For most crops, however, marketable yield can be expressed as a linear function of evapotranspiration, i.e.,  $\psi_2 = 0$ . In the analytical derivations which follow, linear relationships are assumed. For the empirical analysis, a quadratic relationship is assumed for cotton, while a linear relationship is assumed for processing tomatoes.

To model the relationship between evapotranspiration and the quantity and quality of applied water, we adopt a functional form developed by van Genuchten and Hoffman, and extended by van Genuchten (1987).<sup>2</sup> Evapotranspiration can be described as a function of the stress faced by the plant due to water deficit and/or root zone salinity. Empirical estimation suggested an S-shaped relationship between evapotranspiration and stress:

$$(10) \quad e = \frac{\bar{e}}{1 + \left(\frac{ah_m + h_c}{h_{50}}\right)^b},$$

where  $\bar{e}$  (feet/year) is the maximum evapotranspiration under nonstressed conditions,  $h_c$  (feet) represents osmotic pressure,  $h_m$  (feet) is matric pressure head,  $h_{50}$  (feet) denotes the stress at which the yield is reduced by 50%, and  $a$  and  $b$  are scalars. A common assumption within the salinity literature is to define osmotic pressure,  $h_c$ , as proportional to the salt concentration of the seasonal applied water,  $c$  (U.S. Regional Salinity Laboratory). Accordingly, we assume  $h_c = \phi c$ , where  $\phi$  is a scalar. Matric pressure and the seasonal water application are assumed to be related by the following power function:

$$(11) \quad h_m = \beta w^\delta,$$

where  $\beta$  and  $\delta$  are scalars.<sup>3</sup>

<sup>2</sup> The functional forms estimated in van Genuchten and Hoffman, and in van Genuchten (1987) use water uptake by the plant, rather than evapotranspiration, as the dependent variable.

<sup>3</sup> This function is based on assuming a proportional relationship between water applications and soil water content, combined with a simplification of the expression presented by van Genuchten (1978):

$$h_m = \frac{\left[\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{-1/m} - 1\right]^{1/n}}{\alpha},$$

where  $\theta$  (feet) is the volumetric water content in the soil;  $\theta_s$  (feet) is the field saturated water content;  $\theta_r$  (feet) denotes the residual water content; and  $\alpha$ ,  $m$ , and  $n$  are empirical constants.

**Table 1. Estimated Coefficients for Crop-Water Production Functions (8) and (12) for Each of the Four Crop-Irrigation Systems**

Response Functions	Cotton		Tomatoes	
	Furrow (n = 216)	Drip (n = 216)	Furrow (n = 156)	Drip (n = 156)
<b>Yield, equation (8):<sup>a</sup></b>				
$\bar{e}$	0.47	0.53	0.66	0.66
$\psi_1$	0.60	0.69	37.38	37.38
$\psi_2$	-0.12	-0.17	0	0
<b>Evapotranspiration, equation (12):<sup>b</sup></b>				
$\alpha_1$	$1.3 \times 10^{-5}$	$9.9 \times 10^{-6}$	$1.1 \times 10^{-3}$	$9.9 \times 10^{-4}$
$\alpha_2$	47.06	43.94	21.85	21.25
$\alpha_3$	-0.99	-1.22	-1.46	-1.86
$\alpha_4$	3.14	3.33	2.37	2.47
$R^2$	0.98	0.97	0.99	0.99

<sup>a</sup> OLS was used to fit equation (8). All coefficients are significant at  $p < 0.001$ .

<sup>b</sup> Nonlinear least squares was used to fit equation (12).

Combining equations (10) and (11) and substituting for osmotic pressure,  $e$  is approximated as:

$$(12) \quad e = \frac{\bar{e}}{1 + \alpha_1(c + \alpha_2 w^{\alpha_3})^{\alpha_4}},$$

where

$$\alpha_1 = \left( \frac{h_{50}}{\phi} \right)^b, \quad \alpha_2 = \frac{\alpha\beta\phi}{h_{50}^2}, \quad \alpha_3 = \delta, \quad \text{and} \quad \alpha_4 = \beta.$$

Substituting equation (12) into equations (8) and (9) gives yield ( $y$ ), and deep percolation flows ( $d$ ).<sup>4</sup> It is well recognized that  $w$  is positively related to  $y$ , and  $c$  is negatively related to  $y$ ; hence, we expect the parameters  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_4$  are all positive, and  $\alpha_3$  is negative. Because the S-shaped function described in equation (12) is influenced by the spatial distribution of the applied water, the parameters  $\alpha_1$ – $\alpha_4$  are estimated for each specific crop-irrigation system.

The empirical analysis focuses on two crops and two irrigation systems. To account for potential differential responses arising due to differences in the salt tolerance of a particular crop, production functions are analyzed for cotton (a relatively salt-tolerant crop) and tomatoes (a moderately salt-sensitive crop) (Maas and Hoffman). Further, to account for potential differences in crop response to differences in water application uniformity, each crop is analyzed under a furrow irrigation system with 0.5-mile runs and a more uniform drip irrigation system. A measure of the uniformity of water application for an irrigation system is its Christensen Uniformity Coefficient (CUC). The greater the CUC, the more uniform the water application. For our analysis, the furrow irrigation system has a CUC of 70, while the drip irrigation system has a CUC of 90.

<sup>4</sup> With respect to other functional forms for describing yield response to water and salinity applications appearing in the literature, Letey and Dinar preferred a quadratic function to either linear or log-log functions, while Plessner and Feinerman used the exponential (Mitscherlich) function.

Table 1 presents the estimated coefficients associated with equations (8) and (12) for each of the four crop-irrigation systems. These coefficients were estimated using a meta-modeling procedure consisting of two steps. First, data sets composed of  $w$ ,  $c$ , and the corresponding  $y$  and  $e$  were generated from a steady-state seasonal model (as detailed in the appendix). Second, regressions were run using the simulated data points to estimate the coefficients associated with equations (8) and (12). Sample sizes varied from 216 observations for cotton to 156 observations for tomatoes. Ordinary least squares (OLS) was used in fitting equation (8), and resulted in  $p$ -values of less than 0.001 for each parameter. A nonlinear least squares method was used to estimate equation (12). This iterative method, which also chooses parameter values so as to minimize the sum of squared residuals, resulted in  $R^2$  values of greater than 0.97 for each crop irrigation system combination. Figure 1 illustrates the correspondence between the estimated evapotranspiration response functions and the simulated data for each crop-irrigation system combination.

### Revenue and Costs

Production and price data are presented in table 2 and correspond to prices and practices related to the San Joaquin Valley (SJV).<sup>5</sup> Nonwater production costs, which include costs of factors such as planting, land preparation, weed cultivation, and fertilizer, also account for tile and drainage system costs; the opportunity cost of land was excluded. The historically weighted average surface water rate paid by growers from 1997 to 1999 is used to represent the price of surface water. The weighted average component accounts for the variety of rates farmers pay to the Bureau of Reclamation for Central Valley Project water. The price of groundwater includes the pumping and lift costs associated with drawing the groundwater from the unconfined aquifer as well as the costs of applying gypsum. Finally, the salinity concentrations for both water sources, measured in decisiemens per meter (dS/m), approximate the actual concentrations of surface water and groundwater (Tanji and Karajeh).

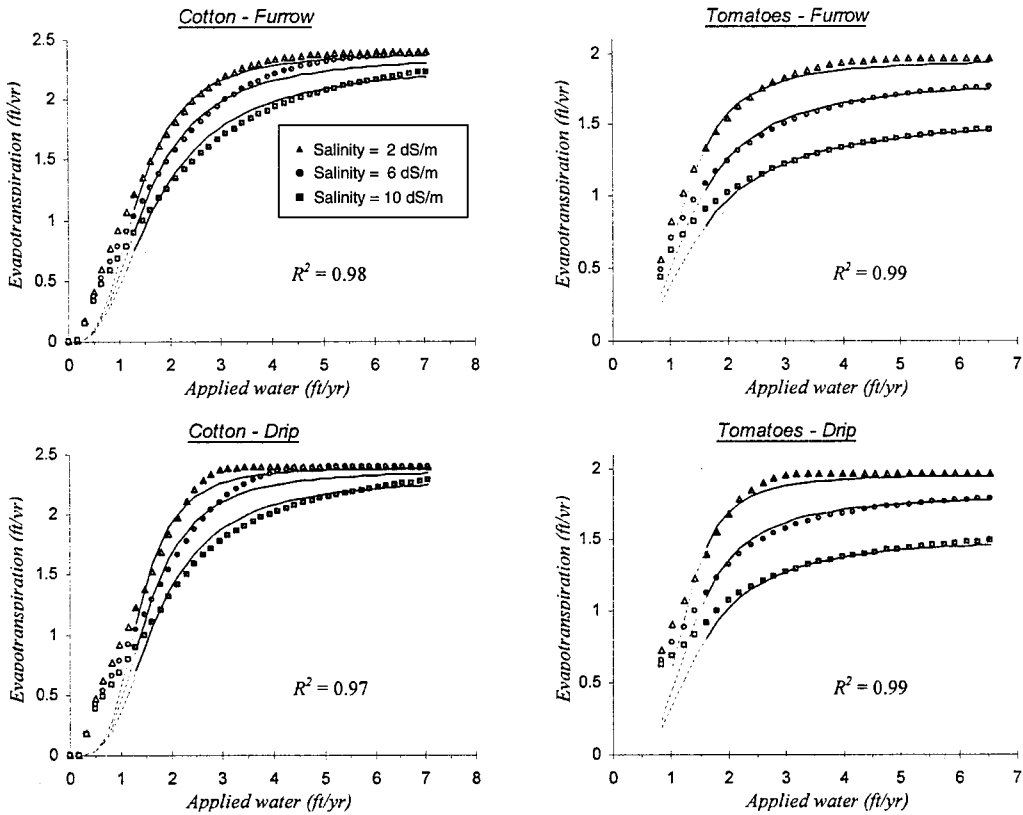
The costs of deep percolation flows account for restrictions mandating no out-of-region discharge of drainage from the SJV. In response to these restrictions, growers often dispose of the deep percolation flows in an on-site evaporation pond. Growers using evaporation ponds must also provide compensating habitat for birds.<sup>6</sup> To account for these restrictions and mandates, the price of deep percolation flows is represented as:

$$(13) \quad \lambda = p^u + \frac{\gamma_{ep} + r\gamma_{ch}}{\kappa},$$

where  $p^u$  is the pumping cost,  $\gamma_{ep}$  is the annualized construction and maintenance costs of the evaporation pond,  $\gamma_{ch}$  is the annualized construction and maintenance costs of the compensating habitat,  $r$  is the size requirement for the compensation habitat relative to the evaporation pond, and  $\kappa$  is the evaporation rate. Based on the 1990 guidelines

<sup>5</sup> While our results are based on price and cost data within the SJV, we generalize the results to applications beyond this region, to the Coachella and Imperial valleys in southern California specifically. It should be noted that price and cost parameters will likely vary across these regions for a variety of reasons, including differences in soil type and irrigation district. Such potential differences do not impact the methodology or issues identified here.

<sup>6</sup> Because bird mortality has been linked to selenium levels within the evaporation ponds, alternative habitat and bird hazing techniques on the evaporation ponds are required.



Note: Functions were fitted to data generated by crop-water-salinity model (appendix) according to salinity levels of 0, 2, 4, 6, 8, and 10 dS/m.

**Figure 1. Evapotranspiration response functions for each crop-irrigation system combination using nonlinear least squares regressions**

suggested for managing agricultural drainage and salt in the SJV (SJV Drainage Program), an initial 1:1 ratio of compensating habitat acreage to evaporation pond acreage is assumed. Values of these parameters are presented in table 2.

An important assumption associated with equation (13) is that hydrologic balance need not be maintained at the field level. To mimic a solution which would maintain hydrologic balance at the regional level, we assume additions or subtractions to the water table under one field will affect the level of the water table, and subsequently the drainage costs, associated with some other field. Two scenarios justify internalizing these external costs (or benefits if  $d < w^e$ ), represented by  $\lambda$  in the above equations. First, consider a grower with multiple fields who has a zero drainage disposal restriction. Positive contributions to the water table under one field must be balanced by equally negative contributions under another field (or set of fields). Alternatively, consider the water district with no out-of-region drainage disposal restriction. The shadow value to the region of positive (negative) contributions to the water table under one field is the additional drainage costs (drainage savings) these contributions create elsewhere.

The constrained maximization problem associated with equations (1)–(3), (6)–(7), (9), and (12) is solved using a nonlinear optimization procedure from the GAMS/CONOPT

**Table 2. Production, Prices, and Parameter Data**

Description	Values	
<b>IRRIGATION SYSTEM:<sup>a</sup></b>		
	<b>Furrow 0.5</b>	<b>Drip</b>
Christensen Uniformity Coefficient (CUC)	70	90
Capital recovery costs (\$/acre/year)	23.29	191.53
Operating & maintenance costs (\$/acre/year)	3.03	61.89
Fixed energy costs (\$/acre/year)	0.99	0.99
Pressure head (feet)	10	50
Pressurization costs (\$/acre-foot)	1.1	5.5
<b>Nonwater Production Costs:<sup>b</sup></b>		
Tomatoes (\$/acre/year)	636.77	751.14
Cotton (\$/acre/year)	604.83	744.93
<b>CROP:</b>		
	<b>Cotton</b>	<b>Tomatoes</b>
Output prices (\$/ton) <sup>c</sup>	1,489.70	55.17
<b>Harvest-Related Costs:<sup>d</sup></b>		
General harvest costs (\$/acre)	61.00	54.86
Yield-related costs (\$/ton)	0.04374	12.69
Revenue-related costs (% of lint revenue)	0.5	NA
<b>WATER:</b>		
	<b>Surface Water</b>	<b>Groundwater</b>
Water price (\$/acre-foot)	41.30 <sup>e</sup>	18.66 <sup>f</sup>
Salinity concentration (dS/m)	0.7	10.0
<b>DEEP PERCOLATION FLOWS:</b>		
Pumping costs (\$/acre-foot)		1.33
Construction/maintenance costs (\$/acre/year) <sup>g</sup>		117.40
Compensating habitat costs (\$/acre/year) <sup>h</sup>		1,504.20
Evaporation rate (feet/year) <sup>i</sup>		5.32
Ratio of compensating habitat to evap. pond acreage <sup>h</sup>		1:1

<sup>a</sup> Sources: University of California Committee of Consultants on Drainage Water Reduction (1988); Posnikoff and Knapp (1997). All costs are in 1999 dollars. Capital recovery costs assume a 5% interest rate. Furrow and drip irrigation systems are assumed to have a 5- and 8-year life expectancy, respectively.

<sup>b</sup> Nonwater production costs include costs associated with seed, land preparation, planting, machinery, fertilizer, etc. Opportunity costs of land and cash overhead are not included. Data come from University of California Cooperative Extension crop budgets for cotton and tomatoes (1999, 2000).

<sup>c</sup> Average price per ton of cotton lint and tomatoes in Westlands Water District, California, 1997–1999.

<sup>d</sup> Source: University of California Cooperative Extension (2000); NA denotes not applicable.

<sup>e</sup> Weighted average price per acre-foot in Westlands Water District, 1997–1999.

<sup>f</sup> Price includes pumping and gypsum costs.

<sup>g</sup> Source: Summers (1983).

<sup>h</sup> Source: Evaporation Ponds Technical Committee (1999), based on 1990 guidelines proposed by the San Joaquin Valley Drainage Program.

<sup>i</sup> Source: Oster et al. (1999).

solver system. The decision variables include applied surface water and applied groundwater. The optimization problem is run separately for each crop-irrigation system combination, allowing for an investigation of the crop-specific responses to changes in various parameters and constraints.

### Irrigation with a Single Water Source

We first consider a grower confronting a single source of irrigation water. Such is the situation for growers in the Imperial Valley of California, where the only viable source of irrigation water is from the Colorado River, given the poor quality and quantity of groundwater in that region. The objective is to choose the quantity of water that maximizes



profits to land and management. Setting  $w^g = 0$  in equation (1), the optimal level of applied irrigation water satisfies

$$(14) \quad p^y y_w = p^s + p^d(1 - e_w),$$

where  $y_w$  is the marginal product of an additional unit of water, and  $e_w$  is the marginal increase in evapotranspiration from an additional unit of water. By definition,  $e_w \leq 1$ . Thus irrigation water is applied until the marginal benefits of another unit of irrigation water equal the marginal costs, represented by the cost of purchasing a unit of water plus disposal costs.

With growing environmental concerns about drainage disposal, future costs of disposal are likely to increase. Indeed, in 1993, growers in California who were using evaporation ponds to dispose of their drainage water were faced with additional regulations intended to minimize potential wildlife impacts. One mandate required growers to install compensating habitat at a 1:1 ratio to their evaporation pond acreage. In our framework, changing the required ratio of compensating habitat to evaporation pond acreage changes the price of drainage. The impact of a change in the price of drainage on the optimal level of applied irrigation water,  $w^*$ , can be evaluated by differentiating equation (14) with respect to  $p^d$ :

$$(15) \quad \frac{dw^*}{dp^d} = \frac{1 - e_w}{(p^y y_{ww} + p^d e_{ww})},$$

where  $y_{ww}$  and  $e_{ww}$  are the second derivatives of  $y$  and  $e$  with respect to  $w^*$ , respectively. According to the second-order conditions associated with profit maximization, and given the linear relationship between  $y$  and  $e$  [i.e.,  $\psi_2 = 0$ , as defined in equation (8)], both  $y_{ww}$  and  $e_{ww}$  should be negative. Consequently, for any  $w^* > 0$ ,  $dw^*/dp^d \leq 0$ .

Table 3 gives empirical results for changes in the price of drainage water. Changing the ratio of compensating habitat to evaporation pond acreage varies the price of drainage water. The first column in table 3 mimics a situation for which no compensating habitat is required, whereas the three remaining columns correspond to an increasing ratio of compensating habitat to evaporation pond acreage.<sup>7</sup> As expected, increases in the price of drainage disposal decrease both profits and applied water usage. For both cotton and tomatoes, increases in  $p^d$  disproportionately impact the profits under a furrow irrigation system relative to a drip irrigation system. As observed in table 3, there is a greater reduction in profits, applied water usage, and deep percolation flows under the furrow system than under the drip system. Furthermore, increases in  $p^d$  may induce growers to switch irrigation technologies. Under the baseline situation, a profit-maximizing grower would likely choose furrow irrigation to grow cotton. Yet, if the compensating habitat requirement increases by approximately 50%, profit-maximizing behavior suggests switching to drip irrigation.

Similar results have been reported elsewhere in models focusing on the quantity, rather than quality (i.e., saline) aspects of optimal irrigation management. For example, Caswell, Lichtenberg, and Zilberman found that growers, in response to an increase in drainage charges, reduce pollution costs by switching to a more efficient irrigation technology.

<sup>7</sup> Prior to 1995, there were no compensating habitat requirements in the SJV. After 1995, a ratio of compensating habitat to evaporation pond acreage of 1:1 was mandated. Recently, the mandated 1:1 ratio has been suggested to go beyond what is needed to adequately protect wildlife (Evaporation Ponds Technical Committee).

**Table 3. Profits and Production Responses to Changes in the Price of Drainage for a Single Water Source**

Description	Ratio of Compensating Habitat Acreage to Evaporation Pond Acreage <sup>a</sup>			
	No Habitat Required ( $p^d = \$23$ )	0.5:1 ( $p^d = \$165$ )	Baseline 1:1 ( $p^d = \$306$ )	1.5:1 ( $p^d = \$448$ )
<----- COTTON ----->				
<b>Furrow 0.5-Mile System:</b>				
Profits (\$/acre/year)	308	222	163	113
Yield (tons/acre/year)	0.665	0.634	0.614	0.599
Applied water (feet/year)	2.89	2.38	2.19	2.08
Deep percolation flows (feet/year)	0.83	0.48	0.38	0.33
<b>Drip Irrigation System:</b>				
Profits (\$/acre/year)	200	165	144	129
Yield (tons/acre/year)	0.675	0.656	0.645	0.637
Applied water (feet/year)	2.50	2.19	2.08	2.01
Deep percolation flows (feet/year)	0.37	0.18	0.12	0.01
<----- TOMATOES ----->				
<b>Furrow 0.5-Mile System:</b>				
Profits (\$/acre/year)	1,169	992	872	777
Yield (tons/acre/year)	47.49	45.48	43.94	42.65
Applied water (feet/year)	3.58	2.82	2.54	2.37
Deep percolation flows (feet/year)	1.69	0.99	0.74	0.61
<b>Drip Irrigation System:</b>				
Profits (\$/acre/year)	1,104	993	919	862
Yield (tons/acre/year)	47.98	46.62	45.57	44.69
Applied water (feet/year)	2.97	2.47	2.29	2.17
Deep percolation flows (feet/year)	1.07	0.61	0.45	0.36

Note: Profits are returns to land and management.

<sup>a</sup>The baseline (\$306) represents the current 1:1 compensating habitat acreage to evaporation pond acreage [Evaporation Ponds Technical Committee (1999), based on 1990 guidelines proposed by the San Joaquin Valley Drainage Program]; the alternative prices for  $p^d$  (i.e., \$23, \$165, and \$448) are associated with respective habitat-to-pond ratios of 0:1, 0.5:1, and 1.5:1.

Another scenario analyzed involves the impacts of increased salinity concentrations in the irrigation water. Such a scenario is conceivable both spatially and temporally.<sup>8</sup> Differentiating equation (14) with respect to  $c$  gives:

$$(16) \quad \frac{dw^*}{dc} = - \frac{y_{wc}}{y_{ww}},$$

where  $y_{wc}$  is the cross-partial derivative of  $y$  with respect to  $w$  and  $c$ . The denominator is negative; however, the numerator's sign depends on the cross-partial term,  $y_{wc}$ . Compelling arguments for a positive or nonpositive  $y_{wc}$  are provided in the literature (refer to Plessner and Feinerman). Given that yield is specified as a linear function of equation (12), the sign of  $y_{wc}$  depends on the level of  $w^*$  relative to  $w^o$ , where  $w^o$  is defined as the

<sup>8</sup> For instance, within the Colorado River one observes increased salinity buildup in the lower Colorado Basin states relative to the Upper Colorado Basin states (Kanazawa 1994). Furthermore, salinity buildup in agricultural regions within southern California is a likely outcome if (and when) California reduces its consumption of Colorado River water from its current 5.2 million acre-feet to its legal entitlement of 4.4 million acre-feet (*Western Water*, March/April 2002).

**Table 4. Profits and Production Responses to Changes in Level of Salinity for a Single Water Source**

Description	Level of Salinity (dS/m)			
	Baseline <sup>a</sup> ( <i>c</i> = 0.7)	( <i>c</i> = 4.0)	( <i>c</i> = 7.0)	( <i>c</i> = 10)
<----- COTTON ----->				
<b>Furrow 0.5-Mile System:</b>				
Profits (\$/acre/year)	163	44	-73	-194
Yield (tons/acre/year)	0.614	0.582	0.545	0.489
Applied water (feet/year)	2.19	2.28	2.34	2.37
Deep percolation flows (feet/year)	0.38	0.59	0.77	0.92
<b>Drip Irrigation System:</b>				
Profits (\$/acre/year)	145	36	-75	-197
Yield (tons/acre/year)	0.650	0.622	0.593	0.555
Applied water (feet/year)	2.08	2.19	2.28	2.343
Deep percolation flows (feet/year)	0.12	0.34	0.54	0.74
<----- TOMATOES ----->				
<b>Furrow 0.5-Mile System:</b>				
Profits (\$/acre/year)	872	447	-21	-440
Yield (tons/acre/year)	43.94	38.16	29.47	18.91
Applied water (feet/year)	2.54	2.91	2.97	2.62
Deep percolation flows (feet/year)	0.74	1.27	1.56	1.48
<b>Drip Irrigation System:</b>				
Profits (\$/acre/year)	919	517	20	-462
Yield (tons/acre/year)	45.57	40.46	31.78	20.88
Applied water (feet/year)	2.29	2.68	2.83	2.61
Deep percolation flows (feet/year)	0.45	0.98	1.35	1.42

Note: Profits are returns to land and management.

<sup>a</sup>The baseline represents the current salinity level (dS/m) for surface water in the San Joaquin Valley.

level of applied water for which  $y_{wc}$  is zero. If  $w^* > w^0$ , then  $y_{wc} > 0$ , and thus  $dw^*/dc > 0$ .<sup>9</sup> Under this condition, increases in the salinity concentration of the water lead to increases in application rates.

Table 4 reports the empirical results for increases in the salinity of a single source of irrigation water. For cotton, increases in salinity lead to increases in water use and decreases in profits. While the profit from growing tomatoes also decreases with increases in salinity, applied water rates first increase and then decrease. Consistent with the theory above, when  $w^* > w^0$ ,  $dw^*/dc > 0$ . That is, initial increases in  $c$  increase optimal applied water,  $w^*$ , up to the point where  $w^0 = w^*$ . After this point, optimal applied water is decreasing in  $c$ .

<sup>9</sup>Let  $w^0$  be the level of the applied water in which  $y_{wc} = 0$ , where  $w^0$  can be isolated from the cross-partial derivative of equation (13):

$$w^0 = \left( \frac{1}{\alpha_2} \left( \frac{\alpha_4 - 1}{\alpha_1(\alpha_4 + 1)} \right)^{1/\alpha_4} - \frac{1}{\alpha_2} c \right)^{1/\alpha_3}$$

If  $w^* > w^0$ , then  $y_{wc} > 0$ , and  $dw^*/dc > 0$ . That is, the increase in the salinity level is compensated by an increase in the water application. This approach is only appropriate for signing  $y_{wc}$  for tomatoes because cotton has the additional complexity associated with transforming output from vegetative to lint production.

### Irrigation with Two Potential Water Sources

The second application addresses optimal irrigation rates at the field level given two sources of irrigation water, including a relatively nonsaline surface water source and a much more saline groundwater source. Such an application mimics the situation confronting many growers in the SJV. Following the characteristics described in table 2, the surface water and groundwater sources have baseline salinity concentrations of 0.7 dS/m and 10 dS/m, respectively. Given the framework specified in equation (1), the optimal levels of applied irrigation water,  $w^s$  and  $w^g$ , are found by solving the following first-order conditions:

$$(17) \quad p^y y_{w^s} = p^s + p^d(1 - e_{w^s}),$$

$$(18) \quad p^y y_{w^g} + \lambda = \gamma_p + \gamma_g + p^d(1 - e_{w^g}),$$

where  $y_{w^g}$  and  $e_{w^g}$  are the marginal change in yield and evapotranspiration from an additional unit of groundwater, respectively, and all other parameters are as previously defined.

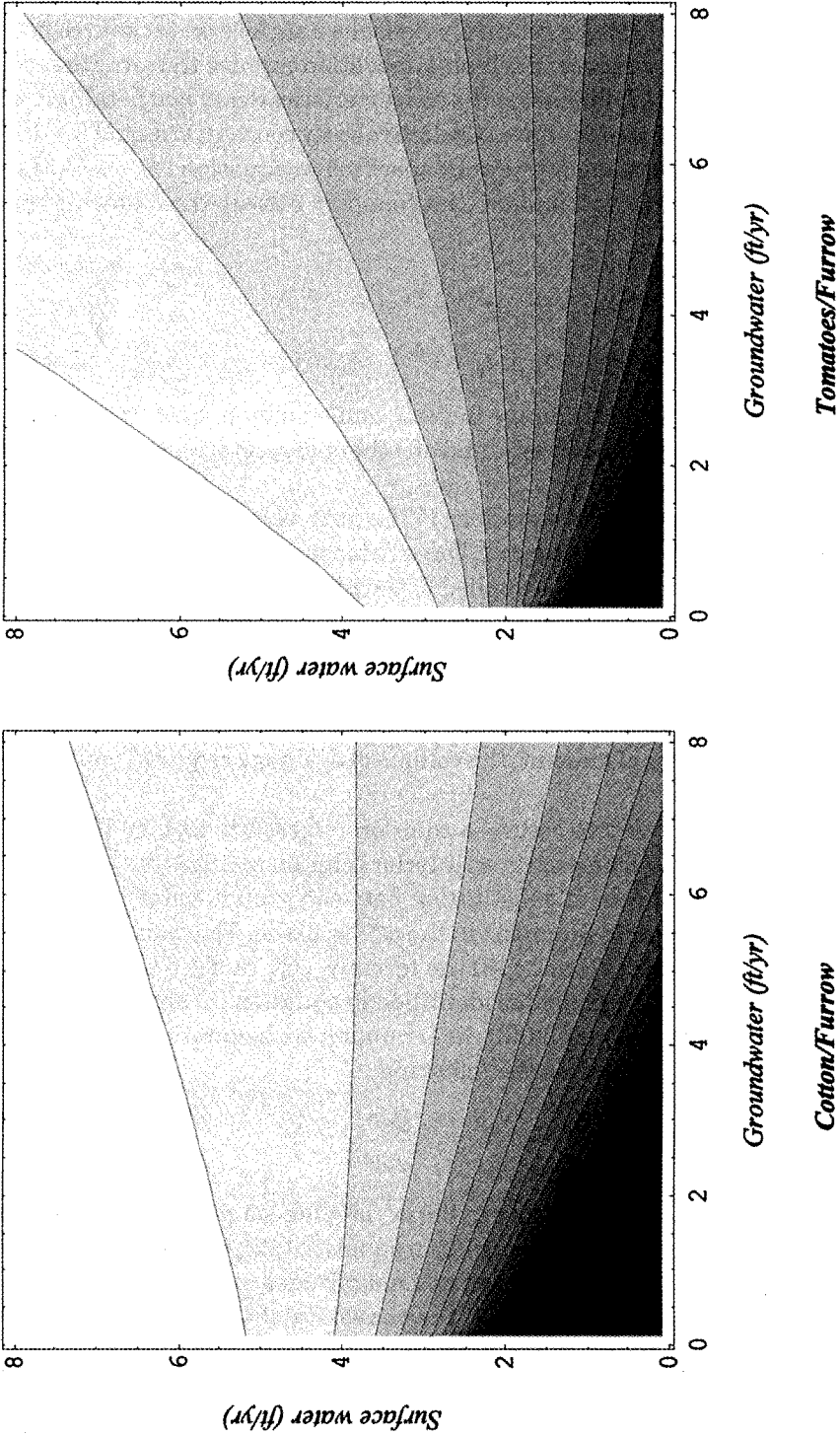
The marginal efficiency condition in equation (17) for surface water is identical to the condition in equation (14) for a single source. The efficiency condition in equation (18) suggests groundwater will continue to be applied to the point where the marginal benefits of another unit equal the marginal costs, represented by the pumping, gypsum, and disposal costs. Note, in contrast to equation (17), equation (18) includes the additional benefit (i.e., shadow value) of subtractions to the water table from using groundwater. This framework reflects the fact that any amount of groundwater used for irrigation necessarily decreases, by an equal amount, the volume of drainage required for disposal elsewhere.

For an optimal interior solution to occur—a solution referred to as blending—both equations must hold. Within our framework, an interior solution requires the water price ratio must equal the marginal rate of substitution between groundwater and surface water, i.e., the slope of the iso-yield functions in the  $w^s:w^g$  plane. This can be shown by first substituting into equations (17) and (18) the terms  $y_{w^s}/\psi_1$  and  $y_{w^g}/\psi_1$  for  $e_{w^s}$  and  $e_{w^g}$ , respectively, based on the relationships identified in equation (8) assuming linearity, and recognizing  $p^d = \lambda$  from equation (3). Rearranging each equation and dividing by each other reveals blending requires the following:

$$(19) \quad \frac{\gamma_p + \gamma_g}{p^s + p^d} = \frac{y_{w^g}}{y_{w^s}} = - \frac{dw^s}{dw^g}.$$

Indeed, convexity of the iso-yield contours in the  $w^s:w^g$  plane is a necessary condition for an interior solution. For the function specified in equation (12), this necessary condition amounts to  $\alpha_3 < -1$ .<sup>10</sup> As shown by the sign and magnitudes of the  $\alpha_3$  parameters in table 1, such a condition is met. Graphically, the convexity of the iso-yield curves is illustrated in figure 2, where cotton and tomato yields are plotted in the  $w^s:w^g$  plane. The lighter shaded areas represent higher yields. Note, the slope of each iso-yield curve reflects the combined effects of both the level of water and the salinity concentration

<sup>10</sup> Results are available from the authors upon request.



Note: The lighter-shaded contours are associated with higher yields.

Figure 2. Surface water and groundwater isoquants for alternative cotton and tomato yields

from each source.<sup>11</sup> Further scrutiny of the curvature of these isoquants suggests that while the iso-yield curves may be convex, they are nearly linear. And while the slight curvature of the isoquants implies the possibility of an optimal interior solution, the near linearity indicates for most combinations of prices such a solution is highly unlikely.

In fact, an investigation of the profits within the  $w^s:w^g$  plane reveals a nonconcave function, with corner solutions representing the maximum profits. For example, consider the case of tomatoes illustrated in figure 3. The contours represent varying profit levels under a drip irrigation system for different combinations of applied surface water and groundwater. The lighter shaded areas represent higher profit levels. Each panel corresponds to a different compensating habitat-to-evaporation pond acreage ratio,  $r$  in equation (13). When  $r = 0.5$  (figure 3a), profits are maximized at a single point ( $w^s = 2.47$ ) along the  $w^s$  axis, thereby implying a corner solution of surface water alone. When  $r = 1.0$  (figure 3b), profits are again maximized at a single point ( $w^s = 2.28$ ) along the  $w^s$  axis. Yet when  $r = 1.5$  (figure 3c), profits are maximized at a single point ( $w^g = 6.4$ ) along the  $w^g$  axis. In all three cases, no interior solutions were chosen, regardless of the relative prices. Relative prices of surface water to groundwater, though, do determine which corner solution is optimal.

Table 5 presents the empirical results of the optimization problem with two water sources for each crop-irrigation system based on the baseline situation ( $r = 1.0$ ). As shown, the optimal application rates for groundwater and surface water correspond to corner solutions. The factor driving the use of groundwater for three out of the four combinations is the drainage reduction credit the grower receives from using groundwater. Specifically, our framework internalizes the external benefits which might accrue to other fields from groundwater withdrawals under our field. For the tomatoes-furrow combination, the upper limit on applied water in our yield-response estimation is a binding constraint. As shown in table 5, furrow irrigation uses substantially more water than drip regardless of crop type. Furrow irrigation is also shown to be slightly more profitable than drip irrigation for growing cotton, but not tomatoes. Differences in water use and salt sensitivity are the critical factors driving these irrigation choice differences.

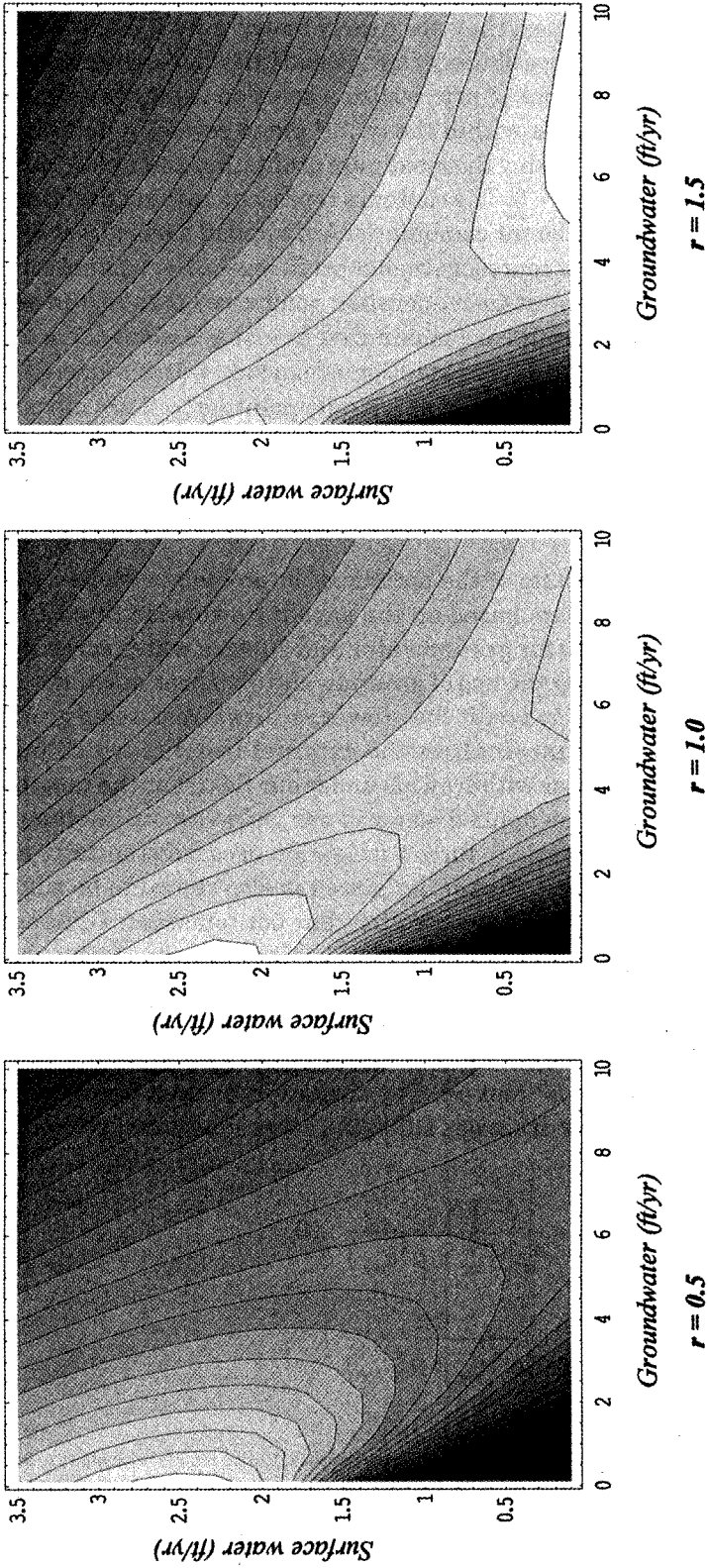
Similar to our first application, we can use the first-order conditions in equations (17) and (18) to illustrate the potential impacts of changes in the compensating habitat requirement on the choice variables  $w^s$  and  $w^g$ . The change in compensating habitat translates into a change in the price of drainage. Differentiating equations (17) and (18) with respect to  $p^d$  leads to:

$$(20) \quad \left. \frac{dw^s}{dp^d} \right|_{w^g=0} = \frac{1 - e_{w^s}}{(p^y y_{ww} + p^d e_{ww})} \leq 0,$$

$$(21) \quad \left. \frac{dw^g}{dp^d} \right|_{w^s=0} = \frac{-e_{w^g}}{(p^y y_{ww} + p^d e_{ww})} \geq 0,$$

---

<sup>11</sup> The combined effects from the two independent sources can lead to some counterintuitive results in an effort to achieve higher crop yields. For example, groundwater acts as a substitute, albeit imperfect, for surface water in maintaining a specific level of output for lower yield levels. The negatively sloped iso-yield curves capture this relationship. Yet, as the particular yield level increases, groundwater becomes less of a substitute. For instance, maintaining higher levels of yield in the event of additional applications of groundwater requires compensation in the form of additional units of fresh water. This phenomenon is illustrated by the positively sloped iso-yield curves.



Note: The lighter-shaded contours are associated with higher profits.

**Figure 3. Iso-profit contours for tomatoes/drip irrigation, under alternative ratios for compensating habitat acreage to evaporation pond acreage**

**Table 5. Baseline Estimates for Each Crop-Irrigation System Combination Given Two Irrigation Water Sources**

Description	Crop-Irrigation System			
	Cotton		Tomatoes	
	Furrow	Drip	Furrow	Drip
Profits (\$/acre/year) <sup>a</sup>	929	821	912	919
Yield (tons/acre/year)	0.661	0.668	29.92	45.57
Applied water (feet/year) <sup>b</sup>	7.10	5.50	6.40	2.28
Surface water (feet/year) <sup>c</sup>	0.00	0.00	0.00	2.28
Groundwater (feet/year) <sup>d</sup>	7.10	5.50	6.40	0.00
Deep percolation flows (feet/year)	5.06	3.42	4.98	0.45

<sup>a</sup> Profits are returns to land and management.

<sup>b</sup> Upper bound on applied water for function presented in equation (12) for tomatoes is 6.40 feet/year (see figure 1).

<sup>c</sup> Salinity concentration in surface water is 0.7 dS/m.

<sup>d</sup> Salinity concentration in groundwater is 10.0 dS/m.

where the  $w^g = 0$  and  $w^s = 0$  notations denote corner solutions. As discussed above, both denominators in these equations are negative, and  $e_w \leq 1$ . Therefore,  $dw^s/dp^d \leq 0$  and  $dw^g/dp^d \geq 0$ , suggesting the direction of the response by growers to increases in the price of drainage depends on whether the grower is using surface water or groundwater.

Table 6 reports the results from increasing the price of drainage on the profits of each crop-irrigation system when growers confront two possible sources of irrigation water. Consistent with the theory for those growers using groundwater, increases in the price of drainage lead to increases in application rates. Alternatively, for those growers using surface water, increases in the price of drainage lead to decreases in application rates. Groundwater is the optimal irrigation source for growing cotton, a relatively salt-tolerant crop. Because our framework internalizes the benefits of reducing deep percolation flows, increases in  $p^d$  lead to increases in profits for those growers using groundwater.

Alternatively, surface water is the optimal irrigation source for tomatoes, at least when the disposal costs are low. For some  $p^d$  above \$165/acre-foot, the optimal water source for a grower using furrow irrigation switches from surface water to groundwater. Consequently, further increases in  $p^d$  lead to increases in both applied groundwater and profits. In the case of drip irrigation, tomato growers are shown to use surface water until some  $p^d$  above \$306/acre-foot, at which point groundwater becomes the profit-maximizing water source.

### Irrigating with Two Water Sources Under Constraints

Institutional and physical factors often exist that constrain water application rates. We first analyze the impact on groundwater usage and profits of a binding constraint on the availability of surface water. Growers in the SJV often confront restrictions on the amount of surface water they can purchase from the Central Valley Project (Kanazawa 1991). We then consider the impacts on profits from constraints on total irrigation volume. The yield-response functions for each crop in the previous two sections were estimated for applied water rates between 1.3 and 7.3 (acre-feet) for cotton, and 1.5 and



**Table 6. Profits and Production Responses to Changes in the Price of Drainage for Two Water Sources**

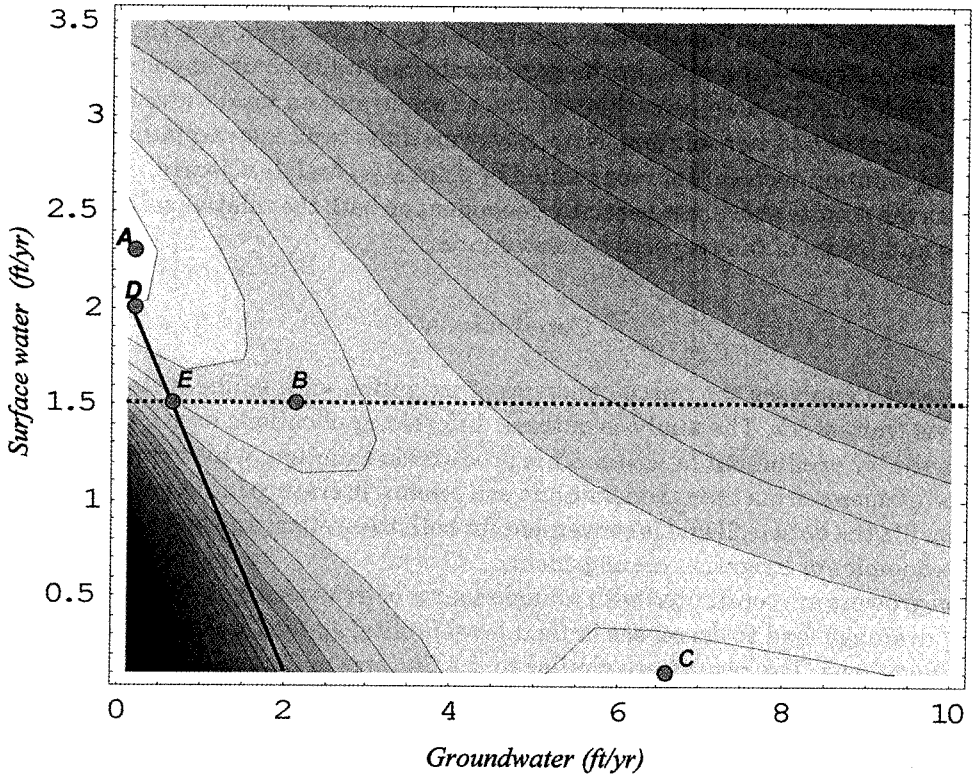
Description	Ratio of Compensating Habitat Acreage to Evaporation Pond Acreage <sup>a</sup>			
	No Habitat Required ( $p^d = \$23$ )	0.5:1 ( $p^d = \$165$ )	Baseline 1:1 ( $p^d = \$306$ )	1.5:1 ( $p^d = \$448$ )
←----- COTTON ----->				
<b>Furrow 0.5-Mile System:</b>				
Profits (\$/acre/year)	360	642	928	1,217
Yield (tons/acre/year)	0.648	0.656	0.661	0.662
Applied water (feet/year)	5.59	6.38	7.10	7.30
Surface water (feet/year)	0.00	0.00	0.00	0.00
Groundwater (feet/year)	5.59	6.38	7.10	7.30
Deep percolation flows (feet/year)	3.62	4.37	5.06	5.25
<b>Drip Irrigation System:</b>				
Profits (\$/acre/year)	240	528	821	1,118
Yield (tons/acre/year)	0.657	0.664	0.668	0.671
Applied water (feet/year)	4.41	4.99	5.50	5.96
Surface Water (feet/year)	0.00	0.00	0.00	0.00
Groundwater (feet/year)	4.41	4.99	5.50	5.96
Deep percolation flows (feet/year)	2.39	2.93	3.42	3.86
←----- TOMATOES ----->				
<b>Furrow 0.5-Mile System:</b>				
Profits (\$/acre/year)	1,169	992	912	1,113
Yield (tons/acre/year)	47.49	45.48	29.92	29.92
Applied water (feet/year)	3.58	2.82	6.40	6.40
Surface Water (feet/year)	3.58	2.82	0.00	0.00
Groundwater (feet/year)	0.00	0.00	6.40	6.40
Deep percolation flows (feet/year)	1.70	0.99	4.98	4.98
<b>Drip Irrigation System:</b>				
Profits (\$/acre/year)	1,104	993	919	971
Yield (tons/acre/year)	47.90	46.62	45.57	29.94
Applied water (feet/year)	2.97	2.47	2.28	6.40
Surface Water (feet/year)	2.97	2.47	2.28	0.00
Groundwater (feet/year)	0.00	0.00	0.00	6.40
Deep percolation flows (feet/year)	1.07	0.61	0.45	4.97

Note: Profits are returns to land and management.

<sup>a</sup>The baseline (\$306) represents the current 1:1 compensating habitat acreage to evaporation pond acreage [Evaporation Ponds Technical Committee (1999), based on 1990 guidelines proposed by the San Joaquin Valley Drainage Program]; the alternative prices for  $p^d$  (i.e., \$23, \$165, and \$448) are associated with respective habitat-to-pond ratios of 0:1, 0.5:1, and 1.5:1.

6.4 (acre-feet) for tomatoes. While the upper bounds on these water applications are associated with a positive, albeit small, marginal physical product, salinity-related adverse impacts on soil structure and infiltration potential can arise (Shennan et al.). Salinity impacts, which likely differ across soil type, in effect limit the amount of water that can be applied.

The impacts of both of these constraints on optimal water management and profits are illustrated in figure 4. Similar to figure 3b, figure 4 shows the iso-profit contours in the  $w^s:w^g$  plane associated with growing tomatoes with  $r = 1.0$ . Point A represents the optimal solution given no constraints on water availability. As shown, this solution consists of 2.3 acre-feet of surface water alone.



**Figure 4. Iso-profit contours for tomatoes/drip irrigation, with constraints on surface and total applied water ( $r = 1.0$ )**

Now suppose availability of surface water is limited to some rate less than 2.3 acre-feet per year. Growers in the SJV, for example, have faced Central Valley Project water entitlements which vary from year to year depending on a range of factors, including drought conditions. In 1988, for instance, growers received 100% of their entitlement of 2.45 acre-feet/acre, while in 1992 they received only 25% of their entitlement, amounting to 0.9 acre-feet/acre (U.S. Department of the Interior 1989, 1992).

For illustrative purposes, a limit of 1.5 acre-feet/acre is imposed and represented by the dashed line in figure 4. Viable surface water-groundwater combinations are limited to the area below the dashed line. Based on the iso-profit contours presented in figure 4, the optimal strategy occurs at point B, an interior solution, or point C, a corner solution of groundwater alone. It is easy to imagine a constraint between 1.5 and 2.3 acre-feet/acre which would lead to an unambiguous interior solution. Alternatively, a constraint below approximately 1.25 acre-feet/acre would result in point C again being the optimal solution. In each case, it is interesting to note how groundwater, as a supplemental source of irrigation water in this application, substitutes for surface water. Based on our results, whether or not this supplemental source is used in conjunction with surface water depends, in part, on the level of the constraint.

Now consider the effect of a constraint on total water applications, composed of the sum of surface water and groundwater. For illustrative purposes, we set the limit on total water application at 2.0 acre-feet/acre, which is represented by the solid oblique

line in figure 4. Under this constraint, only combinations of surface water and groundwater lying on or within the interior of this line are viable options to the grower. As observed from figure 4, the strategy shown to maximize profits occurs at point *D*, a corner solution. Indeed, it is easily seen that any linear constraint on total water applications will likely lead to a corner solution. Note, however, if the two constraints are combined, a blending solution such as that represented by point *E* is possible. Clearly, these results, as well as the results above, are partially dependent on both the relative salinity concentrations and prices of the respective water source.

### Conclusions

This research analyzes the microeconomics of irrigation with saline water in a static field-level framework. The analysis of three different applications uses a unique crop-water-salinity production function. This production function, which combines well-accepted elements from the agronomic and soil science literature into a single tractable function, fits the data well and is convenient for both theoretical and empirical analyses of the economics of irrigation management.

When growers are confronted with a single source of irrigation water, increases in the price of drainage lead to decreases in field-level profits, applied water rates, and deep percolation flows. The results are similar to the findings of Caswell, Lichtenberg, and Zilberman (and others) who concluded increased disposal costs increase the relative attractiveness of water-conserving irrigation technologies. While the results suggest increases in salinity decrease profits regardless of crop type, there is ambiguity surrounding the relationship between changes in salinity and the optimal applied water usage. Conditions under which increases in salinity of the irrigation water require more or less irrigation water are identified. Specifically, whether the optimal water application rate,  $w^*$ , increases or decreases with increases in salinity depends on the level of  $w^*$  relative to  $w^0$ , where  $w^0$  is defined as that level of applied water for which  $y_{wc}$  is zero.

In many instances, growers have access to two sources of irrigation: a low-saline surface water source, and a high-saline groundwater source. Here we find that blending two heterogeneous sources of irrigation water is an unlikely solution from an efficiency perspective. Analogous results were found by Knapp and Dinar, and by Dinar, Letey, and Vaux. For those growers using surface water, increases in the price of drainage lead to decreases in profits and applied water; for growers using groundwater, increases in the price of drainage lead to increases in both profits and applied water. This outcome results from placing a positive shadow value on groundwater withdrawals reflecting water table management as well as dynamics which may be present at the farm or regional levels.

Groundwater can serve as a substitute irrigation source in the presence of surface water scarcity. Similar to Feinerman and Yaron, we find constraints on the availability of surface water can lead to optimal water management that includes blending. Whether the binding constraint on surface water leads to a marginal or nonmarginal increase in groundwater usage (possibly even a corner solution consisting of groundwater alone) depends on a number of factors, including the relative salinities and prices of the irrigation sources, as well as the level of the constraint. Limits on the total allowable irrigation application are likely to lead to profit-maximizing solutions consisting of corner solutions.

It should be noted that the analysis here is at the field level and does not consider responses such as changing crop type or irrigation system. Clearly, allowing additional flexibility will likely reduce the magnitude of the impact of price or parameter changes on profits. Furthermore, the empirical results (i.e., profits, applied water, and deep percolation flows) are driven in part by the positive shadow value on drainage reductions from groundwater usage. Estimation of this shadow value requires farm- and regional-level analyses taking into account general opportunities for source reduction and disposal. Our simplifications allowed for a more detailed and lucid analysis of potential profit-maximizing responses at the field level.

Finally, while our analysis has identified situations for which blending may or may not be part of a profit-maximizing management scheme, the matter is largely empirical, and thus additional research on the topic seems warranted, perhaps using dynamic intra-seasonal models or internalizing additional factors, such as plant density as it relates to saline water use (Feinerman).

[Received November 2001; final revision received April 2002.]

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### Appendix: The Steady-State Seasonal Model

This appendix describes the crop-water-salinity model used in the first step of the meta-modeling procedure for estimating the response function  $e(w, c)$  in equation (12), and  $y(e)$  in equation (8). The model produces data sets consisting of  $w$ ,  $c$ , and the corresponding values of  $e$  and  $y$  for each crop and irrigation system. In general, many such models are available in the scientific literature. The model used here is a seasonal model which strikes a balance between realism, data needs, and computational effort at a level appropriate for economic policy analysis. We caution this would not be an appropriate model for intra-seasonal irrigation scheduling, for example, which would require a more detailed transient model.

As with most models in the scientific crop-water literature, this model is algorithmic, requiring an iterative procedure for solution. There is no known closed-form solution; hence, numerical methods on the computer are necessary. Using ordinary least squares and nonlinear least squares regression methods, the outputs of the data generation procedure are translated into functional forms convenient for economic analysis; this is the second step of the meta-modeling procedure.

#### *Plant-Level Model*

The plant-level production function model is based on Letey, Dinar, and Knapp, with parameter values generally specified from Letey and Dinar. Plant evapotranspiration (ET),  $e^p$ , is given by:

$$(A1) \quad e^p = e^w e^r,$$

where  $e^w$  is plant-level ET with nonsaline water, and  $e^r$  is relative ET (the proportionate reduction in ET due to salinity effects). Nonsaline plant-level ET is specified as:

$$(A2) \quad e^w = \min[w^p, \bar{e}],$$

where  $w^p$  is the irrigation water applied to the plant, and  $\bar{e}$  is maximum ET if water and salinity are not limiting. Maas and Hoffman determined yield was linearly decreasing in soil salinity after an initial threshold. Under the assumption that yield is linearly related to ET, their results imply:

$$(A3) \quad e^r = \begin{cases} 1 & \text{if } s \leq \underline{s}, \\ \frac{\bar{s} - s}{\bar{s} - \underline{s}} & \text{if } \underline{s} \leq s \leq \bar{s}, \\ 0 & \text{if } s \geq \bar{s}, \end{cases}$$

where  $s$  is soil salinity measured as the electrical conductivity of a saturated extract,  $\underline{s}$  is the threshold salinity level beyond which yield (and ET) decline, and  $\bar{s}$  is the soil salinity level beyond which there is no yield.

Soil salinity is calculated from a relation developed by Hoffman and van Genuchten. Under steady-state conditions and assuming an exponential water uptake distribution, they establish:

$$(A4) \quad s = \frac{c}{2} \frac{w^p}{w^p - e^p} \left[ 1 + 0.2 \ln \left[ \exp(-5) + (1 - \exp(-5)) \frac{w^p - e^p}{w^p} \right] \right],$$

where  $c$  is the salinity concentration of the irrigation water. Substituting (A2) and (A3) into (A1) gives plant-level ET as a function of soil salinity which, when combined with (A4), constitutes a two-equation system in two variables ( $e^p$  and  $s$ ) given the infiltrated water depth and salt concentration of the irrigation water. This system is solved using a Newton-Raphson procedure (aside from some special cases outside the various threshold values such as  $w^p < \underline{e}$ , where  $\underline{e}$  is the minimal ET needed for crop production).

Considerable experimental evidence suggests vegetative plant-level yield,  $v^p$ , is linearly related to ET:

$$(A5) \quad v^p = \begin{cases} 0 & \text{if } e^p \leq \underline{e}, \\ \frac{e^p - \underline{e}}{\bar{e} - \underline{e}} \bar{v} & \text{if } \underline{e} \leq e^p, \end{cases}$$

where  $\bar{v}$  is the vegetative yield obtained at maximum ET. Marketable plant-level yield is then given by:

$$(A6) \quad y^p = \mu_1 + \mu_2 v^p + \mu_3 (v^p)^2.$$

In many instances, such as the case of tomatoes, marketable yield and vegetative yield are identical, implying  $\mu_1$  and  $\mu_3 = 0$ , and  $\mu_2 = 1$ . Yet for a few other crops, such as cotton, excessive vegetative growth can reduce marketable yield, in which case the polynomial relation is used (Letey and Dinar).

### Field-Level Model

Irrigation water is distributed nonuniformly over the field for a variety of reasons. Thus it is necessary for additional water beyond crop ET to be applied to ensure adequate irrigation for all parts of the field. Excess water beyond crop ET is needed also for salt leaching, as described above.

Following the early irrigation engineering literature (Seginer; Feinerman, Letey, and Vaux), we assume a spatial distribution function for water and then integrate over the field. Let  $\rho$  denote the infiltration coefficient; this gives the fraction of field-level average water depth,  $w$ , which infiltrates at a particular point in the field. Field-level ET and crop yield for each crop-irrigation system are calculated as:

$$(A7) \quad e = \int_0^{\infty} e^p[\rho w, c] g(\rho) d\rho,$$

$$(A8) \quad y = \int_0^{\infty} y^p[\rho w, c] g(\rho) d\rho,$$

where  $g$  is the spatial density function for the infiltration coefficients typical for an irrigation system, and  $e^p$  and  $y^p$  are plant-level ET and crop yield, as calculated from the above relations.

Following Knapp (1992), we assume a lognormal distribution for the infiltration coefficients. The mean value of this distribution equals 1 for mass balance. The standard deviation of the distribution depends on the irrigation system, with less uniform irrigation systems having larger standard deviations. The standard deviations are calculated to fit the Christiansen Uniformity Coefficient (CUC) typical for the irrigation system, where CUC = 70 and CUC = 90 for furrow 0.5-mile and furrow drip systems, respectively. Field-level deep percolation flows and salt concentrations of these flows are estimated as:

$$(A9) \quad d = w - e,$$

$$(A10) \quad e^d = \frac{cw}{d}.$$

The first relation follows from mass balance. The second relation follows from the assumption of steady-state root-zone conditions, implying salts entering the system in the irrigation water equal salts leaving in the deep percolation flows.