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On-Farm Management of Agricultural Drainage Water: An Economic Analysis

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ABSTRACT

This paper analyzes optimal management strategies for farms with limited natural drainage and no access to off-farm disposal facilities. A representative farm with conditions typical of a drainage problem area in the San Joaquin Valley is considered, using a long-run steady-state model. Optimal, profit-maximizing water applications were significantly less for this farm than would be profitable for a farm with no drainage problems. Relatively high yield levels were maintained, and the required pond size was relatively small. Comparatively little crop switching occurred relative to that on a farm with unlimited natural drainage, and drainwater reuse was not profitable when all costs were considered.

Access to an off-farm disposal facility brought significant benefits, and a moderate discharge fee significantly reduced effluent volumes. A plausible amount of underground drainage flow to the farm had little effect. With uniform water applications, returns to land and management are significantly greater than with non-uniform applications, and the pond size is almost negligible. Water application levels are almost identical in the limited and unlimited drainage cases, when water is applied uniformly.

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INTRODUCTION

SUBSTANTIAL AMOUNTS OF FARMLAND in the San Joaquin Valley suffer from a lack of adequate drainage, and the problem will probably get worse in coming years. A widely discussed solution to the problem is construction of a valleywide drain, running the length of the San Joaquin Valley and draining all affected areas. To date, only a small portion of this drain has been built, and there is substantial financial and environmental opposition to its completion. It is not clear when, if ever, the valleywide drain will be completed.

The purpose of this research is to investigate the possibilities for on-farm management of agricultural drainage problems. Specific topics addressed include efficient management strategies when natural drainage and external facilities for disposal of drainwater are limiting, maintenance of profitable levels of operation under such conditions, benefits to farmers from construction of external drainage facilities, and quantities that would flow to those facilities under several pricing schemes. The results should be useful in decision making in areas with limited off-farm drainage, and in evaluating public investment in external facilities. Although the analysis is framed in terms of an individual farm, many concepts and results may also apply at the regional level, if drainage is disposed of in evaporation ponds constructed on otherwise productive land.

We will begin with some background information on the nature of the problem and a review of the few economic studies that have addressed drainwater management problems. Then we will discuss some alternatives for managing drainwater problems on farms. Following that, a mathematical model for analyzing drainwater management at the farm level will be developed and then applied to a representative farm in an area with high water table problems.

NATURE OF THE PROBLEM

The San Joaquin Valley is one of the most productive agricultural areas in the world. It is bounded to the north by the Sacramento–San Joaquin Delta, to the east by the Sierra Nevada Mountains, to the south by the Tehachapi Mountains, and to the west by the Coast Ranges. The northern half of the valley drains to the San Joaquin River. The southern half is essentially a closed basin, but has a valley trough, like that in the northern half, roughly one-third of the way from the valley's western boundary to its eastern boundary.

Much of the land to the west of the valley trough is underlaid by shallow, relatively impervious layers of clay. Over time, irrigation water draining through the root zone accumulates on these layers and the water table begins to rise. If the water table rises high enough, crop yields and agricultural productivity may decline. This can happen because of reduced aeration in the root zone, increased salinity in the soil, and with

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some crops (e.g., cotton), excessive vegetative growth resulting in reductions of marketable yield. Current estimates are that some 119,000 hectares are subject to inadequate drainage. This is projected to increase to approximately 405,000 hectares by 2085 if no action is taken (San Joaquin Valley Interagency Drainage Project 1979). These figures represent 6.5 percent (current) and 23 percent (projected) of the approximately 1.8 million hectares currently irrigated in the San Joaquin Valley.

Farmers generally correct high water table situations by installing drain lines in fields and then disposing of the water off-farm. The difficulty in most affected areas of the San Joaquin Valley is that facilities for off-farm disposal are extremely limited. North of Westlands Water District, drainwater may be reused for irrigation, routed to wildlife refuges, or returned to the San Joaquin River. This last option may be limited in the future if stronger water quality standards are imposed. In the past, some farmers in Westlands Water District have had access to the federally constructed San Luis Drain, which flows into Kesterson Reservoir. Only about 5,000 acres have been served by the drain (Kelley and Nye 1984), though, and flows into the drain are scheduled to be shut off by June 1986. Tulare Lake Drainage District currently disposes of its saline drainage water in evaporation ponds on marginally productive farmland, but not all areas have this sort of unproductive land available for drainage disposal. Substantial amounts of farmland are currently without access to adequate off-farm drainage facilities.

A widely discussed solution to drainage problems in the San Joaquin Valley is construction of a drain line to extend from Bakersfield in the south to Suisun Bay in the north. A comprehensive analysis by the San Joaquin Valley Interagency Drainage Program (1979) concluded that the proposed drain was technically feasible in that it would maintain agricultural productivity with minimal impacts on water quality in the delta area; that the benefits from constructing the drain were greater than the costs; and that it was preferable to the other options considered. Nevertheless, substantial opposition to the drain continues, due to the expense involved ($1 billion) and environmental concerns (Beck 1984). In particular, the recent finding of selenium-caused birth defects in waterfowl at Kesterson has heightened concerns about the effects of disposing of drainwater in the delta area. It is not clear whether this valley drain will be constructed.

In the absence of off-farm facilities, questions arise as to whether or not drainwater problems can be managed by individual farmers or groups of farmers using evaporation ponds and other methods. Previous work on this topic is very limited. Yaron and Olian (1973), Moore, Snyder, and Sun (1974), Matanga and Marino (1979), Feinerman and Yaron (1983), and others have analyzed salinity and irrigation management at the farm level in situations of unlimited drainage. Fitz, Horner, and Snyder (1980) investigated optimal spacing and installation depths for drain lines in fields, but did not address the question of drainwater disposal. Rhoades (1977) has analyzed the biological and physical aspects of drainwater reuse, but without considering the economic aspects. More recently, Wichelns and Horner (1984, unpublished report) formulated a dynamic model for an individual field, which allows changes over time in soil salinity and the height of the water table as functions of leaching water, soil amendment, and groundwater relief pumping. Their analysis yielded substantial insights; however, they considered only one crop (barley), they did not consider several options for reducing drainage problems (crop switching, drainwater reuse), and they assumed that drainage water could be disposed of off-farm at some predetermined price. That assumption cannot now be made in many areas of the San Joaquin Valley, for the reasons given above. Our study attempts to address these issues.

OPTIONS TO REDUCE OR DISPOSE OF DRAINWATER ON FARMS

Several options are available to reduce the quantity of drainwater produced by a farm and to dispose of the remaining flow in the absence of natural or external drainage facilities. These include:

- Constructing evaporation ponds
- Reducing per-acre water applications
- Changing the cropping patterns
- Reusing drainage water from one crop to grow other crops
- Improving application efficiency through changes in irrigation systems and management practices

Each of these management options has advantages and disadvantages. Evaporation ponds can dispose of excess drainage water, but in most areas they require that productive cropland be retired. Applying less water per acre reduces drainwater quantities, but may result in lower yields. Different crops have different evapotranspiration requirements and salt tolerances, so cropping patterns can be adjusted to reduce the impact of a high water table or salinity level and to reduce the quantity of drainwater produced. In many cases, however, this may mean a shift from higher-valued crops to lower-valued crops. Reuse of drainwater saves on freshwater use and provides an alternative means of drainage disposal, but the salt concentration of drainwater is likely to be significantly higher than that of fresh water so higher soil salinity and reduced yields may result. Improving application efficiency means that less water will be needed to ensure that all parts of the field receive adequate supplies, reducing the total quantity of drainwater produced while maintaining yields. This is also likely to be paired with increased expenses in the form of new or refurbished irrigation equipment and more labor-intensive management.

These options interrelate and cannot be analyzed independently. The choice of crops, irrigation quantities, and other factors are influenced by the costs imposed by the resulting drainwater flows, costs that in turn depend on those same factors. For example, reducing irrigation quantities will reduce drainage flows. If an evaporation pond is used for disposal of drainage flows, additional land will be available for growing crops. However, the additional profits from growing these crops, and the opportunity costs of the drainage flows, depend on the level of irrigation, crops grown, and so on. As another example, consider the situation where additional drainage flows raise the water table and reduce crop yields. Again, choice of irrigation quantities, drainwater reuse, and crops will affect the volume of drainage flows and, hence, the water table. However, the impact of these flows and their costs depend in turn on what crops are grown.

Only the first four options are considered here. Conceptually, the fifth option—choice of irrigation systems—is easily incorporated into the analysis, but the data are difficult to obtain. Costs are available for the different systems, and emission/application uniformities can be assigned using theoretical models and empirical observations. However, there are several conceptual and empirical difficulties in relating crop yields to emission/application uniformities. A discussion of the difficulties involved may be found in Letey (1985).

ASSUMPTIONS

Our study considers an individual farm with a fixed quantity of land available for growing crops and maintaining an evaporation pond. The land is assumed to be of uniform quality and to have a single source of irrigation water. Several different crops can be grown and their acreages are allowed to vary within limits. The quantity of water applied per acre is variable, and drainwater from one crop may be used for irrigating other crops. The farm is assumed to have limited natural drainage in the sense that there is a shallow layer of relatively impermeable material (clay) that restricts the downward flow of water, so that irrigation results in a high water table if no action is taken. Initially, we suppose the farm has no access to external facilities for off-farm disposal of drainwater. Later, we consider several levels of access in order to estimate the benefits from construction of external facilities.

Figure 1 illustrates the farm's drainage situation. The irrigation water is composed of fresh water from the external source and drainwater reused for irrigation. The quantity of water percolating downward to the saturated zone is determined by the quantity and quality of irrigation water and the choice of crops. Some water may percolate past a leaky clay layer, and lateral flows may transport subterranean water onto or off of the farm depending on the elevation of the water table relative to the water tables of neighboring farms. The height of the water table can be controlled by installing drain lines. The flow of water into these lines is determined by the height of the water table at the beginning of the irrigation season, volume of water draining downward from the root zone, lateral flows onto or off of the farm, and deep percolation past the clay layer. The drainage effluent is then removed and either reused for growing crops, sent to the evaporation pond, or disposed of in external facilities.

In this analysis we assume that the water table is maintained below levels that would cause yield losses on the farm. This is accomplished by first installing drain lines in the fields at an appropriate depth and spacing. Effluent from the drain lines is then either reused for irrigation or disposed of in the evaporation pond or external facilities. The evaporation pond must be large enough to hold all drainage flows sent to it, and the land used for the pond reduces available crop acreage. The assumption that the water table is maintained below levels causing yield losses is not restrictive. In some situations it may not be physically possible or economically optimal to install drain lines such that maximum yields are obtained (Fitz, Horner, and Snyder 1980). Such cases can be handled by modifying the crop production functions.

Assuming that all effluent in the drain lines is removed, a given depth and spacing of drain lines will establish a steady-state water table level. Initially, the water table may be above or below the steady-state level, but over time it can be expected to converge, on average, to this level. In our analysis, we assume that this water table has already been reached and focus on the problem of maintaining it at the same level.

Short-run problems, such as reaching the desired level or fluctuations near that level caused by random influences, are not considered here.

Soil salinities are also calculated in the analysis, assuming steady-state conditions. This means that enough leaching water is applied every year to keep soil salinities unchanged on average. The actual salinity level achieved is determined endogenously in the model. Under these conditions the annual quantity of salt entering the root zone in the irrigation water is equal to the annual quantity leaving in the drainage water. Interseasonal management of soil salinity under conditions of adequate drainage is considered by Yaron and Olian (1973), Matanga and Marino (1979), and Dinar and Knapp (1986), among others, and Wichelns and Horner (1984, unpublished report) consider the case of limited drainage. Although changes in soil salinity over time can be incorporated, they greatly complicate the analysis and involve soil salinity relations for which very limited empirical evidence exists. In addition, results in Dinar and Knapp (1986) for two crops grown continuously (alfalfa and cotton) suggest that optimal steady-state soil salinities are reached fairly quickly. The use of steady-state soil salinity levels allows a richer treatment of management options and, in our judgment, captures the essence of the problem, in that maintaining agricultural productivity over long periods of time requires that, on average, salt entering the soil must equal salt leaving the soil.

A related issue is salt accumulation in the pond. We assume that salt is removed from the pond on a periodic basis. Depending on the depth of the pond and fixed costs for salt removal, it may be desirable to allow salt to accumulate in the pond for several years before cleaning. The present value of salt removal costs per ton of salt deposited annually in the pond are based on the salt removal costs at the time of cleaning and the length of time between cleanings.

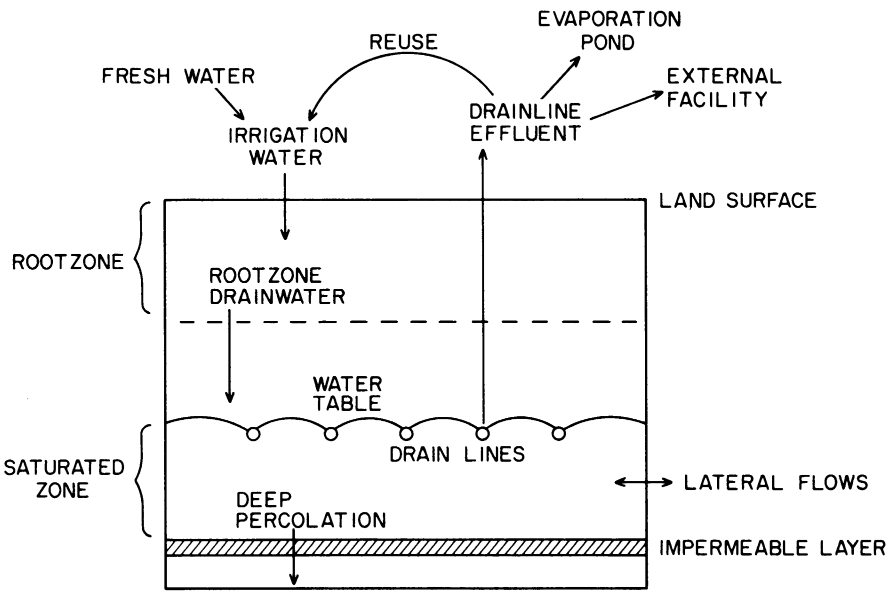

Fig. 1. Irrigation and drainage on the representative farm.

Under these conditions, the economic problem is to choose crop acreages, water quantities and qualities, and an evaporation pond size to maximize annual profits, subject to restrictions on available land, cropping patterns, and drainage flows. A mathematical model for solving this problem is formulated in the next section. We view our model and the ensuing empirical results as a long-run analysis. We are interested in developing management strategies that will maintain productivity on the farm for indefinite periods of time, once the appropriate water table and soil salinity levels have been reached. We do not consider the short-run problem of getting from the water and salinity levels in existence at the start of management to the desired long-run steady-state levels.

MODEL

The variables in the problem are defined as follows:

X_i = area of the i^{th} cropping activity (hectares)
W_i = quantity of fresh water used in the i^{th} cropping activity (ha-cm/yr)
Q_i^p = quantity of drainwater from the i^{th} cropping activity that is sent to the evaporation pond (ha-cm/yr)
Q_i^e = quantity of drainwater from the i^{th} cropping activity that is disposed of in the off-farm facility (ha-cm/yr)
Q_{ij} = quantity of drainwater from the i^{th} cropping activity that is reused on the j^{th} cropping activity (ha-cm/yr)
D^p = volume of underground flows to the farm disposed of in the evaporation pond (ha-cm/yr)
D^e = volume of underground flows to the farm disposed of in the off-farm facility (ha-cm/yr)
A = area of the evaporation pond (hectares)
$i,j = 1,\ldots,n$, where n denotes the number of possible cropping activities

A *cropping activity* is a particular combination of crop type and quantity and quality (salinity) of irrigation water. For example, alfalfa grown with 150 cm of fresh water is one cropping activity, while cotton grown with 75 cm of mixed water is another cropping activity. Defining cropping activities in this way allows us to formulate the problem as a linear programming problem.

The variables are subject to constraints of land, water quantity, water quality, drainage water balance, lateral inflow, evaporation pond size and effectiveness, drainwater export, and drainwater disposal.

Land Constraint

[1] $$\Sigma X_i + A \leq L$$

In equation 1, L denotes the amount of land available for productive activities on the farm. The land constraint restricts the total amount of land used for growing crops and maintaining an evaporation pond to no more than the amount of land available to the grower. The constraint assumes that the evoporation pond is constructed on land that could otherwise be used to grow crops. In some areas, poor quality land with few alternative uses can be used for ponds, but in areas where no such land exists, ponds cut into prime agricultural land.

Water Quantity Constraints

Let w_i denote per-hectare water requirements for the i^{th} cropping activity. Total water used on the i^{th} cropping activity is then w_iX_i, and this water can be supplied either from the freshwater source or from drainwater of other cropping activities. Mathematically,

$$w_iX_i = W_i + \sum_{j \in J_i} Q_{ji} \tag{2}$$

for all cropping activities i, where $i = 1,\ldots,n$. Here, J_i is the set of all cropping activities that can supply drainwater to be used in irrigating the i^{th} cropping activity. This set can be defined arbitrarily depending on the situation under consideration. The specification used for this paper is described later.

Water Quality Constraints

As noted earlier, each cropping activity specifies the salt concentration of the irrigation water applied in that activity. The water quality constraints guarantee that the specified water quality is met. Let $\bar{c}$ represent the salt concentration of the fresh water, and d_j the salt concentration of drainage water from the j^{th} cropping activity. The concentration of irrigation water in the i^{th} cropping activity is given by

$$\frac{\bar{c}W_i + \sum_{j \in J_i} d_jQ_{ji}}{W_i + \sum_{j \in J_i} Q_{ji}}$$

where, again, J_i is the set of cropping activities that send drainwater to the i^{th} cropping activity. This concentration must equal c_i, the salt concentration of the irrigation water specified in the i^{th} cropping activity. By setting c_i equal to the above expression, multiplying through by the denominator, and substituting from equation 2, we arrive at the linear constraints

$$c_iw_iX_i = \bar{c}W_i + \sum_{j \in J_i} d_jQ_{ji} \tag{3}$$

for $i = 1,\ldots,n$. These constraints are redundant for cropping activities that use only fresh water (i.e., J_i empty). To avoid numerical difficulties, these constraints are dropped for cropping activities using only fresh water when solving on the computer.

Drainage Water Balances

Drainwater from a particular cropping activity is either reused, evaporated in the pond, or exported from the farm if facilities are available. The drainwater quantity constraints restrict the combined quantities disposed of and reused to no more than the quantity produced. Letting q_i be the quantity of drainwater produced per hectare by the i^{th} cropping activity, then

$$[4] \qquad q_i X_i \geq \sum_{j \in J_i'} Q_{ij} + Q_i^p + Q_i^e$$

where J_i' is the set of cropping activities that can use drainwater from the i^{th} cropping activity. The left side of equation 4 gives the total quantity of drainwater produced by the i^{th} cropping activity, and the right side gives disposals plus reuse, which cannot exceed the quantity produced.

Lateral Inflow Constraint

Another constraint restricts the quantity of lateral inflows disposed of in the pond and in an off-farm facility to no more than the total underground inflows of drainage water to the farm. This can be expressed as

$$[5] \qquad D^p + D^e \leq \text{LINFLW}$$

where LINFLW is an exogenous parameter giving the volume of lateral drainage inflows to the farm (ha-cm/yr).

Evaporation Pond Constraint

The following constraint requires that the evaporation pond be large enough to evaporate all drainwater sent to it in a given year.

$$[6] \qquad \sum_i Q_i^p + D^p \leq (1/\beta) e A$$

In this equation, β is an engineering factor accounting for land needed for roads, dikes, and other uses to build the evaporation pond, and e is the annual rate of effective evaporation from the pond (ha-cm/yr).

Drainwater Export Constraint

Total flows to an off-farm facility are restricted by quota. We express the restriction as

$$[7] \qquad \sum_i Q_i^e + D^e \leq \text{QEXP}$$

where QEXP is the annual quota of drainwater that can be shipped to an off-farm drainage facility (ha-cm/yr). As discussed later, we consider several alternative levels of QEXP.

Drainwater Disposal Constraint

$$[8] \qquad \sum_i q_i X_i + \mathrm{LINFLW} \leq \mathrm{NDRN} + \sum_i \sum_j Q_{ij} + \sum_i Q_i^p + \sum_i Q_i^e + D^p + D^e$$

Here NDRN is natural drainage on the farm (ha-cm/yr) and is equal to lateral underground outflows from the farm plus deep percolation through the confining clay layer. This constraint is essentially a steady-state condition for the water table underlying the farm. The left-hand side of equation 8 is the volume of drainwater produced on the farm plus underground inflows. The right-hand side is the sum of drainwater disposals to natural drainage, reuse, evaporation from the pond, and off-farm facilities. This constraint ensures that sufficient drainwater is disposed of annually to prevent increases in the height of the water table.

Cropping Constraints

Finally, there are constraints that restrict the total amount of land that can be devoted to any particular crop.

$$[9] \qquad \Sigma X_i \leq b_k(L-A)$$

Each crop type (alfalfa, cotton, etc.) has one such constraint. The summation in equation 9 is for all the cropping activities corresponding to the k^{th} crop. The quantity $L-A$ represents the total amount of land available for growing crops on the farm, and b_k is the largest fraction that can be devoted to the k^{th} crop. A desired cropping pattern can be set in the model by replacing the inequality in equation 9 with an equality, and setting b_k at an appropriate level. The crop constraints reflect crop rotations, risk, land qualities, and other factors.

Objective Function

The objective function for the optimization problem is

$$[10] \qquad \begin{aligned} \pi = {} & \sum_i (p_i y_i - v_i - k)X_i - p^w \sum_i W_i - \gamma \sum_i Q_i^p - (\gamma + p^e) \sum_i Q_i^e \\ & - \gamma D^p - (\gamma + p^e) D^e - \sum_i \sum_j \tau_{ij} Q_{ij} - M - V \cdot A - R \cdot L \\ & - a \sum_i d_i Q_i^p - a d' D^p \end{aligned}$$

In this equation, p_i is the price of the crop type associated with the i^{th} cropping activity ($/ton), net of harvest and marketing costs; y_i is yield; v_i includes all nonwater variable production costs of the long run ($/ha), not including costs associated with land and management; k is the annualized cost of installing and maintaining the tile drains on the farm ($/ha); p^w is the price of fresh water ($/ha-cm); γ is the variable cost related to the shipment of drainwater to the pond or off-farm facility ($/ha-cm); p^e is the charge per unit of drainage flows discharged into the external disposal facility ($/ha-cm); τ_{ij} is the variable cost of drainage water from cropping activity i reused on cropping activity j ($/ha-cm); M is the annualized capital and maintenance cost of pipes and pumps needed for the reuse system ($/yr), where $Q_{ij} = 0$ implies $M = 0$;

V is the annual per-unit area cost of constructing and maintaining the evaporation pond (\$/ha); R is the annualized capital cost of the pipe system that conveys drainwater from the fields to the evaporation pond or off-farm facility (\$/yr); a is the annualized cost of salt removal (\$/ton); and d' is the salt concentration of lateral inflows to the farm (dS/m). Land costs are not included in equation 10, since the amount of land available to the farm is fixed and of uniform quality. Management costs are also not included in equation 10, since these are likely to be relatively invariant with respect to the variables, and hence do not influence the optimization problem considered here. The objective function is interpreted as the returns to land and management.

The optimization problem is to find values for X_i, W_i, Q_i^p, Q_i^e, Q_{ij}, D^p, D^e, and A that maximize equation 10 subject to equations 1 through 9 and non-negativity conditions. The farm is assumed to be a price taker in both input and output markets. Since the objective function and constraints are linear, this is a linear programming problem. The problem was solved using the MINOS program (Murtagh and Saunders 1977).

DATA

The empirical analysis is for a representative farm in Buena Vista Water District, which is located in Kern County. Buena Vista Water District has substantial acreage with poor drainage (San Joaquin Valley Interagency Drainage Program 1979). We are not considering an actual farm, but rather a hypothetical farm with conditions representative of the water district as a whole. The farm is assumed to have 259 hectares of productive land that can be used for growing crops and constructing an evaporation pond. The base year for the analysis is 1983. Where required, an interest rate of 6 percent is used. This is intended to be a real interest rate, which is the appropriate rate for the long-run problem considered here. A discussion of the use of real and nominal interest rates in benefit-cost analyses is provided by Hanke, Carver, and Bugg (1975).

Five crops are considered here: alfalfa, wheat, sugarbeets, cotton, and barley. Together, these represent 87.5 percent of the total irrigated cropland in Buena Vista Water District for 1975 (Watson, Nuckton, and Howitt 1980). Data on crop prices were collected from the Kern County Agricultural Commissioner for the years 1971 to 1983. These data were converted to 1983 dollars using a USDA production cost index, and then averaged to obtain expected crop prices in 1983 dollars for future years. These prices are listed in table 1. Data on harvest and production costs were obtained from 1980 University of California Cooperative Extension farm budgets. Farm budgets for 1982 are available for cotton but not for the other crops, so to maintain consistency we used 1980 budgets for all crops. These costs were adjusted to 1983 dollars using the same inflator as for crop prices, and they too are reported in table 1. Nonwater production costs include both variable costs (seed, fertilizer, pesticides, etc.) and fixed costs (machinery and buildings). They do not include water costs, which are treated separately in the objective function. They also do not include land and management costs, for reasons given in the previous section.

Production functions are required to generate yield (y_i), quantity of drainage water (q_i), and quality (salt concentration) of drainage water (d_i) as a function of the quantity

(w_i) and quality (c_i) of irrigation water applied in the i^{th} cropping activity. The production functions used here combine a distribution function for water applications over the field and a crop response function estimated under uniform water application conditions. A general description of the production functions follows. More details may be found in Dinar, Letey, and Knapp (1985), the references cited in that paper, and the references cited below.

Our basic approach to specifying the crop response functions under uniform water applications follows Letey, Dinar, and Knapp (1985). (Solomon [1984] provides a related development.) These three relations form the basis for this approach:

- Soil salinity as a function of the leaching fraction (drainage volume/irrigation volume) and the salt concentration of the irrigation water
- Relative yield as a function of soil salinity
- Evapotranspiration as a function of relative yield

For a given quantity and quality of irrigation water, these relations form a system of three equations and three unkowns that can be solved numerically to determine crop yield and the quantity and quality of drainage water. By solving for alternative quantities and qualities of irrigation water, we generate the required crop response functions, assuming that water is applied uniformly over the field.

The first relation in the uniform crop response function is specified assuming steady-state soil salinities and an exponential water uptake function (Hoffman and

TABLE 1. PARAMETERS FOR THE PRODUCTION OF FIVE CROPS ON THE REPRESENTATIVE FARM*

Parameter	Alfalfa values	Wheat values	Sugarbeet values	Cotton values†	Barley values
Crop price ($/ton)‡	96.58	160.39	42.11	1,760.00(L) 178.05(S)	150.24
Maximum yields (ton/ha)§	20.61	6.18	65.68	1.36(L) 2.28(S)	4.67
Harvest cost ($/ton)¶	26.31	13.73	3.77	253.69	13.73
Nonwater variable costs ($/ha)¶	363.27	263.15	729.40	766.59	194.50
Fixed production costs ($/ha)¶#	279.87	58.77	165.92	449.61	50.35
Uniformity of applied irrigation water§					
Standard deviation	.35	.18	.09	.26	.35
Christiansen uniformity coefficient	73	86	93	80	73

*All monetary values are constant 1983 dollars.

†L = lint, S = seed.

‡Calculated as an average of 1971 to 1983 prices from Kern County Agricultural Commissioner Reports.

§Estimated by authors (see text).

¶Based on University of California, Cooperative Extension Farm Budgets for 1980.

#Annualized capital cost not including land, management, and property taxes. Recomputed using 6 percent real rate of interest.

van Genuchten 1983). The second relation is specified using coefficients presented in Maas and Hoffman (1977) for various crops. The third relation is estimated from a number of published studies relating yields to evapotranspiration for the crops considered here. Details and parameter values for the specific crops are available in Letey and Dinar (1986). Maximum yields under nonsaline conditions with nonlimiting water supplies are required to complete the analysis. These were estimated through a calibration procedure described below.

Irrigation waters usually infiltrate nonuniformly over the field. This means that some parts of the field receive more water than other parts of the field when a given volume of irrigation water is applied to the field as a whole. This nonuniformity has implications for crop yield and drainwater quantity and quality. Our approach for handling nonuniform water applications follows Letey, Vaux, and Feinerman (1984). Using this approach, the field is divided into a number of subplots and the depth of water applied in each subplot is assumed to be a constant fraction B_i of the average depth of water applied to the field as a whole. This fraction is assumed to be invariant with respect to total irrigation water applied to the field as a whole, but differs across subplots. Given the B_i, the depth of water in each subplot can be calculated for a given volume of irrigation water applied to the field. The crop yield and the quantity and quality of drainage water are then calculated for each subplot using the uniform crop response functions just described. Crop yield and drainwater quantity and quality for the field as a whole are obtained by summing over the subplots.

More generally, B can be defined as a random variable giving the depth of irrigation water at any point in the field divided by the average irrigation depth over the entire field. The probability distribution of B gives both the fraction of the field having a specified value of B in the discrete case and the fraction of the field having B values that lie within some interval in the continuous case. This probability distribution is assumed to be invariant with respect to total irrigation volumes applied to the field.

There are several difficulties in attempting to estimate a probability distribution for B. First, there appears to be relatively little field data available for measuring the uniformity of water applications. Theoretical models of irrigation systems could be used to predict these uniformities, but their empirical validity in an actual situation is not clear. Second, water application uniformities are likely to differ substantially from one locale to another. Third, there are conceptual difficulties in applying nonuniformity distributions, since to some extent the plant can integrate soil moisture from the surrounding area. Letey (1985) provides a general discussion of the difficulty of measuring application uniformities.

In view of the difficulty of obtaining the required data, we devised a calibration procedure to estimate maximum yields and application uniformities. A normal probability distribution is assumed for B. Feinerman, Letey, and Vaux (1983) demonstrate that the mean of this distribution equals 1. This leaves only two parameters—maximum yield and the standard deviation of B—to be estimated. Data on observed yields and water applications in Kern County in 1975 were obtained, respectively, from Agricultural Commissioner reports and from Highstreet, Nuckton, and Horner (1980). Using 1975 price and cost data, profit-maximizing yields and water applications were computed for a range of maximum yields and standard deviations. We then selected the standard deviation and maximum yield that resulted in calculated yields and water applications most closely matching he observed yields and water applications. The procedure was then repeated using average price, cost, and observed yield data for 1979 to 1983, except that standard deviations were held constant at the level estimated from the first calibration. The values obtained through this procedure are given in table 1 and appear to be quite reasonable. Additional confirmation of the validity of these production functions is given later.

Values and their sources for the water-related parameters are given in table 2. Salt removal costs are based on a Bureau of Reclamation study (Stroh, personal communication) in which salts are transported by rail to the delta area and then by barge

TABLE 2. WATER-RELATED PARAMETERS: SYMBOLS, DESCRIPTIONS, AND VALUES

Symbol*	Description	Value†
$\bar{c}$	Salt concentration of fresh water	0.71 dS/m
e	Effective evaporation from pond	162.2 cm/yr
β	Land factor for roads and dikes	1.18
k	Annualized tile drainage costs	$81.72/ha
p^w	Freshwater price	$1.25/ha-cm
a	Annualized salt removal cost per ton of salt deposited in pond	$39.87
γ	Energy cost to pump drainwater from cropping activities to pond	$0.06/ha-cm
τ_{ij}	Energy price to pump drainwater from cropping activity i for reuse on cropping activity j	$0.26/ha-cm
M	Annualized capital and maintenance costs for drainwater reuse system	$10,925.13
V	Annualized pond construction costs	$224.39/ha
R	Annualized capital costs for collector drains	$26.27/ha

*$\bar{c}$ is taken from Rhoades (1977).

e is calculated from regional average pan evaporation (238 cm/yr, U.S. Dept. of Commerce, *Climatological Data,* 1965 to 1974), average rainfall (12.57 cm/yr, U.S. Dept. of Commerce, *Climatological Data,* 1965 to 1974), with adjustments for large surface area (0.77; Summers 1983) and for salinity (0.95). The salinity adjustment factor was estimated using data in Turk (1970) and a 30-year cleaning policy (see text).

β is taken from Summers (1983).

k is estimated using data in Fitz, Horner, and Snyder (1980).

p^w is estimated using data in Watson, Nuckton, and Howitt (1980).

a is based on salt removal costs at time of cleaning (Stroh, personal communication) and a 30-year cleaning policy.

γ and τ_{ij} are estimated assuming an energy cost of $0.05/kwh and a pumping plant efficiency of 60 percent.

M is estimated using data in Summers (1983), Fereres et al. (1981), and Fitz, Horner, and Snyder (1980). M is composed of $803 for pump capital and maintenance and $10,122 for pipes.

V is estimated using data in Summers (1983).

R is estimated using data in Summers (1983), Fitz, Horner, and Snyder (1980), and Fereres et al. (1981).

†All monetary values are constant 1983 dollars.

to a dump site 10 miles out in the ocean. Both the effective evaporation rate from the pond and the annualized salt removal costs are affected by the frequency with which the pond is cleaned. Cleaning the pond less frequently lowers the average effective evaporation rate from the pond, because the average salt concentration for the time between cleanings is higher. However, annualized salt removal costs are reduced, since the cleaning bill is delayed. Based on preliminary runs of the model, a 30-year cleaning policy was selected. This allows the evaporation pond sufficient capacity to hold drainage flows, and represents a reasonably profitable strategy compared to other cleaning policies.

A specific layout of the farm must be assumed to calculate costs for pumping, disposal, and reuse of drainage water. The farm was assumed to be square, with tile drains installed in four 160-acre (64.8-ha) fields. Drainwater is collected at a sump at the bottom corner of each quarter section, pumped to the surface and then drained by gravity through a system of collector pipes to the evaporation pond at the bottom corner of the farm. Drainwater to be used for irrigation is then pumped to the top corner of the farm for redistribution through the farm's irrigation system. We estimated drainwater pumping costs, capital costs of the collector system, and pumping and capital costs for drainwater reuse with this geometry. The average gradient was assumed to be 2.6 feet per mile in the east-west direction and 4.7 feet per mile in the north-south direction. These figures are based on data from the California Department of Water Resources (1977).

Cropping patterns are based on 1970 to 1980 acreage data for Buena Vista Water District. Two cropping patterns are considered. The first simulates the current situation, in which cotton, alfalfa, sugarbeets, wheat, and barley are grown on 70, 13, 6, 3, and 8 percent of the available crop land, respectively. The second is an endogenous cropping pattern with upper limits of 70, 20, 20, 15, and 15 percent for the five crops. The upper limits are based on maximum acreages for each crop in the district from 1970 to 1980, except for cotton, which reflects a 3-year rotation.

The model formulated in the previous section is very general with respect to drainwater reuse. To keep the problem manageable, we arranged the crops in order of increasing salt tolerance as measured by the maximum soil salinity that can be achieved without reducing crop yields, and allowed drainwater to be reused no more than once and only on a crop of higher salt tolerance than the crop supplying the drainwater. Since the overlap of wheat (a winter crop) and cotton (a summer crop) occurs after the irrigation season for wheat, reuse of wheat drainwater on cotton is not allowed.

We considered five water qualities for each of the four eligible crops with drainwater reuse, and a single water quality for model runs when drainwater reuse was not considered. The lowest salt concentration considered is always that of fresh water ($\bar{c}$), while the highest for any particular crop is sufficient to maintain at least 90 percent of the maximum possible yield without exceeding the maximum concentration of drainwater available for reuse by that crop. Except where noted, 10 water quantities are considered for each water quality and crop type. These quantities are chosen to maintain yields between 90 and 100 percent of the maximum yield achievable with a given salt concentration. The 90 percent lower limit is based on an extensive preliminary analysis, which showed that yield levels would be maintained above this level. Restricting the range of alternate water quantity levels in this manner increases the accuracy of the problem's solution. All results were checked to ensure that water applications were not at the lower bound for any crop.

UNLIMITED NATURAL DRAINAGE

Results are presented in this section for a farm where natural drainage is not limiting (NDRN = ∞). In this case, all drainage water is disposed of naturally and no evaporation pond or off-farm facility is required. This provides a basis for comparison to farms with limited natural drainage and serves to verify some aspects of the model. All other parameter values are as described in the preceding section. Results are given in table 3 for both current and endogenous cropping patterns.

Average applied water depth is 100 to 104 cm depending on the cropping pattern. This is well within the range of typical water applications in the region. With endogenous cropping patterns, both cotton and sugarbeets are grown to their limits, and alfalfa takes up the remaining acreage. As expected based on previous linear programming studies, the endogenous cropping pattern is less diversified than current, observed cropping patterns. This is due to several factors not included in the model—risk, variations in land quality, and grower expertise—so generally we will give results for both current and endogenous cropping patterns. In both cases profit-maximizing yields are quite close to maximum yield levels (99 percent).

Drainwater quantities are approximately 33 ha-cm/ha in both cases. If an evaporation pond were to be installed to dispose of all drainage flows and there were no other changes in management practices, approximately 20 percent of the farm area would be required for the pond. This figure is quite close to current recommendations of 20 to 25 percent (e.g., Hanson 1984), which apparently are based on observed

TABLE 3. SELECTED LINEAR PROGRAMMING RESULTS FOR THE REPRESENTATIVE FARM WITH UNLIMITED NATURAL DRAINAGE

Variable	Current cropping pattern value	Endogenous cropping pattern value
Quantity of fresh water:		
Total (ha-cm/yr)	25,910	26,840
Average applied depth (cm/yr)	100	104
Cropping pattern (% of cropped area):		
Alfalfa	13	10
Wheat	3	0
Sugarbeets	6	20
Cotton	70	70
Barley	8	0
Weighted average yield (% of maximum yield)	99	99
Drainwater produced (ha-cm/yr)	8,719	8,537
Returns to land & management ($/ha of farmland/yr)	970	1,124

Farm size = 259 ha, NDRN = ∞

drainage flows in tile lines, with no other management practices to reduce or eliminate drainage flows. This result verifies the production functions used here.

OPTIMAL MANAGEMENT WITH LIMITED NATURAL DRAINAGE

The main results of our study are described in this section. The farm is assumed to have no natural drainage (NDRN = 0), no access to external facilities for drainwater disposal (QEXP = 0), and no lateral underground inflows (LINFLW = 0). No natural drainage is an overly conservative assumption, in that some deep percolation of drainage water through the confining layer is likely in most situations. Alternative values for access to external facilities and for lateral inflows will be considered in subsequent sections.

Results are given in table 4 for optimal management for both current and endogenous cropping patterns and with and without drainwater reuse. The total volume of fresh water used on the farm is significantly lower than the volumes used when drainage is not limiting (table 3). In part, this is due to a reduction in cropland from installation of the pond, but much more significant is the reduction in the quantity of water applied per unit area of cropland. Depending on the case considered, average water quantities per hectare of cropland are 33 to 36 percent lower than for unlimited natural drainage. This reduction results in lower yields, but also reduces the quantity of drainage flows, and hence the size of evaporation pond needed.

While the volume of irrigation water is reduced under optimal management when drainage is limited, relatively high average yield levels are still maintained. These range from 94 to 97 percent of maximum, depending on the particular case being considered. Likewise, pond sizes are quite small under optimal management. They range from 3 to 7 percent of the total land area, considerably less than the previous estimates discussed in the previous section. With endogenous cropping patterns, both cotton and sugarbeets are grown to their limits, and wheat and barley take up the remainder under no reuse and under reuse, respectively. The cropping pattern in the endogenous case is therefore similar to the current cropping pattern—cotton takes up most of the acreage.

Drainage flows produced on a farm with limited drainage (table 4) are considerably less than flows with unlimited natural drainage (table 3). Under the conditions of table 4, drainage flows on the farm with reuse are roughly twice as large as those with no reuse. However, the flows reused more than make up the difference, so both the volume of water evaporated and the size of the pond are less under reuse. Returns to land and management are $25 per hectare greater with reuse under the current cropping pattern, and equal under the endogenous cropping pattern. Based on the re ults, reuse would appear to be optimal in the former case but not in the latter. One qualification to this result is that only the general effects of salinity have been evaluated. When specific ion effects and the risk inherent in adapting a new technology are considered, the perceived benefits of adapting reuse will decline and it may no longer be optimal. A second qualification is that only one specific reuse system is being evaluated here, and alternative designs may result in lower capital costs and

TABLE 4. SELECTED LINEAR PROGRAMMING RESULTS FOR THE REPRESENTATIVE FARM WITH NO NATURAL DRAINAGE AND NO ACCESS TO EXTERNAL DISPOSAL FACILITIES

Variable	Current cropping pattern		Endogenous cropping pattern	
	Values with no reuse	Values with reuse	Values with no reuse	Values with reuse
Quantity of fresh water:				
Total (ha-cm/yr)	17,295	16,892	16,840	16,647
Average applied depth (cm/yr)	72	67	68	66
Size of evaporation pond (% of farm acreage)	7	3	5	3
Cropping pattern (% of cropped area):				
Alfalfa	13	13	0	0
Wheat	3	3	10	0
Sugarbeets	6	6	20	20
Cotton	70	70	70	70
Barley	8	8	0	10
Weighted average yield (% of maximum yield)	94	95	95	97
Drainwater produced (ha-cm/yr)	2,401	4,990	1,791	3,547
Drainwater reused (ha-cm/yr)	0	3,905	0	2,482
Drainwater evaporated (ha-cm/yr)	2,401	1,085	1,791	1,065
Returns to land & management ($/ha of farmland/yr)	594	619	756	756

Farm size = 259 ha, NDRN = QEXP = LINFLW = 0

higher returns for installation of a reuse system. Patterns of drainwater flow in the endogenous case are given in table 5.

Returns to land and management are positive in all cases considered, implying that costs for all other production factors can be met in the long run. It is quite likely that the value of land in nonagricultural uses in the area being considered is low, so operation will remain economically viable under the assumed price and cost conditions so long as the value of the manager's time in alternative occupations is less than the returns to land and management. This result assumes that prices and

TABLE 5. PATTERN OF DRAINWATER REUSE UNDER OPTIMAL MANAGEMENT AND ENDOGENOUS CROPPING PATTERN

Source of drainwater	Destination of drainwater	Drainwater quantity	Drainwater quality
		ha-cm/yr	*dS/m*
Sugarbeets	Cotton	613	5.60
Cotton	Barley	1,870	4.45

costs remain constant at average 1971 to 1983 levels in real dollars. Under current conditions (1985–1986), returns to land and management would be substantially reduced and possibly negative.

EXTERNAL FACILITIES

Differing levels of access to an off-farm facility for disposal of drainage water also affect optimal management on the farm. As before, the drainage water is collected from sumps in the individual fields, and then transported via the collector system to the low corner of the farm where it is sent to the off-farm collector system. Results are given in table 6, assuming unlimited access to a free off-farm facility, no natural drainage (NDRN = 0), and no lateral inflows (LINFLW = 0).

Without reuse, the results are quite similar to the situation of unlimited natural drainage (table 3). This is to be expected, since the only differences are the energy cost of pumping drainage water, which is quite low, the capital cost of the collector system, which is fixed and does not vary with the level of the decision variables, and

TABLE 6. SELECTED LINEAR PROGRAMMING RESULTS FOR THE REPRESENTATIVE FARM WITH NO NATURAL DRAINAGE AND UNLIMITED ACCESS TO A FREE EXTERNAL DISPOSAL FACILITY

	Current cropping pattern		Endogenous cropping pattern	
Variable	Values with no reuse	Values with reuse	Values with no reuse	Values with reuse
Quantity of fresh water:				
Total (ha-cm/yr)	25,910	23,965	26,840	24,987
Average applied depth (cm/yr)	100	93	104	96
Cropping pattern (% of cropped area):				
Alfalfa	13	13	10	10
Wheat	3	3	0	0
Sugarbeets	6	6	20	20
Cotton	70	70	70	70
Barley	8	8	0	0
Weighted average yield (% of maximum yield)	99	99	99	99
Drainwater produced (ha-cm/yr)	8,718	11,381	8,536	10,738
Drainwater reused (ha-cm/yr)	0	4,754	0	4,167
Volume of drainwater to external facility (ha-cm/yr)	8,718	6,627	8,536	6,570
Salinity of drainwater to external facility (dS/m)	2.11	2.57	2.23	2.70
Returns to land & management ($/ha of farmland/yr)	860	831	1,014	984

Farm size = 259 ha, NDRN = LINFLW = 0, QEXP = ∞

the installation costs of the drain tile, which are the same for all crops. The quantity of fresh water used, cropping pattern, average yields, and drainwater produced are identical to those in the unlimited natural drainage situation. Returns to land and management are lower, reflecting the additional costs of disposing of drainage water.

Drainwater reuse is profitable when only the energy costs of pumping are considered, but it is not profitable when capital costs are included. This is consistent with results in the previous section, where the net benefits from drainwater reuse are low even with no access to an external facility. Drainwater is a possible substitute for fresh water imported to the farm, so in areas with high freshwater costs, drainwater reuse might be profitable even with adequate access to external disposal facilities. However, additional runs showed that reuse is not profitable when capital costs are included for freshwater prices as high as $10 per ha-cm.

The benefits from access to an external facility can be determined by finding the difference between returns to land and management under optimal management with access to external facilities (table 6) and returns to land and management under optimal management without access to external facilities (table 4). Under current cropping patterns, the benefits are $241 per hectare per year, and under endogenous cropping patterns the benefits are $258 per hectare per year.

Management issues associated with construction of an external facility for drainage disposal include the appropriate size or capacity of the system and the charge to be placed on drainage flows into the facility. For economic efficiency, the facility should be of a size such that the marginal benefits from an increase in capacity just equal the marginal costs of expanding capacity. Likewise the charge for drainwater discharges to the facility should be equal to the long-run marginal cost of disposal, where disposal costs include the variable costs of disposal, capital costs of the system, and costs of associated environmental damages. This is true, provided that the benefits of monitoring effluent volumes (and possibly qualities) are greater than the costs of monitoring. Addressing these issues requires knowledge of the benefits to farmers from alternative levels of access to the drainage facility and the volume of flows forthcoming at different charge levels for drainage effluent.

Table 7 gives selected results for the representative farm, assuming unlimited access to the external facility but with varying charge levels for drainwater effluent. For charges above $40 per ha-cm, no drainwater is disposed of in the external facility and the farm is operated as if no external facility were present. Below $40 per ha-cm, drainwater disposals in the external facility increase steadily as the price decreases. The maximum level is reached at a price of zero. The salinity of the drainwater disposals, measured as electrical conductivity (EC), decreases as the price decreases; however, the total salt load off the farm increases. Depending on the final disposition of the drainwater, it may also be useful to charge for the salt contained in the drainage water, but we do not consider this option. Benefits to the farm increase as the price decreases, but they only become significant at prices less than $15 to $20 per ha-cm. Social benefits from drainwater disposal in the external facility equal the benefits to the farm plus the revenue received by the operator of the facility. As the price decreases, the farm captures an increasing portion of the total benefits, and at a price of $0 per ha-cm the farm captures all the benefits, since revenues are zero. By aggregating the benefits over all farms in the region for various levels of drainage flows and then

TABLE 7. SELECTED LINEAR PROGRAMMING RESULTS FOR THE REPRESENTATIVE FARM WITH UNLIMITED ACCESS TO AN EXTERNAL FACILITY AT VARIOUS DRAINWATER DISPOSAL COSTS*

	Charge per ha-cm for drainwater disposal in external facility								
Variable	**$40**	**$35**	**$30**	**$25**	**$20**	**$15**	**$10**	**$5**	**$0**
Volume of drainwater to external facility (ha-cm/yr)	0	221	301	1,010	1,731	1,838	1,886	3,135	8,536
Salinity of drainwater (dS/m)	0	13.71	12.77	11.27	7.18	6.82	6.67	4.40	2.23
Quantity of salt deposited in facility (mt/yr)	0	194	246	728	795	802	805	883	1,218
Returns to land & management ($/ha of farmland/yr)	756	757	763	774	803	837	873	924	1,014
Farm benefits from access to facility ($/ha of farmland/yr)†	0	1	7	18	47	81	117	168	258
Social benefits from access to facility ($/ha of farmland/yr)‡	0	31	42	115	181	187	190	229	258

Farm size = 259 ha, NDRN = LINFLW = 0, QEXP = ∞.

*Assumes both no drainwater reuse and endogenous cropping patterns.

†Farm benefits from access to the external facility equal the returns to land and management at the specified level minus the returns to land and management with no access to the external facility (column 3, table 4).

‡Social benefits equal farm benefits plus revenue from the disposal charge.

comparing the costs of constructing alternate-sized facilities, we can determine the optimal size for a facility.

Figure 2 shows how much drainwater is disposed of in the external facility at various prices. This graph can be interpreted as an annual demand curve for the farm's external drainwater capacity. As can be seen, the quantity of drainage water reduces dramatically (by up to 63 percent) when the price increases from $0 to $10 per ha-cm. Price increases above $10 per ha-cm result in much smaller reductions

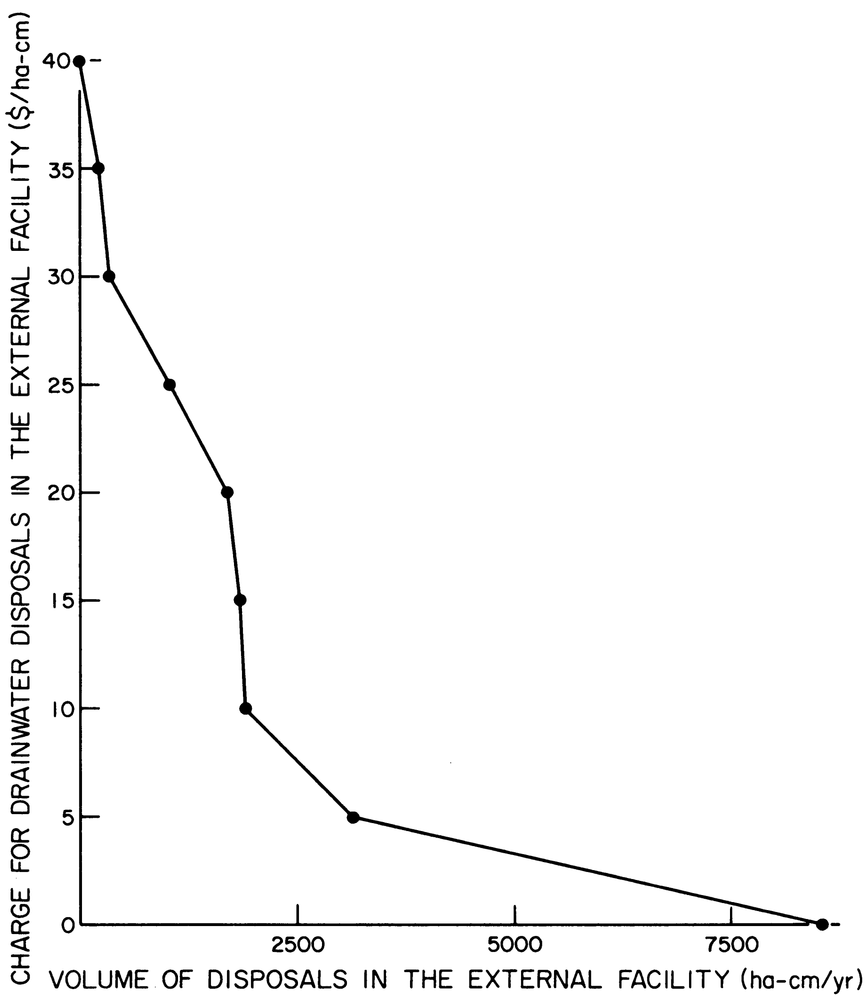

Fig. 2. Quantity of drainwater disposed of in the external facility for the representative 259-hectare farm at various price levels.

in the quantity of drainage flows. These results suggest that drainwater disposal capacity may be significantly overbuilt if no charge is imposed on flows to the facilities or if the charges are not related to the flow volume. This conclusion must be qualified to the extent that the costs of actually monitoring drainage flows are high or the costs of expanding capacity are low. Given a desired maximum flow to the facility, the curve in figure 2 can be used to find a price that will maintain flows at or below this level.

Figure 3 illustrates the social benefits and the individual farm benefits from various levels of access to the external facility. The social benefits curve is approximately concave, so the marginal benefits (the benefits from adding another unit of drainage flow to the facility) are declining as drainage flows to the facility increase. The benefits curve for the farm starts out convex, and then becomes concave. This implies that marginal benefits to the farm first increase, and then decrease, as drainage flows to the facility increase, so that after some point adding capacity to the drainwater disposal facility will yield diminishing returns. Social benefits minus private (farm) benefits

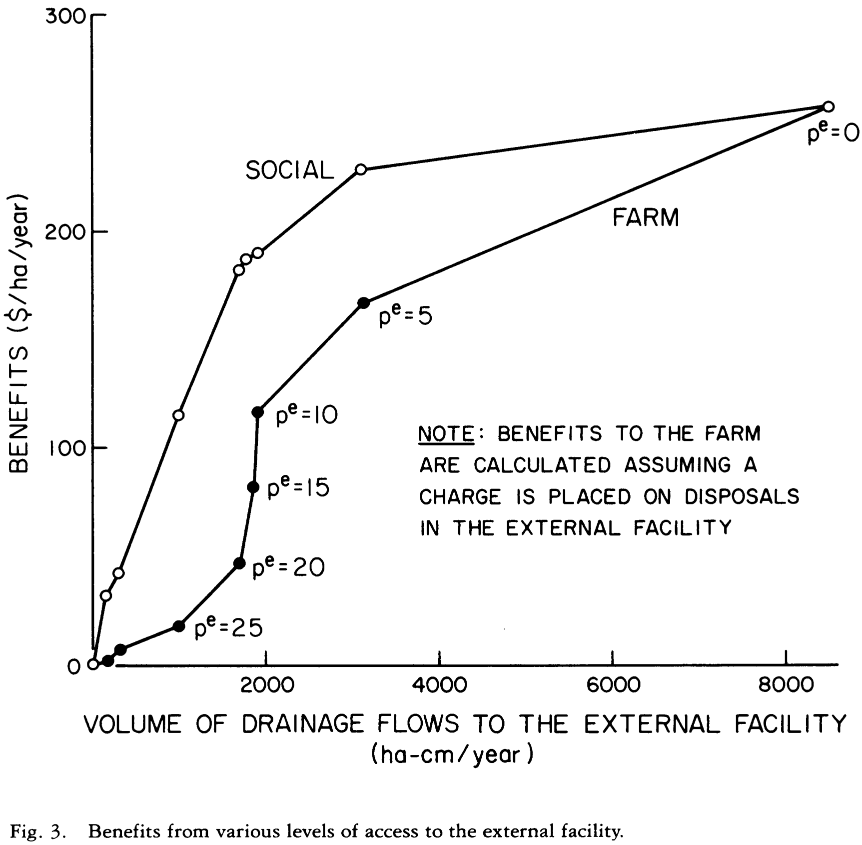

Fig. 3. Benefits from various levels of access to the external facility.

equal the revenue from the charge on drainage flows to the external facility. This difference first increases, and then decreases, as drainage flows to the external facility increase.

In some cases it may be impossible or prohibitively expensive to monitor drainage flows from individual farming operations. An alternative to charging per unit of drainage flows is to place an additional charge on the price of fresh water. This will reduce the volume of drainage flows and provide an additional source of revenue to construct disposal facilities. Table 8 reports results for the representative farm under different water prices with unlimited access to a free external facility. Optimal water applications, endogenous cropping patterns, and no reuse are assumed. Increasing the price of fresh water from $1.25 per ha-cm to $4 per ha-cm results in a substantial reduction (61 percent) in the quantity of flows to the disposal facility. The salt concentration of the effluent increases, but the total salt load decreases as the price of irrigation water increases.

Returns to land and management are significantly less at the higher prices. At a price of $4 per ha-cm, returns to land and management are only slightly higher than with no access to an external facility at the original freshwater price of $1.25 per ha-cm (column 3 of table 4). Comparing the effluent charge scheme to increases in the price of fresh water, we see that a charge of $5 per ha-cm of drainage water reduces flows to the facility more than a charge of $4 per ha-cm of irrigation water, yet the returns to land and management are $145 per hectare greater under the effluent charge. Thus, for a comparable reduction in drainage flows, an increase in the price of irrigation water is likely to imply a more severe impact on returns than the effluent

TABLE 8. SELECTED LINEAR PROGRAMMING RESULTS FOR THE REPRESENTATIVE FARM, WITH UNLIMITED ACCESS TO A FREE EXTERNAL DISPOSAL FACILITY AT VARIOUS IRRIGATION WATER PRICES*

Variable	Freshwater price per ha-cm					
	$1.25	$1.50	$1.75	$2.00	$3.00	$4.00
Volume of drainwater to external facility (ha-cm/yr)	8,536	7,196	6,131	6,131	4,665	3,330
Salinity of drainwater (dS/m)	2.23	2.50	2.65	2.65	3.24	4.19
Quantity of salt deposited in facility (mt/yr)	1,218	1,151	1,040	1,040	967	893
Returns to land & management ($/ha of farmland/yr)	1,014	989	966	944	860	779
Change in returns to land & management ($/ha of farmland/yr)†	258	233	210	188	104	23

Farm size = 259 ha, NDRN = LINFLW = 0, QEXP = ∞, PEXP = 0

*Assumes both no reuse and endogenous cropping patterns.

†The change in returns to land and management equals the returns to land and management at the indicated price minus the returns to land and management with no access to the external facility (column 3, table 4).

charge. This impact can be reduced by allowing the irrigation price to depend on the quantity of water applied per unit area, or by rebating some of the additional revenue received, as long as the rebate is not related to the quantity of irrigation water applied.

LATERAL FLOWS

The previous analysis assumed that there were no lateral underground flows of drainage water onto the farm. Existing empirical evidence on the magnitude of lateral flows is slim, the significance of such flows is debatable, and flows are likely to vary substantially depending on location. The issue is further complicated in that if individual operators or water districts find it profitable to control their water tables through evaporation ponds or other management strategies, lateral flow may reduce or even cease.

Table 9 lists lateral flows onto the farm calculated under alternative parameter values. The flows range from a low of 222 to a high of 3,270 ha-cm per year, and are based on equations for flows to drainlines. Table 10 gives results from the linear programming model for several levels of lateral inflows onto the farm. Natural drainage (NDRN) and access to external drainage facilities (QEXP) are both assumed to be zero.

Optimal freshwater quantities for the farm are smaller with lateral inflows (table 10) than with no lateral inflows in an otherwise similar situation (columns 4 and 5 of table 4). This is due to a reduction in available cropland caused by an increase in evaporation pond size to accommodate the lateral flows. The quantities applied per

TABLE 9. DRAINAGE FROM ADJACENT LANDS ONTO 259-HECTARE REPRESENTATIVE FARM UNDER ALTERNATIVE ASSUMPTIONS*

R†	**K**‡	**h**§	**s**¶	**Drainage volume**#
cm/yr	*cm/day*	*cm*	*m*	*ha-cm/yr*
3.0	15.2	609.6	164.7	321
15.2	3.0	609.6	23.5	222
15.2	15.2	609.6	64.1	629
15.2	30.5	609.6	85.4	839
15.2	61.0	609.6	146.4	1,431
15.2	304.8	609.6	335.5	3,270
30.5	15.2	304.8	33.55	654
30.5	15.2	609.6	42.7	839
30.5	15.2	1,219.2	51.9	1,011

*Height of water table above laterals at midpoint = 1.2 meters, inside diameter of laterals = 10.7 centimeters, drain assumed to be installed on property boundary.

†R = net recharge depth on surrounding land area.

‡K = hydraulic conductivity.

§h = height of drain tiles above impervious layer.

¶s = distance between laterals divided by 2.

#Drainage volumes calculated using equations in van Schilfgaarde (1974, p. 203).

TABLE 10. SELECTED LINEAR PROGRAMMING RESULTS FOR THE REPRESENTATIVE FARM WITH NO NATURAL DRAINAGE AND NO ACCESS TO EXTERNAL DISPOSAL FACILITIES UNDER ALTERNATE VALUES OF LATERAL INFLOWS*

	Lateral inflows (LINFLW) in ha-cm/yr							
	500		1,000		1,500		3,000	
Variable	Values with no reuse	Values with reuse	Values with no reuse	Values with reuse	Values with no reuse	Values with reuse	Values with no reuse	Values with reuse
Quantity of fresh water:								
Total (ha-cm/yr)	16,604	16,414	16,367	16,180	16,131	15,946	15,421	15,245
Average applied depth (cm/yr)	68	66	69	66	68	66	68	66
Size of evaporation pond (% of farm)	6	4	8	6	9	7	13	11
Cropping pattern (% of cropped area):								
Alfalfa	0	0	0	0	0	0	0	0
Wheat	10	0	10	0	10	0	10	0
Sugarbeets	20	20	20	20	20	20	20	20
Cotton	70	70	70	70	70	70	70	70
Barley	0	10	0	10	0	10	0	10
Weighted average yield (% of maximum yield)	95	97	95	97	95	97	95	97
Drainwater produced (ha-cm/yr)	1,766	3,497	1,741	3,448	1,716	3,398	1,640	3,248
Drainwater reused (ha-cm/yr)	0	2,447	0	2,413	0	2,378	0	2,273
Drainwater evaporated (ha-cm/yr)	2,266	1,550	2,741	2,035	3,216	2,520	4,640	3,976
Returns to land & management ($/ha of farmland/yr)	707	706	658	657	609	607	462	459

Farm size = 259 ha, NDRN = QEXP = 0

*Endogenous cropping pattern only.

unit area of cropland are the same. With lateral inflows, evaporation pond areas range from 4 to 13 percent of total farm area, depending on the volume of lateral inflows and whether or not drainwater is reused. While larger than ponds for farms without lateral flows, they are still significantly smaller than the ponds specified in current recommendations, even for the largest volume of lateral inflows considered. Cropping patterns and yields are identical to those without lateral inflows. Quantities of drainwater produced and reused per unit area of cropland are also identical to those with no lateral inflows. As before, drainwater reuse is optimal when only the variable costs are considered, but not when the capital costs are included. Returns to land and management go down by 6 to 39 percent, depending on the value of lateral inflows. For most of the parameter values reported in table 9, the effects of lateral flows on evaporation pond size and on returns to land and management are relatively moderate.

From the results given in table 10 and other results not presented, it can be seen that, in this analysis at least, optimal management policies per unit area of cropland are independent of the volume of lateral inflows. With uniform land quality as assumed here, the opportunity cost of drainage flows is independent of the pond size, so the optimal policies on the remaining cropland will be identical. The linear programming results with no lateral flows or no natural drainage can be applied to situations where lateral flows and natural drainage are not equal to zero by adjusting the pond size and cropland area, applying the optimal decisions per unit area, and recalculating returns to land and management.

Economies of scale should also be noted with respect to lateral flows. As the farm gets larger, the area increases more than proportionally to its perimeter. On larger farms, more of the externalities associated with the drainage water are internalized, and the effects of lateral flows on relative pond areas and returns to land and management are reduced. This provides an incentive to expand operations in areas with limited drainage and no access to external disposal facilities.

IRRIGATION UNIFORMITY

Irrigation waters are typically distributed nonuniformly over a field. This results in excess water in some parts of the field, exacerbating the drainage problem. To some extent, uniformity of water applications can be improved by changing irrigation systems and management practices. As discussed earlier, however, it appears difficult to relate crop yields and other variables to water application distributions, so choice of irrigation systems was not included in the linear programming analysis. Results given in this section assume that irrigation water is applied uniformly over the field, and represent the best that can be expected from improvements in irrigation uniformity.

Results are given in table 11 for the main scenarios considered in this paper. The first is a situation of unlimited natural drainage. Compared to the analogous situation with nonuniform water applications (column 3 of table 3), applied water quantities are reduced by 26 percent, the cropping pattern remains the same, and returns to land and management increase by 5 percent. The second scenario assumes no natural drainage and no access to external facilities. Compared to the analogous situation with nonuniform applications (table 4), freshwater applications per unit area decrease

TABLE 11. SELECTED LINEAR PROGRAMMING RESULTS FOR THE REPRESENTATIVE FARM UNDER VARIOUS CONDITIONS WITH PERFECT IRRIGATION UNIFORMITY

	Scenarios				
	(1) Unlimited natural drainage*	(2) Limited natural drainage†		(3) External facility‡	
Variable	Values	Values with no reuse	Values with reuse	Values with no reuse	Values with reuse
Quantity of fresh water:					
Total (ha-cm/yr)	19,363	17,057	17,014	19,363	19,188
Average applied depth (cm/yr)	75	67	66	75	74
Size of evaporation pond (% of farm)	0	1	1	0	0
Cropping pattern (% of cropped area):					
Alfalfa	10	0	0	10	10
Wheat	0	10	10	0	0
Sugarbeets	20	20	20	20	20
Cotton	70	70	70	70	70
Barley	0	0	0	0	0
Weighted average yield (% of maximum yield)	100	100	100	100	100
Drainwater produced (ha-cm/yr)	765	342	499	765	898
Drainwater reused (ha-cm/yr)	0	0	193	0	308
Drainwater evaporated (ha-cm/yr)	0	342	306	0	0
Drainwater to external facility:					
Quantity (ha-cm/yr)	0	0	0	765	590
Salinity (dS/m)	0	0	0	18	23
Returns to land & management ($/ha of farmland/yr)	1,179	911	869	1,071	1,029

Farm size = 259 ha, endogenous cropping patterns, LINFLW = 0

*NDRN = ∞, QEXP = 0, $p^e = \infty$

†NDRN = 0, QEXP = 0, $p^e = \infty$

‡NDRN = 0, QEXP = ∞, $p^e = 0$

by 3 percent or less depending on reuse, the pond decreases to less than 1 percent of the farm area, the cropping pattern remains similar (barley shifts to wheat with reuse), relative yields increase to 100 percent of maximum, and returns to land and management increase by 15 to 21 percent, depending on reuse. In the uniform case, reuse is not profitable when capital costs are included.

The third scenario is unlimited access to a free off-farm disposal facility. Compared to the analogous situation (table 6), freshwater applications decrease by 23 to 28 percent depending on reuse, the cropping pattern remains the same, and relative yields increase to 100 percent. The quantity of drainwater disposed of off-farm decreases by 91 percent; however, the salt concentration of the effluent is roughly eight times larger. Returns to land and management increase by 5 to 6 percent in the uniform case, while benefits from unlimited, free access decrease to $160 per hectare per year in the uniform case. As before, reuse is not profitable when all costs are considered.

The overall conclusion that emerges from table 11 is that application uniformity has a significant impact on evaporation pond areas and returns to land and management. It also reduces applied water quantities substantially when drainage is not limiting. The impact on relative yields is somewhat less, because relatively high yields were maintained in the nonuniform case. The impact of uniformity on flows to the external facility is quite large (an order of magnitude); however, this is partially offset by the increased salt concentration of the effluent. By comparing table 11 to earlier results, we can also see that the benefits from increasing irrigation uniformity are greatest in the limited drainage situation (see also Dinar, Letey, and Knapp 1985). The irrigation system should be upgraded if costs are less than benefits.

CONCLUSIONS

Our study analyzes optimal management strategies for farms with limited natural drainage and no access to off-farm drainwater disposal facilities. A representative farm in the San Joaquin Valley of California is considered using a long-run steady-state model. Under optimal management with no lateral inflows, a relatively small evaporation pond is required—3 to 7 percent of the total farm area. This compares to pond sizes of 20 percent or more of farm area that would be required under current, unlimited drainage practices. The results also suggest that significant reductions in water applied per hectare of cropland pay, when compared to the case for which drainage is not limiting. This reduction in turn reduces the required size of the evaporation pond, while still maintaining relatively high crop yields (94 to 97 percent of maximum).

We found relatively small differences in cropping patterns when comparing limited drainage to the unlimited drainage case. This is due in part to the salt-tolerance and profitability of cotton, the major crop grown in the area, and in part to our assumption that the water table is maintained below depths that would cause yield losses. Cropping patterns change more significantly in situations where it is physically impossible or economically undesirable to maintain the water table at this depth. Drainwater reuse was profitable when only the pumping costs associated with reuse were considered, but not when capital costs were included. Capital costs are likely to vary substantially, however, depending on the layout of the farm and the design of the reuse system, so this cannot be considered a general result.

With no access to external facilities, returns to land and management are significantly lower than returns with unlimited drainage, but the returns are positive and substantial in all cases. In the area considered here, the opportunity cost of the land in nonagricultural uses is probably low. Therefore, our results suggest that farm operations can remain viable over the long run, provided that the opportunity costs of management are not too large, an economical means of salt disposal from the ponds such as the one used here can be found, and crop prices return to average 1971 to 1983 levels in real terms.

Annual benefits from unlimited access to a free off-farm facility were also computed. These ranged from $241 to $258 per hectare of farmland, depending on whether current or endogenous cropping patterns were followed. These benefits do not account for the costs of providing the facilities. Our results suggest that a moderate fee on drainwater sent to off-farm facilities will reduce the volume of such effluent significantly. This option requries serious consideration if the marginal cost of expanding capacity in the facility is significant.

Optimal management with different degrees of underground drainage inflow to the farm was also considered. At its most plausible level, the effect of the flow was moderate. For all flow levels considered, evaporation pond areas remained relatively small—less than 13 percent of the total farm area—and returns to land and management were positive and significant. Other results assumed that irrigation water was applied uniformly to the field. Returns to land and management increased significantly under perfect uniformity, and the pond area was almost negligible—less than 1 percent of the farm area. Compared to the nonuniform case, however, there was very little change in the quantity of water applied per unit area of cropland when natural drainage and access to external facilities were limited.

Current discussion of the San Joaquin Valley's salinity and drainage problems assumes for the most part that on-farm evaporation ponds will require 20 percent or more of available farmland, and that they represent only a short-term, interim solution to the drainage problem. The results of our study suggest that the pond sizes required may be significantly smaller under optimal management and that they may be economically viable over long periods of time depending on crop prices, production costs, and the availability of an economical means of salt residue disposal. Whether or not they actually are preferable to regional or valleywide solutions to the drainage problem cannot be determined without a cost-benefit analysis of the various alternatives.

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