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Irrigation Management and Investment Under Saline, Limited Drainage Conditions
3. Policy Analysis and Extensions

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Water demand is characterized for the cotton-cotton-tomatoes rotation considered in the previous paper (Knapp, this issue (*b*)). Demand is found to be price inelastic. However, currently low water prices imply that fairly moderate increases in water prices can result in large water savings. A marginal cost curve for source control of drain water emissions is constructed. Moderate increases in drainage emissions fees can result in large reductions in drain water emissions with relatively small impacts on income. Management response and income effects from increased water salinity are estimated. The model is also extended to consider drain water reuse. Typical optimal management with reuse is low-volume, low-quality water on first-year cotton, improved quality and quantity on second-year cotton, and the highest quality water on salt-sensitive tomatoes. An approach to maximization of multifield farm-level returns is proposed using decentralized pricing and the field-level optimization model.

INTRODUCTION

This paper applies the empirical model developed in the previous two papers [*Knapp*, this issue (*a*), (*b*)] to a series of policy issues. The first topic considered is agricultural water demand. In general, agriculture faces increasing competition for available supplies. The reasons are (1) new water source development is either prohibitively expensive or faces strong opposition on environmental grounds, and (2) water sources currently used for agriculture are challenged by increased growth in residential and industrial water use with oftentimes greater capacity to pay than agriculture. Clearly, an efficient and equitable allocation of water between sectors in the economy requires an understanding of the determinants of agricultural water demand. At the same time, groundwater aquifers underlying major agricultural areas are experiencing declines in available stocks and/or quality. As a common property resource, groundwater is likely to be used inefficiently [*Gisser and Sanchez*, 1980]; previous research indicates that the demand for water is a key determinant of the benefits from groundwater management and hence of whether the resource should be managed or left unregulated [*Feinerman and Knapp*, 1983]. In contrast to most previous studies, agricultural water demand is estimated here in the context of a dynamic model which accounts for both spatial variability and soil salinity.

Agricultural producers are both affected by, and contribute to, environmental degradation. Here I will consider two particular instances of importance to western growers. The first is the potential salinization of irrigation water with consequent declines in yield and increased production costs. The second is environmental damages associated with drainage water from irrigated production. General issues for each topic include the optimal response and net returns for various parameter values, social marginal benefits/costs from alternate levels of regulation, and implications for policy.

Irrigated agriculture is both a user of increasingly scarce water supplies as well as a contributor to environmental degradation via drainage flows. One strategy which addresses both problems is drain water reuse. This saves on the use of fresh water and reduces the outflow of drainage water from the agricultural sector with consequent reduction of environmental degradation. Here the field-level model developed in the first two papers will be extended to consider irrigation from two different water sources differing in salinity and cost. Optimal management will be considered in the context of the cotton-cotton-tomatoes rotation. Benefits from drain water reuse are then estimated under alternate conditions and compared to available cost estimates for instigating use of brackish drain water.

The analysis of the above issues is carried out using the field-level model and data developed in the previous two papers. As will be seen, this will yield some qualitative conclusions about policy likely to hold at a more general level, and it at least provides regulatory authorities order-of-magnitude estimates likely to hold across a range of conditions and land areas. Nevertheless, it is still the case that higher levels of aggregation need to be considered in general. At the farm level, risk aversion and joint constraints across fields require that operation of all fields must be considered simultaneously. At the regional level, joint constraints may hold across farms, and output levels may be sufficiently large relative to the market that demand effects need to be considered.

Conceptually, the field-level model developed here can be extended to the farm or regional level by combining the equations and constraints for individual fields in a single optimization model. This would appear to be the standard approach. While simple, the resulting problem would likely be computationally intractable for any realistic situation. An alternative approach is explored here using a decentralized pricing mechanism. The basic insight is that while the field-level model may be relatively complex, the joint constraint(s) across fields may be relatively simple, implying that not all information pertaining to a particular field is of direct relevance to the optimal operation of some other field.

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TABLE 1. Optimal Applied Water Depths and Irrigation Systems for Various Water Prices

Water Price, $/(ha cm)	Rotation	Irrigation System	Field-Average Applied Water Depth, cm/yr: Cotton 1	Cotton 2	Tomatoes	Rotation Average
1	1	furrow, 1/2 mile	136	122	140	133
	3	furrow, 1/2 mile	120	122	140	127
	25	furrow, 1/2 mile	120	122	140	127
3	1	furrow, 1/2 mile	122	105	129	119
	3	furrow, 1/2 mile	102	117	120	113
	25	furrow, 1/2 mile	102	117	120	113
6	1	linear move	71	101	77	83
	3	linear move	72	70	88	77
	25	linear move	70	70	88	76
8	1	linear move	70	103	73	82
	3	linear move	70	70	90	77
	25	linear move	70	70	90	77

Parameters used here are $e = 0$, $E[S_0] = 4$ dS/m, $SD[S_0] = 0.01$, and $\rho_0 = 0$. For other parameters, see *Knapp* [this issue (*b*)]; 1 mile equals 1.609 km.

In analogy with a market economy, optimal operation in the aggregate can be achieved by correctly pricing the resource with the individual producing units' being unaware of the details of other producing units. In the application here, the field-level dynamic optimization model is used to determine optimal management of the individual fields, while a shadow price algorithm serves to allocate the scarce resource (irrigation water) in an optimal fashion across the farm.

AGRICULTURAL WATER DEMAND

Quantity demanded of irrigation water depends on the crop, the price of water, and a variety of other factors. This section provides empirical estimates of water demand for the cotton-cotton-tomatoes rotation considered in the previous paper [*Knapp*, this issue (*b*)]. Although the focus is the price of water, several other variables are considered as well in this and the following sections. As the model is dynamic, the analysis is for both the short and long run.

Optimal decision rules for water use are characterized by *Knapp* [this issue (*b*)]. These give optimal water applications and investment in irrigation systems as a function of the crop, type and age of the irrigation system at the beginning of the season, and distribution parameters for infiltration and soil salinity over the field. To investigate water demand, these decision rules are computed for various parameter values using the algorithm of *Knapp* [this issue (*a*)] and then simulated over 25 crop rotations for a field with an initially uniform salt concentration of 4 dS/m. Selected results are given in Table 1. For each of the runs reported there, the system converges to a steady state in the sense defined by *Knapp* [this issue (*b*)] (the "second paper"). More specifically, there may be variation in the values of the state and control variables within a rotation, but after an initial transition period all rotations are identical. Formally, the dynamic system converges in these runs to a limit cycle which will be referred to here as the "steady state" rotation. The results for rotation 1 can therefore be considered short run and results for rotation 25 can be considered long run.

It is apparent from Table 1 that the system converges to the "steady state" rotation quite quickly. By the third rotation the values for applied water for a specified crop within the rotation are essentially at their long-run values. Inspection of the detailed computer results shows that this is true for the other variables as well. This is due in part to the initial condition that the existing irrigation system at $t = 0$ has reached the end of its physical life and must be replaced. Were the simulations to be started under other conditions, then the short and long responses could be expected to be more different. Also consistent with the empirical results reported in the second paper is the observation that there are significant differences of applied water quantities within the rotation, even for the same crop.

The right-hand column in Table 1 reports applied water depths averaged over the rotation. Calculated arc elasticities using these figures range from −0.04 to −0.53 for the short run and zero to −0.59 for the long run, implying that water demand is price inelastic. Note also that there is essentially no difference between the short- and long-run elasticities. While demand is inelastic, significant decreases in applied water can still be achieved. For example, increasing the price of applied water from $1/(ha cm) to $6/(ha cm) reduces rotation-averaged applied water depths by 40% in the long run. This price increase, while large in percentage terms, is still moderate in the sense that some growers in other parts of the state face comparable prices and that the price is still less than that paid by other economic sectors. Considering that agriculture typically uses some 80–90% of developed water in the western United States, even a small reduction in agricultural water use releases a large volume of water relative to that used by residential and industrial users.

Figure 1 illustrates long-run water demand for the cotton-cotton-tomatoes rotation. (Applied water quantities are rotation averages.) As can be seen, water demand is most elastic for low water prices and least elastic for higher water prices. Quantity demanded is zero for an irrigation water price of approximately $20/(ha cm): At this price the present value of returns to land and management are zero for the cotton-cotton-tomatoes rotation. Aside from this, most of the potential reduction in water use occurs for prices less than $5 (ha cm). Further price increases beyond this point reduce quantity demanded only slightly.

Economic analysis of water demand primarily focuses on irrigation water prices. However, other variables can significantly impact applied water volumes as well. Table 2

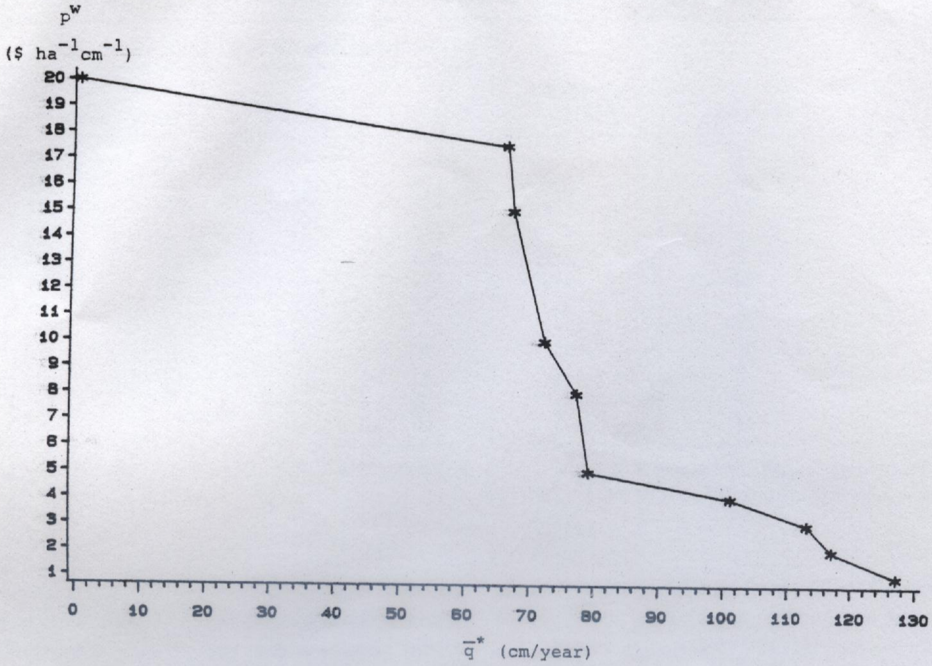

Fig. 1. Long-run water demand for the cotton-cotton-tomatoes rotation (e = 0, ECI = 0.67 dS/m).

considers the effects of alternate initial conditions for soil salinity. Second-year cotton and tomatoes are little affected. However, initial applied water depths (first-year cotton) in Table 2 vary by 3–24% depending on water price and initial soil salinity compared to an initial field-average soil salinity of 4 dS/m. (A more detailed inspection of the effect of initial conditions can be found in the work by *Knapp* [this issue (*b*)]. These variations in quantity demanded could well mask interfarm differences due to water prices alone.

Potentially, the interest rate could affect water demand. In principle, this could happen through changes in the relative costs of irrigation systems, or through a change in the relative weighting of current and future net benefits in the dynamic optimization problem. The effect of an increase in the interest rate is greatest for high water prices where a capital-intensive system is optimal for the base case of r = 5% and where water is scarce. Accordingly, (real) interest rates of 10% and 20% were considered with an irrigation water price of $6/(ha cm). A complicated limit cycle with r = 10% was found. This limit cycle consisted of 5 years of furrow, 1/2 mile (0.8 km), followed by 12 years of linear move, 5 years of furrow, 1/2 mile again, and finally 5 years of furrow, 1/4 mile (0.4 km). Annual applied water depths over this cycle average 84 cm/yr in comparison to 76 cm/yr with r = 5%. The limit cycle with r = 20% consists of 10 years of furrow, 1/2 mile followed by 5 years of furrow, 1/4 mile with an average annual applied water depth of 93 cm/yr. While it is unlikely that such high real interest rates or complicated investment patterns would ever be observed in actuality, these results do serve to illustrate that economic variables besides water price can significantly affect agricultural water demand. The next two sections will consider two further variables with significant implications for agricultural water demand.

TABLE 2. Optimal Applied Water Depths for Various Water Prices and Initial Soil Salinities in the First Rotation

Water Price, $/(ha cm)	$E[S_0]$, dS/m	Field-Average Applied Water Depth, cm/yr		
		Cotton 1	Cotton 2	Tomatoes
1	1	119	123	140
	4	136	127	140
	7	140	127	140
3	1	93	101	120
	4	123	105	130
	7	134	102	130

Parameters used here are ECI = 0.67 dS/m, e = 0, SD[S_0] = 0.01, and ρ_0 = 0. For other parameters, see *Knapp* [this issue (*b*)].

DRAINAGE WATER EMISSION FEES

Drainage water is an inevitable consequence of irrigated agricultural production. This drainage water may take the form of deep percolation below the root zone, flows into a drainage system which are then removed and disposed off-farm, or possibly surface runoff. Here I generally consider only the first two categories as they have the greatest environmental significance. Since plants essentially extract only pure water from the available soil water, some drainage water is necessary in order to maintain salt balance. However, with good quality water the required leaching fraction (drainage water as a fraction of irrigation) is usually quite small. For example, with an irrigation water electrical conductivity of 0.7 dS/m (typical for the area under consideration), required leaching fractions to maintain adequate salt balances for even salt-sensitive crops are 10% or less [*Pratt and Suarez*, 1990]. Generally speaking, most drainage water generated by irrigated agriculture is due to nonuniform water application over the field. Because of nonuniformity, excess water above crop evapotranspiration (ET) must be applied to some parts of the field so that all parts of the field are in some sense adequately irrigated.

TABLE 3. Optimal Values for Selected Variables for Various Irrigation Water Prices and Drainage Disposal/Environmental Costs

Water Price, \$/(ha cm)	e, \$/(ha cm)	Irrigation System	Applied Water Depth,* cm/yr	Deep Percolation,* cm/yr	Annualized Returns to Land and Management, \$ ha^{-1} yr^{-1}
1	0	furrow, 1/2 mile	127	59	1392
	2	furrow, 1/2 mile	110	43	1284
	4	linear move	81	14	1219
3	0	furrow, 1/2 mile	113	46	1151
	2	linear move	80	13	1086
	4	linear move	76	11	1060

Parameters used here are $E[S_0] = 4$ dS/m, $\mathrm{SD}[S_0] = 0.0$, and $\rho_0 = 0.0$; for other parameters, see *Knapp* [this issue (*b*)]; 1 mile equals 1.609 km.

*Limit cycle rotation averages.

Agricultural drainage water generates various costs to society. These may take the form of capital and operating and maintenance costs for facilities needed for disposal of the drainage water. More generally, these flows typically contain a variety of contaminants, including various salts, nitrates, pesticides and possibly heavy metals such as selenium. Consequently, drain water emissions are likely to result in reduced water quality of receiving groundwater and surface water bodies. Drainage flows may also contribute to high water tables resulting in adverse effects on crop production in the same or other areas. For the most part, growers have not been liable for damages caused by drainage flows leaving their fields. As a result, we may expect that drainage flows are excessive compared to an economically efficient solution. This section explores several aspects of what can be an important policy problem in arid zone irrigated agriculture. The reader is referred to *Tanji* [1990] for additional details about the scientific and engineering aspects of agricultural drainage problems.

Table 3 illustrates selected results from the optimization model under varying irrigation water prices and drainage emission fees. A traditional irrigation system (furrow, 1/2 mile (0.8 km)) is optimal for low water prices and emission fees. This corresponds to observed practice for the area under investigation as noted in the second paper. For higher water prices or emission fees, a linear move system with its more uniform applied water distribution becomes economically efficient.

It can also be seen from Table 3 that accounting for disposal and/or environmental costs of drainage water can have a sizable impact on efficient water use. With an irrigation water price of \$1/(ha cm), the results in Table 3 show that, averaged over the rotation in the limit cycle, an increase in the emission fee from zero to \$4/(ha cm) results in a 36% decrease in applied water and a 76% decrease in drainage flows which are defined here as deep percolation below the root zone. However, the corresponding reduction in returns to land and management is about 12%. Comparable results are obtained with an irrigation water price of \$3/(ha cm). Here the same increase in the emission fee results in a 33% reduction in applied water, a 76% reduction in deep percolation flows, and an 8% reduction in returns to land and management.

It should also be noted that the reduction in applied water and drain water emissions can vary over the rotation. For example, with an irrigation water price of \$1/(ha cm), increasing the drainage emission fee from zero to \$4/(ha cm) reduces applied water by 37% for both cotton crops and 36% for tomatoes in the limit cycle. However, comparable reductions for drainage emissions are 88% for first-year cotton, 87% for second-year cotton, and 62% for tomatoes. This pattern reflects the heightened salt sensitivity of the tomato crop.

Optimal pollution control occurs where the social marginal costs of control equal the social marginal benefits from control. Figure 2 illustrates the marginal costs of pollution control for agricultural water, where pollution control is defined as reduction in generated drainage water. Marginal costs are increasing in pollution control over the entire range. The first part of the curve is relatively flat, while the second part of the curve starting at a reduction of 45 cm/yr is relatively steep. This suggests that pollution control in the form of source control is relatively easy up to 45 cm/yr, and relatively difficult after that point. This also corresponds to the observation above that drainage fees up to \$4/(ha cm) reduce net returns by a relatively small amount (12% or less). For the conditions considered here, Figure 2 suggests that, regardless of the level of social marginal benefits of control, the optimal reduction in drainage flows is unlikely to exceed 45 cm/yr.

As with all environmental problems, estimation of marginal social benefits of drain water reduction is exceedingly difficult. This is due to the complexity of the underlying transport and transformation processes, and to the inclusion of nontangible health and ecological benefits. Also marginal benefits are likely to be highly spatially variable. To the author's knowledge, no complete estimates of marginal social benefits of drainage reduction are available for the region under consideration; however, some insight can be gleaned from previous work.

Knapp et al. [1986] consider operation of a farm where all drain water must be disposed of in an evaporation pond. The pond size depends on the volume of drainage flows and displaces productive land. At the optimal solution, drain water disposal costs are \$4.23 per ha cm of drain water after adjusting for inflation. Note that this accounts only for land opportunity costs associated with the evaporation pond and does not include salt removal costs off the farm or ecological damages. *Wichelns* [1991] notes that drainage system operation costs alone for a particular irrigation system are

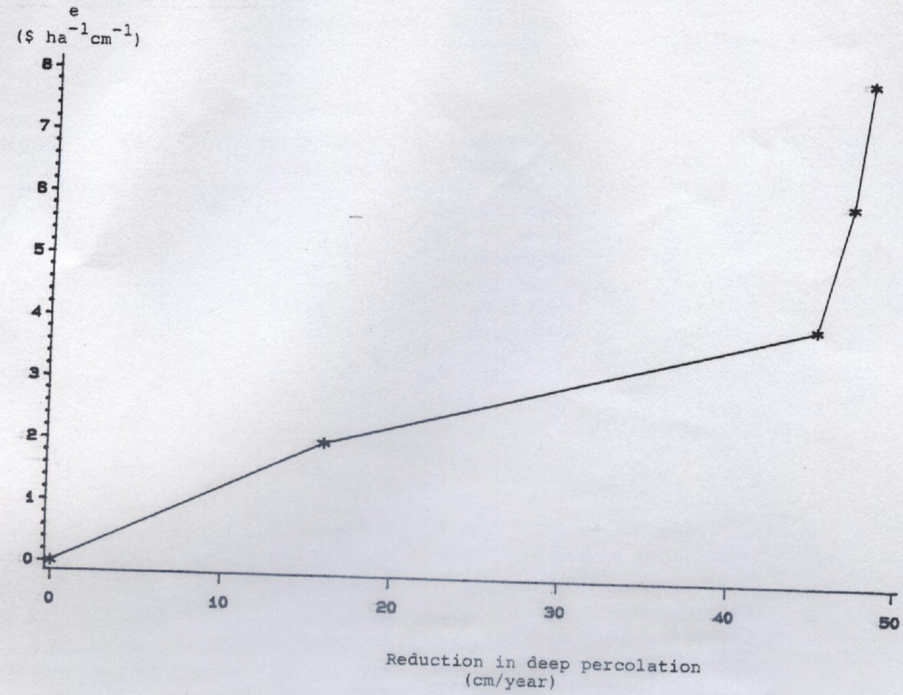

Fig. 2. Long-run marginal cost of pollution control for rotation-averaged drain water from the cotton-cotton-tomatoes rotation (p^w = \$1/(ha cm), ECI = 0.67 dS/m).

\$1.70/(ha cm) of drain water or \$1.62/(ha cm) after adjusting to 1987 dollars; this figure does not include environmental or disposal costs of the drain water once the water leaves the district. After adjusting for inflation, *San Joaquin Valley Drainage Program (SJVDP)* [1990] estimates of cost of treating drainage water to acceptable quality levels range from \$10.38/(ha cm) to \$21.56/(ha cm), not including disposal costs of the residual waste stream.

With these estimates in mind, it can be seen from Figure 2 that the optimal reduction in drainage flows for an irrigation water price of \$1/(ha cm) amounts to some 45–48 cm annually. This accords with might have been expected a priori: Since the marginal cost of control is relatively flat at first, then relatively steep, the optimal reduction likely lies near the juncture. It is also interesting to note that *SJVDP* [1990], based on a comprehensive analysis for the region under consideration and using entirely different data and methods, recommends a 65% reduction in drainage flows produced. This compares with the 76% reduction found here with both irrigation water prices considered in Table 3.

IRRIGATION WATER SALINITY

Another potential problem in arid zone agriculture is salinization of the water supply. This may occur for a number of reasons. Along the Colorado River, irrigation return flows contribute to increased salinity of the river for downstream users. Increased salt loading may be due to the concentrating process of evapotranspiration or to the drainage water's moving through areas of naturally high salt content before flowing into the river. A somewhat different process occurs in Kern County, California. Underlying this area is a large, somewhat closed groundwater basin. Substantial quantities of surface water are imported to the area and groundwater is also used for irrigation. Drainage flows percolating below the root zone eventually reach the aquifer. Since there is minimal outflow from the basin, the implication is that the aquifer will eventually become salinized.

From a policy perspective, various control measures can be taken to control salinity, thereby mitigating downstream effects (see, for example, *Gardner and Young* [1988]). Again, control measures should be taken to the point where the marginal cost of control equals the marginal benefit of control. This section explores optimal management when the irrigation source is increasingly salinized and the attendant costs to growers from that salinization process.

Table 4 gives selected results for varying irrigation water prices and salt concentrations. As can be seen, the concentration of irrigation water has a significant impact on optimal irrigation management. The optimal irrigation system in all cases is a traditional furrow, 1/2-mile (0.8 km) system. However, depending on the price of irrigation water, optimal water applications increase by 28–40% and deep percolation increases by 69–78% when the salinity of the irrigation water increases from 1 to 5 dS/m. The increased applied water

TABLE 4. Optimal Values for Selected Variables for Various Irrigation Water Prices and Salt Concentrations

Water Price, \$/(ha cm)	Electrical Conductivity of Irrigation Water, dS/m	Applied Water Depth,* cm/yr	Deep Percolation,* cm/yr	Annualized Returns to Land and Management, \$ ha^{-1} yr^{-1}
1	1	143	74	1463
	3	163	94	1418
	5	200	132	1310
3	1	116	49	1213
	3	134	67	1126
	5	148	83	978

Here e = 0; optimal irrigation system is furrow, 1/2 mile (0.8 km).
*Limit cycle rotation averages.

depths serve to flush additional salts from the root zone and thus keep soil salinity below levels than those at which it would otherwise be. The percentage reductions in returns to land and management are somewhat more moderate although still quite significant. They range from 10% to 19% for the same increase in irrigation water salinity. Thus to some extent growers can counteract the effects of increased salinity by applying additional water, but with more severe economic consequences when the price of irrigation water is high.

These results can be compared to those of previous studies. *Gardner and Young* [1985] analyze the costs and benefits of salinity control projects along the Colorado River. Using a linear programming model for Imperial Valley agriculture, they estimate annual average damages from a 300 mg/L increase in irrigation water salinity as $46,100 per mg/L. They also cite two other studies which estimate average annual damages as $15,600 per mg/L and $52,870 per mg/L, respectively, for a comparable range of increases in salinity. Converting for salinity units, acreage, and inflation, these studies imply annual average damages of $42/(ha dS/m) to $143/(ha dS/m) over the range of water qualities considered. From Table 4, estimated damages here range from $23/(ha dS/m) to $44/(ha dS/m) depending on the price of water for a comparable range of water qualities.

The results here indicate a somewhat smaller range of damages. One reason is that the cited studies are for the Imperial Valley as a whole and therefore include a higher fraction of salt-sensitive crops than the cotton-cotton-tomatoes rotation considered here. *Gardner and Young* [1985] also assume two possible irrigation frequencies which can somewhat mitigate salinity effects, but use a fixed water application level. Here it is assumed that water applications are completely variable with no limitations on the amount used for irrigation. This allows for increased salt leaching which reduces the effects of high-saline water, but may not be a completely accurate assumption on some soils. Finally, the results here are for the San Joaquin Valley. This has an unknown but probably small effect.

An important finding of the *Gardner and Young* [1985] study was that only five of the 20 salinity control projects being considered were economically efficient. Despite the difference in estimated benefits, the results here would only serve to strengthen that conclusion.

DRAIN WATER REUSE

As noted in the introduction, drain water reuse constitutes a possible solution to both the water allocation and environmental degradation issues facing irrigated agriculture. This section of the paper investigates the potential for drain water reuse at the field level. The analysis is partial in the sense that the cost of obtaining drain water is taken as a given. A more complete analysis would need to be conducted at the farm or regional level, and would entail recognition of the fact that drain water reuse could not exceed the generation of drain water, and that the volume of drain water generated would depend, in part, on the possibility of reusing that water for other crops.

To incorporate drain water reuse in the optimization model, I assume that there are two sources of water available for irrigation. The first is a high-cost, high-quality water source while the second is a low-cost, low-quality water source which can represent the reuse of drain water for crop production. The respective costs and salt concentrations are denoted by p_k^w and c_k, $k = 1, 2$, respectively. In the optimization model, salt concentration of the irrigation water now becomes a control variable in addition to the volume of irrigation water and irrigation system investment. Natural bounds on the concentration control variable are given by

$$c_1 \leq c_{ij} \leq c_2$$

where c_{ij} denotes concentration of the applied water. Recognizing that the salt concentration of applied water is just the weighted average of the concentrations from the two sources, it follows that

$$p^w = \frac{(c_2 - c_{ij})}{(c_2 - c_1)} p_1^w + \frac{(c_{ij} - c_1)}{(c_2 - c_1)} p_2^w$$

where p^w denotes the per-unit cost of the blended water.

The point-level production functions are now defined by

$$\begin{bmatrix} y_{ij} \\ d_{ij} \\ s_{ij+1} \end{bmatrix} = g_j(s_{ij}, q_{ij}, c_{ij})$$

Equations (9), (10) and (11) of *Knapp* [this issue (*a*)] define field-level yields and drainage flows and the moments for the spatial density function. These equations are modified in a straightforward way to incorporate the generalized point-level production functions. Also, the numerical results of *Knapp* [this issue (*b*)] suggest that irrigation system replacement almost always occurs at the maximum physical life of the system; systems are almost never replaced before the end of their physical life even though the optimization model allows for that possibility. The reuse optimization model therefore assumes this result; investment in a new irrigation system is only considered when the existing system is at the end of its physical life. This assumption is made in order to keep the problem computationally tractable.

Incorporating these assumptions and extensions into the model of *Knapp* [this issue (*a*)] defines the reuse dynamic optimization model. The control variables are irrigation system investment, annual field-average applied water depth, and salt concentration of the irrigation water. The state variables remain as before (type and age of the existing irrigation system, first two moments of $\ln s$, and $E[(\ln s)(\ln \beta)]$). The objective function remains as before except that the price of irrigation water is now given by the relation defined above.

Figure 3 illustrates optimal irrigation management with drain water reuse under the specified conditions. The optimal irrigation system is furrow with 1/2-mile (0.8 km) runs in all years. Aside from a brief transition period, the optimal solution converges to a limit cycle. In the limit cycle, optimal applied water depths and salt concentrations are 131 cm/yr and 7 dS/m for first-year cotton, 151 cm/yr and 2.7 dS/m for second-year cotton, and 132 cm/yr and 1.7 dS/m for tomatoes. Field-average soil salinity reaches a high of 7.6 dS/m after the first cotton crop, decreases to 2.7 dS/m after the second cotton crop, and reaches a low of 1.7 dS/m after the tomatoes crop. In general, then, the lowest quantity and quality of water are applied to first-year cotton. Cotton is sufficiently salt-tolerant that high yields are maintained, but soil salinity does increase. Increased quantity and quality of

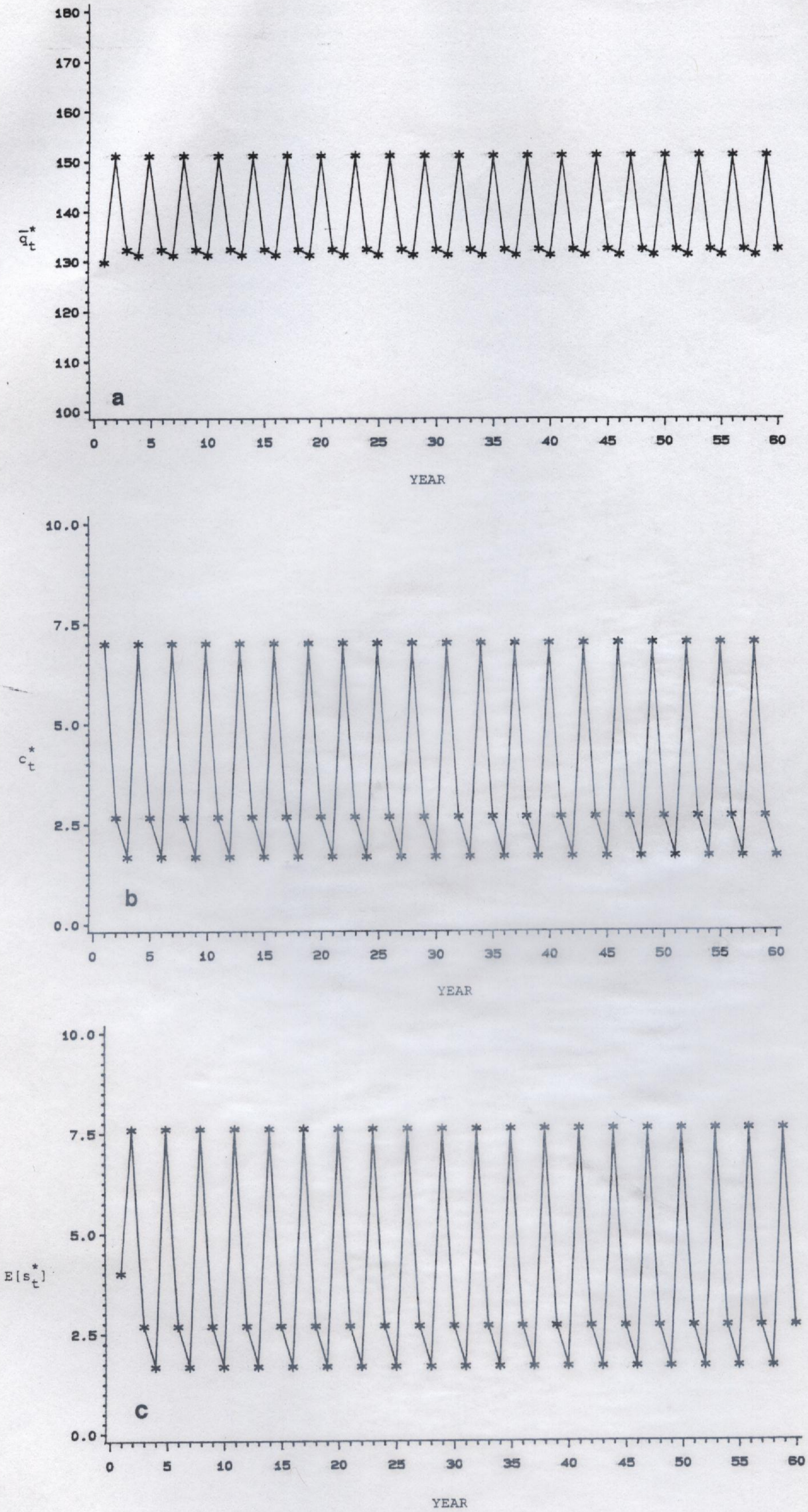

Fig. 3. Selected optimization results versus time with drain water reuse for $p_1^w = \$3/(\text{ha cm})$, $\text{ECI}_1 = 0.67$ dS/m, $p_2^w = \$1/(\text{ha cm})$, $\text{ECI}_2 = 7$ dS/m, and $e = 0$. (*a*) Field-average applied water depth (centimeters per year). (*b*) Salt concentration of the irrigation water (decisiemens per meter). (*c*) Field-average soil salinity (decisiemens per meter).

TABLE 5. Optimal Irrigation Systems and Applied Water Depths With Drain Water Reuse

			Field-Average Applied Water Depth,* cm/yr (Salt Concentration of the Irrigation Water,* dS/m)			
p_1^w	ECI_2	Irrigation System	Cotton 1	Cotton 2	Tomatoes	Rotation Average
3	3	furrow, 1/2 mile	120 (3.0)	174 (3.0)	167 (2.9)	154 (3.0)
5	3	furrow, 1/2 mile	120 (3.0)	176 (3.0)	165 (3.0)	154 (3.0)
3	5	furrow, 1/2 mile	124 (5.0)	213 (5.0)	137 (1.8)	158 (4.1)
5	5	furrow, 1/2 mile	129 (5.0)	255 (5.0)	214 (5.0)	199 (5.0)
3	7	furrow, 1/2 mile	131 (7.0)	151 (2.7)	132 (1.7)	138 (3.7)
5	7	furrow, 1/2 mile	133 (7.0)	236 (7.0)	118 (0.7)	162 (5.5)
3	9	furrow, 1/2 mile	128 (9.0)	134 (1.1)	120 (0.7)	127 (3.6)
5	9	furrow, 1/2 mile	137 (9.0)	189 (7.3)	127 (0.7)	151 (6.0)

$ECI_1 = 0.67$ dS/m; $p_2^w = \$1/(\text{ha-cm})$, $e = 0$; 1 mile equals 1.609 km.
*Optimal values in the limit cycle.

irrigation water are applied to second-year cotton. From the computer results (not presented), this has no impact on cotton yield but does serve to reduce soil salinity for the upcoming tomato crop. Maximum possible ET for tomatoes is less than that for cotton, so less irrigation water is needed. However, the highest-quality water is applied to the tomato crop. This serves to reduce soil salinity consistent with the reduced salt tolerance of the tomato crop.

Table 5 gives results for alternate prices of the good-quality water and for alternate salt concentrations of the poor-quality water source. The general characteristics of optimal management follow that outlined above. A furrow irrigation system with 1/2-mile (0.8 km) runs is used. Applied water depths are greater for the second-year cotton crop compared to the first year, and less water is applied to tomatoes than second-year cotton. Salt concentration of applied water is highest for first-year cotton, lowest for tomatoes, and intermediate for second-year cotton.

Consider now the effects of parameter changes in Table 5. As would be expected, an increase in the price of good-quality water generally implies increased use of the poor-quality water in that the salt concentration of the applied water increases. Holding the price of good water constant at \$3/(ha cm), an increase in the salt concentration of the low-quality source at first increases both the quantity and salt concentration of the applied water consistent with the results in the previous section of this paper. However, at some point the low-quality source becomes sufficiently saline that further increases in its concentration result in decreased usage. Thus both the quantity and salt concentration of the applied water decrease when the salt concentration of the secondary source increases past 5 dS/m. Somewhat similar behavior is observed when the price of the primary irrigation source is \$5/(ha cm) as water volumes begin to decline for the higher concentrations of the secondary source. This behavior is explained in part by the observation that, holding the prices of both sources constant, an increase in secondary source concentration effectively raises the price of irrigation water of a specified concentration.

These results may be compared to the case of no reuse analyzed throughout the previous part of the paper. One difference is that a traditional irrigation system (furrow, 1/2 mile (0.8 km)) is optimal for all conditions in Table 5. This contrasts with the no reuse case where a linear move system is optimal when the price of irrigation water is \$5/(ha cm) and e is zero. A second major difference is in returns to land and management as summarized in Table 6. Here benefits from reuse are measured as the difference in annualized returns to land and management with and without drain water reuse. As would be expected, benefits from reuse increase as the price of good-quality water increases, and decrease as the salt concentration of the poor-quality source increases. In percentage terms, the benefits from reuse can be substantial. For the conditions considered here, allowing drain water reuse increases net returns by 4–40% depending on irrigation water prices and salt concentrations.

The analysis here considers only the benefits from reuse. Cost of reuse depends on the particular situation. One possibility is drilling a well to extract saline water from a shallow aquifer. Another possibility is that the effluent from a drainage system in one field is used for irrigating another field. This involves installation and maintenance of a pipeline system between fields. In any case, installation of a reuse system likely includes capital and operating and maintenance costs, as well as pumping costs for the drain water.

The analysis of *Knapp et al.* [1986] considers the second type of system mentioned above. For the particular layout considered there and after adjustment for inflation, annualized reuse capital and operating and maintenance costs are estimated at \$40/ha, while variable pumping costs associated

TABLE 6. Annualized Returns to Land and Management With and Without Reuse

		Annualized Returns to Land and Management, $\$ \text{ha}^{-1} \text{yr}^{-1}$		Benefits From Reuse	
p_1^w	ECI_2	No Reuse	Reuse	Value, $\$ \text{ha}^{-1} \text{yr}^{-1}$	Percent Increase
3	3	1151	1338	187	16
5	3	954	1333	379	40
3	5	1151	1269	118	10
5	5	954	1232	278	29
3	7	1151	1211	60	5
5	7	954	1143	189	20
3	9	1151	1198	47	4
5	9	954	1069	115	12

$ECI_1 = 0.67$ dS/m, $p_2^w = \$1/(\text{ha cm})$, $e = 0$, $E[S_0] = 4$ dS/m, $SD[S_0] = 0.0$, and $\rho_0 = 0.0$.

with reuse are estimated at \$0.25/(ha cm). Comparing to the benefits in Table 6, it appears that for the situation analyzed here, reuse would be a worthwhile investment when the price of good-quality water is high and the salt concentration of the drain water is low. Reuse would be a marginal investment for the converse situation in Table 6. It should also be noted that this analysis considers only the effects of total salt concentration on plant growth. Specific ion effects may yield differential results depending on the composition of the drain water. Another possible problem not considered here is the uptake of trace metals or other compounds by the plant with possible toxicity effects. (See *Tanji* [1990] for a discussion of these issues.)

Finally, I briefly consider the case where the price of water obtained from the secondary, low-quality source may actually be negative. As noted in the introduction to this section, drain water reuse constitutes a possible disposal mechanism for generated drain water, thereby avoiding the associated disposal/environmental costs. In some situations it could therefore be the case that growers are charged for drain water emissions off the farm but are paid for using drain water to grow crops.

To analyze this possibility, the reuse optimization model was run assuming a fresh water price of \$3/(ha cm), drain water disposal/environmental costs of \$4/(ha cm), drain water concentration of 9 dS/m, a drain water price of −\$3/(ha cm), and a traditional irrigation system. (The drain water price is calculated assuming a \$1/(ha cm) cost of obtaining the drain water.) Optimal applied water quantity (salt concentration) in the limit cycle is 168 cm/yr (9.0 dS/m) for first-year cotton, 272 cm/yr (9.0 dS/m) for second-year cotton, and 118 cm/yr (0.7 dS/m) for tomatoes. Annualized net returns are \$1279/ha. Thus as would be expected, both optimal drain water reuse and net returns increase in comparison to the analogous case in Table 5. Field-average soil salinities are lower after the first-year cotton crop due to the higher volume of water applied, higher after the second-year cotton crop due to the increased salinity of the irrigation water in the second year, and approximately the same after the tomato crop as the increased water volume is used to flush from the root zone the extra salts remaining after the second-year cotton crop.

FARM-LEVEL MODEL

The model developed in this work is a field-level model. In some instances, however, it may be necessary to consider the operation of several fields simultaneously. This could occur for several reasons. Constraints on inputs such as water or machinery time could mean that use on one field implies restrictions on availability for other fields. A second source of jointness could be marketing constraints in which either a minimum or a maximum amount of some particular crop could be sold, or constraints on other outputs such as the maximum allowable volume of drain water flows off the farm. Also, in the stochastic case, a risk-averse utility function implies that the distribution of returns in one field cannot be evaluated separately from the distribution of returns in other fields.

Conceptually, the model developed here can be extended in a straightforward way to a farm-level model by defining a vector of the state and control variables for each field and then maximizing a joint objective function subject to the sets of field-level equations of motion and constraints and any cross-field constraints as appropriate. Although easy to formulate, the problem would probably be computationally infeasible at the present time with any solution method and certainly with the dynamic programming algorithm used here.

This section explores an alternative, decentralized approach to this problem utilizing the field-level model developed earlier. The approach is illustrated for the case where there is a constraint on the maximum amount of water which can be used on the farm as a whole in each year. To keep the problem simple, I assume that there are two fields with two possible irrigation systems (furrow, 1/2 mile (0.8 km) and furrow, 1/4 mile (0.4 km)) considered for each field. Cotton is grown in field 1 and tomatoes in field 2. Drain water reuse is not considered, so there is a single irrigation source and the horizon is taken to be 5 years.

The basic idea is as follows. Let $p^s = (p_1^s, \cdots, p_5^s)$ be a vector of shadow prices for the irrigation water. Given that the farm-level water constraint is binding, these shadow prices will be greater than the actual cost to the grower of purchasing the water. Using these shadow prices, the dynamic optimization model can then be run for each field separately. This determines a vector of applied water volumes used in each field $\bar{q}_i = (\bar{q}_{i1}, \cdots, \bar{q}_{i5})$ and the present value of returns to land and management for each field and hence the farm as a whole. Thus we can write:

$$\pi = w^f(p^s)$$

$$\bar{q}_{it} = w_{it}(p^s) \qquad i = 1, 2; \qquad t = 1, 5$$

where π is the present value of farm-level returns to land and management, w^f gives π as a function of p^s, and w_{it} are the water demand functions in each year for the individual fields. The value of p^s which maximizes π subject to

$$\sum_i w_{it}(p^s) \leq \bar{w} \qquad t = 1, 5$$

gives the optimal solution to the problem where $\bar{w}$ is the annual constraint on irrigation water availability faced by the farm.

Table 7 gives the optimal solution where the initial field-average soil salinity is 4 dS/m, the annual water constraint is 200 (ha cm)/yr, and each field is assumed to be 1 ha in area. As can be seen, the optimal shadow prices are declining over time. The initial soil salinity level is higher than desired; hence water demand is greatest in the first period. Water demand is lowest in the last period due to the finite horizon. As a consequence, shadow prices fall over time. Generally, more water is applied to tomatoes than cotton. Aside from differences in ET, this serves to keep soil salinity lower for the more salt-sensitive and valuable tomato crop. In both instances, the furrow, 1/4-mile (0.4 km) system is used.

It can also be seen that the result of this procedure does not meet the farm-level constraints exactly. There are several reasons for this. First, the search algorithm for the shadow prices is based on a simple grid search, so an exact solution cannot be found. More importantly, the dynamic programming algorithm is also based on a grid search. Thus the optimal solution is a step function of the parameters (here the shadow price of irrigation water). Using a finer mesh for the grid points results in a more accurate solution.

TABLE 7. Selected Optimal Values for Multifield Model With Annual Farm-Level Water Constraint of 200 (ha cm)/yr

		Field 1: Cotton			Field 2: Tomatoes			
Year	Shadow Price, \$/(ha cm)	Irrigation System	$E[S]$, dS/m	$\bar{q}^*$, cm/yr	Irrigation System	$E[S]$, dS/m	$\bar{q}^*$, cm/yr	Farm-Level Water Use, (ha cm)/yr
1	8.5	furrow, 1/4 mile	4.0	74	furrow, 1/4 mile	4.0	107	182
2	8.0	furrow, 1/4 mile	3.9	103	furrow, 1/4 mile	1.1	97	200
3	8.0	furrow, 1/4 mile	2.5	74	furrow, 1/4 mile	1.2	97	171
4	6.0	furrow, 1/4 mile	3.0	79	furrow, 1/4 mile	1.2	97	176
5	5.0	furrow, 1/4 mile	3.3	74	furrow, 1/4 mile	1.2	97	171

The parameters used here are $e = 0$, $E(S_0) = 4$, $SD[S_0] = 0$, and $\rho = 0$. Area of fields 1 and 2 is 1 ha each; 1 mile equals 1.609 km.

This is only a partial explanation, however, since the finite number of irrigation systems introduces an unavoidable element of discreteness. Finally, it may be the case that, given the choice of irrigation system, the optimal solution may be less than the maximum available water after an initial transition period. For example, consider the results in Table 1 where optimal water use for a linear move system is significantly less than 200 cm/yr for the combined cotton and tomato crops.

As noted above, a traditional approach to the farm-level problem would be to combine all the relevant equations of motion, constraints, and variables into a single optimization model. Two possible advantages of the present approach suggest themselves. First, the approach is sufficiently modular that the code for the farm-level model is constructed relatively easily by simply writing a program which calls the field-level model. The standard approach requires specification of an entirely new model. More importantly, consider the specific example addressed here. In determining optimal operation of one field, the only information about other fields which is of direct value is the total water use and marginal value of water on other fields. Information about the joint distribution of soil salinity and water distribution, or the type and age of irrigation systems, on other fields is of no direct consequence for optimal operation of the specified field. When we consider that the difficulty of solving mathematical programming problems increases nonlinearly with the number of variables and constraints, it seems that including constraints and equations of motion for all fields in the same model may be inefficient.

These considerations suggest that when the field-level model is relatively complex and the farm-level constraints are relatively simple, then, for a large enough number of fields, the decentralized algorithm considered here may be computationally more efficient than the standard programming approach. Further research is needed to explore more efficient search algorithms for calculating optimal shadow prices in the decentralized procedure, as well as comparison to the standard programming approach.

CONCLUSIONS

Agricultural water demand is estimated in a dynamic setting for a specific crop rotation (cotton-cotton-tomatoes). Soil salinity and applied water converge to an optimal limit cycle quite quickly (one to two rotations) for the initial conditions considered here. Demand is also found to be inelastic in both the short and long run. This is consistent with previous statistical studies [*Nieswiadomy*, 1988; *Ogg and Gollehon*, 1989]. Some normative programming studies [e.g., *Howitt et al.*, 1980] have reported elastic derived demands for irrigation water; however, these studies are regional in scope and allow crop switching, topics which are not considered here.

While the estimated demand for irrigation water is inelastic, it is still the case that moderate increases in the price of irrigation water can result in significant reductions of irrigation water. This apparent contradiction is resolved by noting that current agricultural water prices are quite low in many regions, including that analyzed here. Thus a moderate increase in the actual price can represent a severalfold increase. For the case considered here, an increase in the price of water from \$1/(ha cm) to \$5/(ha cm) reduces rotation-averaged quantity demanded by 40 cm/yr or 38%. This is a significant amount of water when one considers that agricultural uses generally predominate in most areas of the west. It is also relevant when noting that \$5/(ha cm) can be well below the price paid by other economic sectors for water.

Economists have generally focused on price and crop type as a determinant of agricultural water use; however, a great many other factors influence that choice as well. Other factors considered here include initial soil salinity, disposal and environmental costs for drainage water, salt concentration of the drainage water, the interest rate, and availability of alternate low-cost, low-quality irrigation sources. Somewhat similar conclusions apply to these factors as with irrigation water price: In many cases the implied relations are inelastic; however, significant variations in applied water volumes are observed over a plausible range of values for these other factors. This also has implications for econometric modeling of agricultural water demand. Since there is likely to be a wide range of underlying conditions across farms, nonprice factors must be accounted for if the statistical model is to be accurately estimated and have high explanatory power.

As with the irrigation water demand curve, drainage flows are most elastic for low emission fees and least elastic for higher fees. More precisely, an increase in emission fees from zero to \$4/(ha cm) reduces drainage flows by some 76% for the conditions considered here. Depending on prices, this reduction is achieved either through reduced applied water with traditional irrigation systems or through investment in an irrigation system with higher application uniformity and consequent lower application rates. Corresponding to these results, over a substantial range of emission fees (zero to $4/(ha cm), the percentage reduction in net returns is much lower than the percentage reductions in applied water and deep percolation. This assumes that growers are charged for drainage flows by an amount equal to disposal/environmental costs. If the regulatory instrument is a standard on flows or a set of specified management practices, then the impact on net returns would be even smaller.

More generally, the results obtained here suggest strongly that source control should be an important part of regional drain water management policies. Design of appropriate policy is complicated by the nonpoint character of drainage emissions; however, it seems likely that reasonable regulatory schemes are likely to result in quite substantial drainage water reductions with small impacts on grower net returns.

Increased salinization of irrigation water sources causes damages to downstream users. Optimal response to increased irrigation salinity is an increase in applied water. The response is found here to be inelastic. In particular, a fivefold increase in irrigation water salinity from 1 to 5 dS/m resulted in a 40% increase in applied water. Damages from increased salinity are also found here to be less than previous estimates. This may be attributed to the emphasis here on changes in applied water volumes as a way of mitigating salinity and to the analysis of a rotation with only one salt-sensitive crop.

One response to both increased competition for high-quality water sources and environmental damages from drainage water is drain water reuse. Accordingly, the management model was extended to consider irrigation from multiple water sources differing in cost and salt concentration. Generally, the optimal management strategy with drain water reuse is low-volume, low-quality water for first-year cotton, higher volumes with possibly improved quality water for second-year cotton, and good-quality water for tomatoes. This pattern follows from the relative salt tolerance of cotton compared to the more salt-sensitive tomato crop which follows. The model serves to quantify the relevant magnitudes.

Allowing drain water reuse reduces the derived demand for improvements in irrigation systems. The increase in returns to land and management from drain water reuse is highly dependent on the relative prices and salt concentrations of the alternate water sources. However, for a plausible range of values, increases in net returns of as much as 40% are possible. Costs of drain water reuse are also likely to vary greatly depending on the particular circumstances. Again, for the particular situation considered here, benefits from drain water reuse outweigh the costs of reuse.

Most normative programming models of agricultural water use are static regional or farm-level models. Here the emphasis has been on a field-level model in order to capture the dynamics of soil salinity, spatial variability, and irrigation system investment in as realistic a fashion as possible. Farm-level constraints or jointness across fields implies that operation of several fields may have to be considered jointly. Accordingly, a decentralized approach for optimal farm-level operation is proposed utilizing the field-level model. This is motivated in general by the decentralized approach inherent in microeconomic theory. More specific to the problem here, this allows a modular approach in which field-level models developed for other purposes can easily be combined into a farm-level model without creating a whole new model. In addition, this approach would appear to be computationally efficient when the field-level models are relatively complex but the constraints or jointness across fields are relatively simple. This approach to farm-level modeling with further aggregation to the regional level merits further investigation.

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