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ECONOMIC ANALYSIS OF ON-FARM SOLUTIONS TO DRAINAGE PROBLEMS IN IRRIGATED AGRICULTURE

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Agricultural production in many semi-arid areas over the world is affected by poor drainage and saline conditions. Optimal agricultural management can be considerably different under these conditions than in locations where these problems do not occur. A long-run steady-state model is developed to analyse several management strategies for a farm with limited natural drainage and no access to off-farm facilities. The model is applied to a representative farm in California. Under optimal management, the results suggest relatively small evaporation ponds, a reduction in water application, and little change in cropping patterns. Some drainage reuse is optimal when only variable reuse costs are considered. Returns to land and management are positive in all cases considered and benefits from a free off-farm facility are approximately $260/ha.

Many irrigated agricultural sites in semi-arid areas of the United States, Europe, the Middle East, and other parts of the world suffer from lack of adequate drainage (Donnan and Schwab 1974; Baadsma 1974; San Joaquin Valley Interagency Drainage Program 1979; Framji 1984). This problem is expected to intensify over time and presents a continued threat to crop productivity and food production. Solutions are very expensive and not obviously economically feasible.

Large areas in the fertile Crescent area of Iraq near the Tigris and Euphrates Rivers have severe drainage problems. In the Nile Valley, productive agricultural areas are affected by drainage problems. An estimated two million hectares of the Indus Plain in Pakistan have acute drainage problems. The San Joaquin Valley of California also has substantial areas of irrigated farmland where lack of adequate drainage causes rising water tables and salination of the soil. A widely discussed solution is to construct a valley-wide drain to dispose of drainage from all the affected areas (San Joaquin Valley Interagency Drainage Program 1979). However, there is considerable opposition to the valley-wide drain on

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environmental and financial grounds and it is not clear when, if ever, the valley-wide drain will be completed. Another controversial way to reduce the problem in areas suffering poor drainage is to cease supplying water to farmers for irrigation and to sell it to urban areas (Wahl 1985). The main argument is that water should be transferred only if it has higher value elsewhere. This solution might be economically feasible in some areas. However, it is not legally possible at the present time in the United States.

The purpose of this study is to analyse the possibilities for on-farm management of agricultural drainage problems using evaporation ponds and other strategies. The problem was investigated and reported by Knapp, Dinar and Letey (1986). Previous economic analysis 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 considered salinity and irrigation management at the farm level with 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 disposal of the drainage water. Rhoades (1977) analysed the biological and physical aspects of drainage water reuse but not the economic aspects.

Several management options that can be used to reduce and dispose of the drainage water produced on farms are identified in the next section. A linear programming model for long-run analysis of these strategies is then formulated and applied to an area in the San Joaquin Valley currently suffering from drainage problems. Suggestions are made about ways in which farmers can respond to drainage problems in the absence of off-farm facilities for disposing of drainage water. A basis for estimating the benefits from construction of large-scale, regional systems for collecting and disposing of agricultural drainage waters is provided. While the empirical focus is on California, the analysis should also be useful for other areas with limited natural drainage. The model and results can also be interpreted as applying to a region after adjusting for scale and assuming that all producers in the region follow the same management strategies.

On-Farm Drainage Management Strategies

Several options are available for reducing and disposing of drainage water produced on a farm in the absence of a natural outlet or an external drainage facility. These include reducing applied water quantities per unit area, changing of cropping patterns, reusing drainage water from sensitive crops on more tolerant crops, constructing evaporation ponds, and improving water application efficiency through changes in irrigation systems and management practices.

Each of these options has advantages and disadvantages. Applying less water per unit area reduces drainage but may also result in lower yields (*ceteris paribus*). To practise this option, one needs production functions for quantity and quality of water to calculate application rates under different conditions.

Different crops have different water requirements and salt tolerance so different cropping patterns can be used to reduce the impact of soil salinity or a high water table and also to reduce the quantity of drainage water produced. Similarly, drainage water from sensitive crops can be used on more tolerant crops (Rhoades 1977) to reduce the volume of drainage water to be discharged. Reuse of drainage water saves fresh water and provides an alternative means of drainage disposal. However, the salt concentration in drainage water is higher than that of fresh water so higher soil salinity and reduced yields may result (Letey and Dinar 1986).

Construction of an evaporation pond to dispose of drainage water may require productive land and therefore may reduce potential income.

Improving application efficiency means that less water will be needed to ensure that all parts of the field receive adequate supplies. This might be accompanied by increased capital expenses and more labour intensive management. This option can easily be incorporated into the analysis. However, there are some conceptual and empirical difficulties in relating crop yields to irrigation uniformities (Letey 1985) and therefore the option is not considered in this paper.

The Model

An individual farm with a limited homogeneous area of productive land and an unlimited quantity of fresh water for irrigation with a given salt concentration is considered. A number of alternative crops can be grown and these can be irrigated with different combinations of water quantity and quality. The farm is characterised by an impermeable layer (usually clay) below the root zone which restricts the downward percolation of water and causes a high water table if no action is taken. In this analysis the water table is assumed to be maintained at a level below that causing yield losses. This would be accomplished by installing tile drains at appropriate depths, reducing the volume of drainage water produced on the farm, and by disposing of the collected effluent through reuse or evaporation in the pond. In some situations it may not be physically possible or economically desirable to maintain the water table at depths causing no yield losses. Such cases can be handled by modifying the crop production functions used in the analysis.

Soil salinities are calculated in the model using steady-state relations. This means that sufficient leaching water is applied every year so that the annual quantity of salt entering the root zone equals the quantity leaving and soil salinity remains unchanged on average. Soil salinity increases as the salt concentration of the irrigation water increases or as the leaching fraction (fraction of applied water draining through the root zone) decreases. In addition, salt buildup is periodically removed from the evaporation pond by mechanical means. The model is therefore a long-run steady-state model in that the chosen management strategies can be pursued for indefinite periods of time once the appropriate water table and soil salinity levels have been reached. The actual transition to the steady-state levels is not considered; results in Dinar and Knapp (1986) for cotton and alfalfa suggest that optimal steady-state soil salinities are reached fairly quickly.

The model constraints are as follows:

Land constraint:

$$\sum_i X_i + A \leq L \tag{1}$$

where L is the limited productive land area (ha), A is the pond area (ha) constructed on productive land, and X_i $(i = 1, \ldots, n)$ is the area (ha) of the i-th cropping activity. Cropping activity i is a particular combination of crop type k, $(k = 1, \ldots, \bar{k})$ and quantity and quality of the irrigation water. This definition allows the problem to be formulated as a linear programming problem.

Water quantity constraints:

$$(2) \qquad w_i X_i = W_i + \sum_{j \in J_i} Q_{ji} \quad i = 1, \ldots, n$$

Here w_i is the quantity of water applied per unit area (mm) for the i-th cropping activity, W_i is the total quantity of fresh water (ML) applied to the i-th cropping activity, Q_{ji} is the quantity of drainage water (ML) from the j-th cropping activity which is reused on the i-th cropping activity, and J_i is the set of all cropping activities which can supply drainage water to the i-th cropping activity.[1]

Water quality constraints:

The salt concentration of the irrigation water (c_i) applied to the i-th cropping activity equals the weighted average of the salt concentrations from the various sources. Multiplying by the water quantity and using (2) yields

$$(3) \qquad c_i w_i X_i = \bar{c} W_i + \sum_{j \in J_i} d_j Q_{ji} \quad i = 1, \ldots, n$$

Here $\bar{c}$ stands for the salt concentration of the fresh water (dS/m) and d_j is the salt concentration of the drainage water (dS/m) produced by the j-th cropping activity. These constraints are redundant for cropping activities which use only fresh water (J_i empty). To avoid numerical difficulties, no water quality constraints are specified for cropping activities using only fresh water when solving.

Drainage water balances:

$$(4) \qquad q_i X_i \geq \sum_{j \in J'_i} Q_{ij} + Q_i^p + Q_i^e \quad i = 1, \ldots, n$$

where J'_i is the set of cropping activities which receive drainage water from the i-th cropping activity, q_i is the quantity of drainage water per unit area (ML/ha) produced by the i-th cropping activity, and Q_i^p and Q_i^e are the quantities of drainage water (ML) from the i-th cropping activity delivered to the evaporation pond and the off-farm facility, respectively.

Lateral inflows constraint:

$$(5) \qquad D^p + D^e \leq LINFLW$$

[1] 1 ML (Megalitre) = 100 mm on 1 ha.

where *LINFLW* is an exogenous parameter giving the volume of lateral drainage inflows to the farm (ML a year), and D^p and D^e are the quantities of lateral inflows disposed of in the pond and the off-farm facility, respectively.

Evaporation pond constraint:

$$(6) \qquad \sum_i Q_i^p + D^p \leq (1/\beta)eA$$

Here β is an engineering factor accounting for land needed for roads, dikes and other uses in building the evaporation pond, and e is the annual rate of effective evaporation from the pond (mm a year). This constraint forces the evaporation pond to be large enough to evaporate on an annual basis all drainage volumes sent to it.

Drainage water exports constraint:

$$(7) \qquad \sum_i Q_i^e + D^e \leq QEXP$$

Here *QEXP* is the annual quota of drainage water which can be shipped to an off-farm drainage facility (ML a year). This constraint restricts total flows to an off-farm facility to be less than the allowable quota.

Drainage water disposal constraint:

$$(8) \qquad \sum_i q_i X_i + LINFLW < NDRN + \sum_i \sum_j Q_{ij} + \sum_i Q_i^p + \sum_i Q_i^e + D^p + D^e$$

Here *NDRN* is natural drainage on the farm (ML a year) and equals 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. It ensures that sufficient drainwater is disposed of annually to prevent increases in the height of the water table.

Cropping constraints:

$$(9) \qquad \sum_i X_i \leq b_k \, (L\text{-}A) \qquad k = 1, \ldots, \bar{k}$$

Here the summation is over cropping activities associated with the k-th crop type and b_k is the fraction of available land that can be devoted to growing cropping activities of the k-th crop type. These constraints reflect crop rotations, risk, land qualities and other factors.

Annual returns to land and management (π) are given by

$$(10) \quad \pi = \sum_i (p_i^c y_i - v_i - h)X_i - p\sum_l W_i - \sum_i \gamma(Q_i^p + Q_i^e) - \gamma(D^p + D^e) - \sum_i \sum_j \tau_{ij} Q_{ij}$$
$$- M - V.A - R.L - a\sum_i d_i Q_i^p - ad' D^p$$

where p^c_i is the price (\$/ton) of the crop type associated with the i-th cropping activity net of harvest and marketing costs, y_i is the yield, v_i are all non-water variable production costs of the long run (\$/ha), not including costs associated with land and management, h is the annualised cost (\$/ha) of installing and maintaining the tile drain on the farm, p is the price of fresh water (\$/ML), γ is the variable cost (\$/ML) related to the shipping of drainage water to the pond and/or off-farm facility, τ_{ij} are the variable costs (\$/ML) of drainage water reused from cropping activity i on cropping activity j, M is the annualised capital and maintenance costs of pipes and pumps needed for the reuse system ($Q_{ij}=0$ implies $M=0$), V is the annual per unit area cost of constructing and maintaining the evaporation pond (\$/ha), R is the annualised capital cost of the pipe system which conveys drainage water from the fields to the evaporation pond or off-farm facility, a is the annualised cost of salt removal per unit concentration of the drainage water, and d' is the salt concentration of lateral inflows to the farm. The optimisation problem is to find X_i, W_i, Q_i^p, Q_i^e, D^p, D^e, Q_{ij} and A which maximise (10) subject to the constraints (1) to (9) and the non-negativity conditions.

Data for the Empirical Analysis

The model is applied to a 259 ha representative farm in the Buena Vista Water District. The water district consists of 1700 ha of crop land in the central-western part of Kern County. The district was identified as having poorly drained land (San Joaquin Valley Interagency Drainage Program 1979). The crops considered are cotton, alfalfa, sugar beets, wheat and barley. These crops accounted for 93 per cent of the total area farmed during the period 1970 to 1980. All prices in the analysis are expressed

TABLE 1

Crop Parameters

	Crop				
Parameter	Alfalfa	Wheat	Sugar beets	Cotton[a]	Barley
Crop price (\$/ton)[b]	96.58	160.39	42.11	1760.00(L) 178.05(S)	150.24
Maximum yields (ton/ha)[c]	20.61	6.18	65.68	1.36(L) 2.28(S)	4.67
Harvest cost (\$/ton)[d]	26.31	13.73	3.77	253.69	13.73
Non-water variable costs (\$/ha)[d]	363.27	263.15	729.40	766.59	194.50
Fixed production costs (\$/ha)[d,e]	279.87	58.77	165.92	449.61	50.35
Uniformity of applied irrigation water[c]					
Standard deviation	0.35	0.18	0.09	0.26	0.35
Christiansen Uniformity Coefficient	73	86	93	80	73

Note: All monetary values are constant 1983 dollars.
[a] L = Lint, S = seed.
[b] Calculated as an average of 1971-83 prices from Kern County Agricultural Commissioner Reports for these years.
[c] Estimated by authors (see text).
[d] Based on University of California Cooperative Extension (1981).
[e] Annualised capital cost not including land, management and property taxes. Recomputed using 6 per cent real rate of interest.

in 1983 dollars using a US Department of Agriculture production cost index. A 6 per cent real interest rate was used to annualise all capital costs. Crop production costs and prices are presented in Table 1. Crop prices were calculated as 1970–83 averages (in 1983 dollars) to provide a long-run representative crop price.

Production functions are required for the analysis. These relate crop yield and quantity and quality of drainage water for individual crops to the quantity and quality of irrigation water. Following Dinar, Letey and Knapp (1985), these production functions are synthesised using experimentally determined relations between yield and evapotranspiration, yield and average root zone salinity, average root zone salinity and leaching fraction, and a distribution function for the current water applications over the field. Data for all parameters except maximum yields and the water distribution functions were obtained from published sources (Letey and Dinar 1986) and are available from the authors on request. In view of the difficulty of obtaining data for maximum yields and water distribution functions for current irrigation practices, a calibration procedure to estimate maximum yields and application uniformities for the analysed crops was used (Knapp, Dinar and Letey 1986). The estimated values are reported in Table 1.

Values for the water-related parameters and their sources are given in Table 2. Salt removal costs are based on a Bureau of Reclamation study[2] in which salts are transported by rail to the Delta area and then transported by barge to a dump site ten miles out to sea. Both the effective evaporation rate from the pond and the annualised salt removal costs are affected by the cleaning policy for the pond (that is, how often salts are removed from the pond). As salt accumulates in the pond the evaporation rate is reduced (Turk 1970). Cleaning the pond less frequently lowers the average effective evaporation rate from the pond because the average salt concentration over the interval between cleaning is higher. However, the annualised salt removal costs are also reduced since the cleaning bill is delayed. Based on preliminary runs of the model, a 30-year cleaning policy was selected. This allowed sufficient capacity of the evaporation pond to hold drainage flows and represented a reasonable level of profitability compared with other cleaning policies.

Cropping patterns are based on 1971–80 area data for the Buena Vista District.[3] Two cropping patterns are considered. The first simulates the current situation, in which cotton, alfalfa, sugar beets, wheat and barley are grown on 70 per cent, 13 per cent, 6 per cent, 3 per cent and 8 per cent, of the available crop land, respectively. The second is an endogenous cropping pattern with upper limits of 70 per cent, 20 per cent, 20 per cent, 15 per cent and 15 per cent, respectively, for the five crops. The upper limits are based on maximum areas for each crop during the period 1970 to 1980, except for cotton, where the limit reflects a three-year rotation.

The model formulated in the previous section is very general with respect to the possibilities for drainage water reuse. To keep the problem manageable, the crops are arranged in order of increasing salt tolerance as

[2] C. Stroh (1985), Bureau of Reclamation, Sacramento, California, personal communication.

[3] H. Vaux Jr (1985), University of California, Riverside, California, personal communication.

TABLE 2

Water Related Parameters

Parameter	Description	Value
$\bar{c}$	Salt concentration of fresh water	0.71 dS/m
e	Effective evaporation from pond	1622 mm/yr
β	Land factor for roads and dikes	1.18
k	Annualised tile drainage costs	\$81.72/ha
p	Fresh water price	\$12.50/ML
a	Annualised salt removal costs per ton of salt deposited in pond annually	\$39.87
γ	Energy price for pumping drainage water to pond from cropping activities	\$.60/ML
τ_{ij}	Energy price for pumping drainage water from cropping activity i for reuse on cropping activity j	\$2.60/ML
M	Annualised capital and maintenance costs for drainage water reuse	\$10925.13
V	Annualised pond construction costs	\$224.39/ha
R	Annualised capital costs for collector drains	\$26.27/ha

Note: All monetary values are constant 1983 dollars.
$\bar{c}$ is taken from Rhoades (1977).
e is calculated from regional average pan evaporation (2380 mm a yr, U.S. Department of Commerce, *Climatological Data,* 1965-1974), average rainfall (125.7 mm a yr, U.S. Department of Commerce, *Climatological Data,* 1965-1974), 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 et al. (1980).
p is estimated using data in Watson et al. (1980).
a is based on salt removal costs at time of cleaning (C. Stroh, Bureau of Reclamation, Sacramento, California, personal communication) and a 30-year cleaning policy.
γ, τ_{ij} are estimated assuming an energy cost of \$.05/kwh and a pumping plant efficiency of 60 per cent.
M is estimated using data in Summers (1983); University of California Cooperative Extension (1981); and Fitz et al. (1980). M is composed of \$803 for pump capital and maintenance and \$10122 for pipes.
V is estimated using data in Summers (1983).
R is estimated using data in Summers (1983), Fitz et al. (1980), and University of California Cooperative Extension (1981).

measured by the maximum soil salinity which can be achieved without reducing crop yields, and drainage water is reused no more than a single time and only on crops of higher salt tolerance than the crop supplying the drainage water. Since the overlap between wheat (winter) and cotton (summer) occurs after the irrigation season of wheat, reuse of drainage water from wheat on cotton is not allowed. Some other technical specifications of the model are explained in Knapp, Dinar and Letey (1986).

Results

Optimal management with no external facilities

Drainage water management on a farm with no access to external facilities ($QEXP$ = 0) is considered in this section. The main results are presented in Table 3 under several alternative management strategies. Both

TABLE 3

Linear Programming Results for a Farm with No Natural Drainage and No Access to Off-farm Facilities Under Alternative Management Strategies

Variable	(1) Fixed appln. rates Current crops No reuse	(2) Variable appln. rates Current crops No reuse	(3) Optimal management No reuse	(4) Optimal management Reuse
Quantity of fresh water used (ML/yr)	2060.8	1729.5	1684.0	1664.7
Size of evaporation pond (% of farm)	19	7	5	3
Cropping pattern (% of cropped area)				
Alfalfa	13	13	0	0
Wheat	3	3	10	0
Sugar beets	6	6	20	20
Cotton	70	70	70	70
Barley	8	8	0	10
Weighted average yield (% of maximum yield)	98	94	95	97
Drainage water produced (ML/yr)	666.9	240.1	179.1	354.7
Drainage water reused (ML/yr)	–	–	–	248.2
Drainage water evaporated (ML/yr)	666.9	240.1	179.1	106.5
Returns to land & management ($/ha)	494	594	756	756

natural drainage (*NDRN*) and lateral inflows (*LINFLW*) are assumed to be zero. The assumption of zero natural drainage is overly conservative in that there is likely to be some deep percolation of drainage water through the confining layer. The extent to which lateral flows may be significant is not known. Alternative values for these parameters are considered later.

The first management strategy considered in Table 3 simulates the situation where an evaporation pond is installed but other management decisions are made as if natural drainage was not limited. The current cropping pattern is maintained, there is no drainage water reuse, and only a single water application level is considered for each crop. This level is determined outside the linear programming model and is the amount of water which maximises individual crop profits without considering the costs of the drainage water being produced. In this situation the evaporation pond requires 19 per cent of the farm area. This figure is quite close to current recommendations of 20-25 per cent (Hanson 1984) which are apparently based on observed drainage flows in tile lines with no other management practices to reduce or eliminate drainage flows. This result serves to verify the production functions used here.

With the first management strategy, average yields are maintained at approximately 98 per cent of maximum. Returns to land and management are positive, indicating that all other production costs can be covered.

Whether or not such an operation would actually be viable in the long run depends on the value of land and the owner's time in alternative uses.

The second strategy is identical to the first except that several levels of water application are considered within the linear programming model for each crop. The linear programming model chooses the application level for each crop which maximises profits on the farm as a whole. Average water applications per hectare of cropland are reduced by 27 per cent compared with the first strategy. Total fresh water use is reduced by only 16 per cent because the area being cropped increases. This results in lower yields (94 per cent of maximum). However, drainage flows are also reduced, resulting in a smaller pond (7 per cent of the farm area). Returns to land and management increase by 20 per cent compared with the first strategy.

In the third strategy it is assumed that water application levels and crop areas are chosen within the linear programming model to maximise profits for the farm as a whole. Here cotton and sugar beets are grown to their limits and wheat takes up the remaining area. Both the total quantity of fresh water used on the farm and the size of the evaporation pond are smaller than in the second strategy, and returns to land and management increase by 53 per cent compared with the first strategy.

The fourth strategy allows drainage water reuse in addition to the options already considered. Water quantities, crop areas, and drainage water reuse are calculated within the linear programming model to maximise farm-level profits. In this case cotton and sugar beets are again grown to their limits and barley takes up the remaining area. The pond size is 3 per cent of the total farm area and average yields are maintained at 97 per cent of maximum. Compared with the third strategy, average fresh water application rates decrease slightly from 684 mm a year to 663 mm a year. However, average total water application rates increase from 684 mm a year to 761 mm a year.

Approximately 70 per cent of the drainage water produced is reused. Drainage water is supplied by sugar beets to cotton and by cotton to barley. Drainage water reuse occurs in the fourth strategy when only variable costs are considered. This drainage water reuse is not optimal in the case where capital costs are included; capital costs were estimated under the assumption that the drainage water was collected at the low corner of the farm and then pumped to the high corner for distribution into the irrigation system. Other systems could be imagined and benefits may result in lower capital costs and hence higher returns to installations of a reuse system.

For comparison purposes the model was also run assuming unlimited natural drainage (*NDRN* unrestricted) and other conditions as in strategy 3. In this case, cotton and sugar beets are grown to their limits and alfalfa takes up the remaining area. Average optimal yields exceed 99 per cent of maximum. Total fresh water use on the farm amounts to 2684 ML a year, drainage flows are 871.9 ML a year and returns to land and management are $1124 per ha of farmland per year. These values are significantly larger than those for the farm with no natural drainage.

Benefits from off-farm facilities

Economic analysis of proposals for large-scale, off-farm drainage facilities requires estimates of the benefits to farmers from constructing such facilities and the quantities of drainage water which will be disposed of from the farm at various prices. The model was rerun for the representative farm assuming zero natural drainage and lateral flows as in the previous section (*NDRN* = 0, *LINFLW* = 0), but with unlimited access to a free off-farm facility (*QEXP* unlimited). Only results for the third and fourth strategies (optimal management) are reported here.

Some drainage water reuse occurs in this case when considering only variable costs (energy for pumping). However, total returns to land and management are higher without reuse. It follows that no reuse is the optimal management strategy. With no reuse, total fresh water use on the farm is 2684 ML a year, which is 59 per cent more than the quantity used under optimal management with no access to external facilities. The volume of drainage flows sent to the off-farm facility is 853.6 ML a year or approximately 3.3 ML/ha a year. The quantity of fresh water used, the cropping pattern, average yields and drainage water produced are identical to those in the unlimited natural drainage situation. Returns to land and management are lower ($1014/ha) reflecting the additional cost of disposing of drainage water. Subtracting the returns under optimal management with no off-farm facility yields annual benefits of $258/ha under the assumed parameter values. Assuming a constant marginal value for drainage water shipped off the farm, owners would be willing to pay $78.20/ML for drainage water removals. This number serves as a guideline for the charge which will not reduce the flows of drainage flows to the disposal facility.

Sensitivity analysis

Alternative parameter values are considered in this section. Unless otherwise stated it is assumed that an optimal management strategy is followed, that there is no natural drainage (*NDRN* = 0), and that there is no access to external facilities (*QEXP* = 0).

One area of considerable uncertainty is the lateral movement of drainage water from one farm to another. The issue is complicated by the fact that if individual farmers or water districts find it profitable to control their water tables through evaporation ponds or other management strategies, then the volume of lateral flows, if any, may be reduced.

For the farm size considered here, lateral inflows were estimated at 50 ML a year under plausible values for the water level under the farm, water table levels surrounding the farm, and hydraulic conductivities. In this case no reuse was again found to be optimal. The evaporation pond increased to 6 per cent and returns to land and management decreased to $707/ha. This is a 6 per cent decrease in returns compared with optimal management with no lateral inflows. The cropping pattern and optimal water applications are the same as before. The reason is that with uniform land quality, as assumed here, the opportunity cost of drainage flows is independent of the pond size. Thus the linear programming results presented in Table 3 can be applied to situations where lateral inflows or natural drainage are non-zero by adjusting the pond size and crop land area, applying the optimal decisions on a per-unit area, and recalculating returns to land and management.

Additional runs were made to test the sensitivity of the solutions to the effective evaporation rate from the pond (e). The value of e was decreased

TABLE 4

Impact of Alternative Fresh Water Prices Under Optimal Management and No Reuse of Drainwater

Variable	Fresh water price ($/ML)				
	12.50	15.00	20.00	30.00	40.00
Volume of drainage water to external facility (ML/yr)	853.6	719.6	613.1	466.5	333.0
Salinity of drainage water (dS/m)	2.23	2.50	2.65	3.24	4.19
Returns to land and management ($/ha)	1104	989	944	860	779

by 35 per cent to 1050 mm a year to account for variations in pan evaporation. This figure is based on the smallest pan evaporation in the data set used here to estimate average pan evaporation. In this case, reuse is optimal and cotton and sugar beets are grown to their limits with barley taking the remainder. The evaporation pond actually decreases in this case to 4.2 per cent of the farm area. This is due to the substantial volume of reuse (70 per cent of the total volume produced). Returns to land and management decrease to $740/ha. Annual benefits for the off-farm facility are $278/ha with lateral inflows and $274/ha with the lower effective evaporation rate.

An alternative way to monitor and reduce drainage flows from the farm 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. The model was rerun for the representative farm under different fresh water prices. For all cases, increasing the price of fresh water from $12.50/ML to $40/ML results in a substantial reduction of drainage flows produced. Only results for a farm with unlimited access to a free off-farm facility, no reuse and endogenous cropping patterns, are presented (Table 4). In this case the increase of fresh water price from $12.50/ML to $40.00/ML has resulted in a reduction of 60 per cent in the drainage flows and a decrease of 23 per cent in returns to land and management.

This is a very important issue of private versus social interest. It falls beyond the scope of this paper but should be taken into consideration in a regional solution including a common disposal facility.

Conclusions

Optimal management strategies are analysed for farms with limited natural drainage and no access to off-farm facilities. A representative farm in the San Joaquin Valley of California is considered using a long-run steady-state model. Under optimal management, a relatively small evaporation pond is required (3–5 per cent of the total farm area). This can be compared with pond size of 20 per cent or more which would be required if current (unlimited drainage) practices were maintained. Another conclusion is that it pays to significantly reduce water quantities applied per hectare of crop land compared with the case where drainage is not limiting. This reduces the required size of the evaporation pond while still maintaining yields at a relatively high level (95–97 per cent of maximum).

Relatively small changes in cropping patterns were found compared with the unlimited drainage case (alfalfa replaced by wheat). This is due in part to the fact that the major crop grown in the area (cotton) is relatively salt tolerant and profitable, and in part to the assumption that the water table is maintained below depths causing yield losses. More significant changes in cropping patterns may be observed in situations where it is not physically possible or economically desirable to maintain the water table at this depth. Drainage water reuse was optimal when only the pumping costs associated with reuse were considered, but non-optimal when capital costs were included. However, the capital costs are likely to vary substantially 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 compared to returns with unlimited drainage. However, the returns are positive and substantial in all cases. In the area considered here, the opportunity cost of the land in non-agricultural uses is probably low. Therefore, farm operation can remain viable over the long run provided that the opportunity costs of management are not too large and an economical means of salt disposal from the ponds can be found. Annual benefits from unlimited access to a free off-farm facility were also computed. These ranged from \$241/ha to \$258/ha depending on the parameter values being considered.

In much of the discussion on salinity and drainage problems in the valley it has been assumed that on-farm evaporation ponds will require 20 per cent or more of available farmland and they represent only a short-term, interim solution to the drainage problem. It is suggested here that required pond sizes may be significantly smaller under optimal management and that they may be economically viable over long periods of time. To determine whether or not they are actually preferable to a regional or a valley-wide solution to the drainage problem would require a cost–benefit analysis of the various alternatives.

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