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Effects of drainage salinity evolution on irrigation management

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[1] A soil physics theory of solute movement through a drained saturated zone underlying agricultural land is introduced into a long-term economic analysis of farm-level irrigation management; this is an alternative to the immediate, homogeneous blending assumption employed in previous studies as a base for calculating changes in drainage salinity over time. Using data from California, the effect of drainage salinity evolution is analyzed through a year-by-year profit optimization under the requirement of on-farm drainage disposal. Paths of optimal land allocation among crop production with fresh surface water, saline drainage reuse and evaporation ponds appear to depend on the relative profitability of the first two; that of reuse is affected by the trend of drainage salinity. Tile spacing and environmental regulations associated with evaporation ponds affect the timing of evaporation pond construction. The system converges into a solution involving both drainage-disposal activities; this solution includes an outlet for salts and is therefore sustainable. Following this strategy, the system is asymptotically approaching a steady state that possesses both hydrological and salt balances. Economic implications associated with land retirement programs in California are discussed. *INDEX TERMS:* 1831 Hydrology: Groundwater quality; 6344 Policy Sciences: System operation and management; 1829 Hydrology: Groundwater hydrology; 1842 Hydrology: Irrigation; *KEYWORDS:* drainage, salinity, irrigation, environment, economics, dynamics

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1. Introduction

[2] Drainage generated through deep percolations into the groundwater below irrigated agricultural areas in Californian's San Joaquin Valley (SJV) has a negative impact on society due to the environmental damage it causes. In particular, high selenium concentrations pose a threat to waterfowl, causing mortality if the drainage effluent enters surface water streams. The lack of drainage outlet-canals as well as the regulations prohibiting river discharges entail in-region drainage disposal. Large-scale evaporation ponds have been traditionally used as a disposal solution; however, their operation is now subject to strict requirements for waterfowl-nesting mitigation and provision of compensation habitats to make up for unavoidable wildlife losses. Drainage reuse on salt-tolerant crops is another disposal technique. Such activities consume productive lands and impose additional costs on growers, affecting their agricultural management decisions with regards to cropping patterns, land allocation, efficiency of irrigation systems and water applications [*Wichelns et al.*, 1990].

[3] Profitability in some of the SJV areas affected by a high water table has been significantly reduced. Since there is a governmental obligation to provide drainage services in the SJV, land retirement plans have been promoted by political entities to relieve the authorities from this commitment. (It is suggested that about one-third of the 600,000-acre Westlands Water District (WWD), the largest district in California, will be retired [*Los Angeles Times*, 2001].) Such plans might change the life style of entire communities of farmers and related agricultural and food industries, and are now the subject of a public dispute. According to a recent buyout agreement (December 2002), a full 5% of the 600,000-acre WWD will be fallowed by farmers in return for about $4088/acre. (According to the settlement the federal government and WWD will pay $107 million and $32 million, respectively, for land retirement of 34,000 acres.) Some economic implications of this deal are discussed later in the paper.

[4] The evolution of salinity and drainage problems is a long-running process. Agricultural activities in a particular year affect conditions in subsequent years, particularly water table depth, and salinity levels of soil and drainage; these are the three major state variables of this dynamic problem. Previous economics studies have analyzed combinations of these three elements using various approaches. Most of the analyses focused on the dynamic evolution of soil salinity and its effects on agricultural management; among these analyses are those by *Yaron and Olian* [1973], *Matanga and Marino* [1979], *Yaron and Voet* [1982], *Feinerman and Yaron* [1983], *Dinar and Knapp* [1986], *Knapp* [1992], *Dinar et al.* [1993], and *Plessner and Feinerman* [1995]. Dynamic water table management was analyzed by *Tsur* [1991], who considered groundwater to be an alternative irrigation-water source to surface water. *Knapp et al.* [1990] and *Shah et al.* [1995] viewed a region's underground capacity as an exhaustible resource for drainage storage

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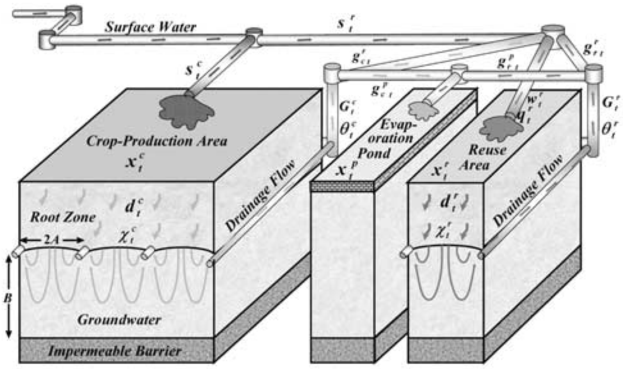

Figure 1. The agricultural-hydrological framework. See color version of this figure at back of this issue.

and accordingly, drainage-system installation was considered an application of a backstop technology. Drainage salinity was introduced into dynamic economic models only together with other state variables. Groundwater quality, water table depth and soil salinity were all taken into consideration in a regional economic simulation model developed by *Hatchett et al.* [1991]. Their analysis allowed for drainage recycling, with drainage concentration being calculated with the assumption that deep percolations are blended immediately and homogeneously with the groundwater in the saturated zone. *Dinar* [1994] and *Knapp* [1997] used the same immediate-homogeneous blending approach in analyses of optimal long-term management of water table depth and groundwater salinity.

[5] The present paper focuses on the dynamics of drainage salinity; in particular, it suggests an alternative approach to the instant-homogeneous blending assumption. There are two major weaknesses associated with this hypothesis: (1) it is unrealistic, especially in agricultural areas resting on top of deep unconfined aquifers, and (2) it implies no influence of the drainage system's tile-line density on the evolution of drainage salinity. Here a specific soil physics theory of solute movement in the groundwater is incorporated into a dynamic economic analysis of agricultural management under drainage-disposal requirements. Features of the hydrological and drainage systems shape the streamline trajectories of deep percolations from the water table toward the tile lines through the saturated zone. These features therefore determine the dependency between drainage salinity level in a particular year and volumes and salt concentrations of deep percolations in previous years. The drainage quality, among other factors, is considered with respect to on-farm drainage-disposal alternatives, i.e., reuse and evaporation ponds. The difference entailed by the solute-movement theory relative to the immediate uniform-blending assumption is in the rate of the drainage salinity evolution; it predicts that drainage salinity grows much faster, and as a result, agricultural profitability declines sooner. This significantly changes the agricultural management paths.

[6] The paper is organized as follows: Section 2 sets the farm-level integrated agricultural management model. A set of linked functions calculates the value of the state variable, the drainage salinity; this is a special form of the equation of motion, which includes simultaneous inter-temporal relationships between many periods. However, it entails an intensive involvement of logical conditions, and hence significantly complicates the numeric search for feasible long-term optimal management paths. Therefore the analysis is limited to a year-by-year optimization. The result is a path of optimal annual managements presuming that farmers' behavior is myopic: they disregard the influences of their periodical activities on gains in sequential periods. Economic data typical of the SJV and biophysical response functions are used. Section 3 provides empirical solutions based on two cropping-pattern alternatives, reflecting the effect of land opportunity costs on the management path and the consequential salt movement in the system; a comparison with results based on the homogeneous blending approach is provided. Influences of tile spacing and of environmental regulations are investigated in sections 4 and 5, respectively; section 6 concludes the paper.

2. Model

2.1. Economic Framework

[7] Consider a farm composed of three activity-areas: crop production, drainage reuse and an evaporation pond, as depicted in Figure 1. Appendix A defines all the model's variables. Drainage is created due to deep percolations associated with agricultural activities in both the crop production and the reuse areas. Drainage systems are installed in these two agricultural plots, and the water table height above an impermeable layer corresponds the depth of the tile lines; this implies no dynamics in the water table depth. The drainage can be disposed of by flowing into an evaporation pond and/or through reuse. Surface water from external sources can be applied to both agricultural sectors.

[8] The decision variables in each year, *t*, are the land allocation among the three activities and the composition of water sources applied in each of them. Given the salinities of the drainage waters created in the agricultural plots, the objective is to set the decision variables in each year of a *T*-year period so as to maximize the farm's annual net-profit:

$$\begin{aligned}\Pi_t = x_t^c\left[p^c y^c\left(s_t^c\right) - \gamma^c - p^s s_t^c\right] + x_t^r\left[p^r y^r\left(w_t^r, q_t^r\right) - \gamma^r - p^s s_t^r\right.\\ \left. - p^g\left(q_t^r\right)\left(g_{ct}^r + g_{rt}^r\right)\right] - \gamma^p x_t^p,\end{aligned} \tag{1}$$

where $w_t^r = s_t^r + g_{c_t}^r + g_{r_t}^r$, and $q_t^r = \frac{s_t^r\theta^s + g_{ct}^r\theta_t^c + g_{rt}^r\theta_t^r}{w_t^r}$. Note that θ_t^c and θ_t^r(the salinity levels of the drainage flows from the crop production and the reuse sectors, respectively) are the two state variables of the dynamic problem.

[9] Maximization of Π_t is subject to land constraint:

$$x_t^c + x_t^r + x_t^p \leq 1, \tag{2}$$

where the total available land is normalized to 1 acre. Keeping the water table at a depth corresponding to that of the drainage systems in the two agricultural areas implies the following hydrological conditions:

$$D_t^c \leq G_{ct}^r + G_{ct}^p; D_t^r \leq G_{rt}^r + G_{rt}^p, \tag{3}$$

or, written explicitly:

$$x_t^c d_t^c\left(s_t^c\right) \leq x_t^r g_{c_t}^r + x_t^p g_{c_t}^p;\; x_t^r d_t^r\left(w_t^r, q_t^r\right) \leq x_t^r g_{r_t}^r + x_t^p g_{r_t}^p; \tag{4}$$

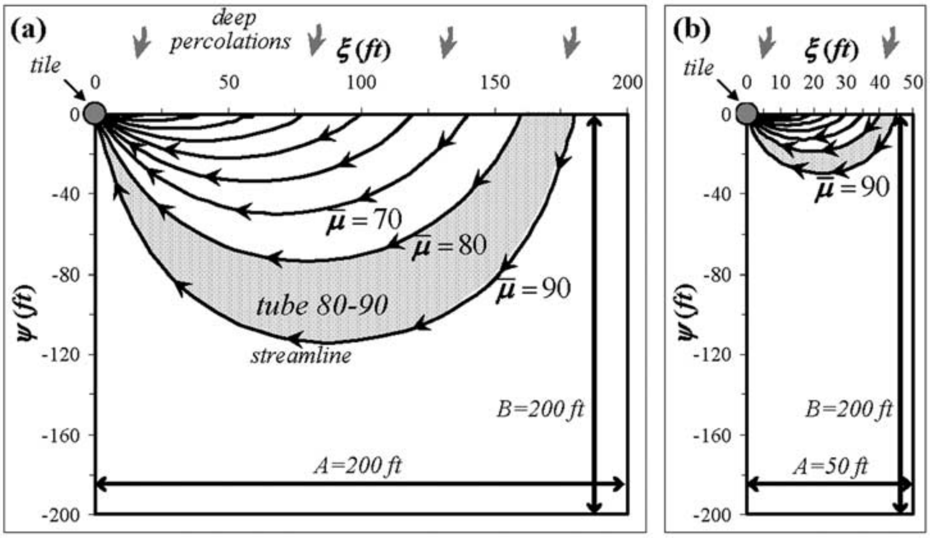

Figure 2. Streamlines and "tubes" in profiles of hydrological drained systems (ξ is lateral distance from the tile line; ψ is depth below the tile) based on a depth of 200 feet (1 foot = 0.3048 m) to an impervious layer (B) and two alternatives of half distance between tile lines (A): (a) A = 200 feet and (b) A = 50 feet.

the volume of drainage generated in each agricultural parcel is not larger than the volume of the deep percolations created in that plot. Additionally, there is an evaporation-rate constraint in the evaporation pond:

$$g_{ct}^{p} + g_{rt}^{p} \leq e^{p}. \quad (5)$$

An upper bound is set for the reuse water application in order to account for soil penetration limits [*Kan et al.*, 2002]:

$$w_{t}^{r} \leq \bar{w}. \quad (6)$$

Finally, nonnegativity constraints are set for all decision variables.

2.2. Drainage Salinity

[10] In each year the drainage salinities, θ_t^c and θ_t^r, depend on sets of previous-years' deep-percolation volumes ($d_0^c, \ldots, d_t^c$ and $d_0^r, \ldots, d_t^r$, respectively) and salt concentrations ($\chi_0^c, \ldots, \chi_t^c$ and $\chi_0^r, \ldots, \chi_t^r$, respectively); features of the hydrological and drainage systems determine this dependency. Formulation of these systems is based on the analytical solution for the streamlines' distribution in a drained, homogeneous, unconfined aquifer under steady state conditions, as presented by *Kirkham* [1958] and later used by *Jury* [1975] for solute travel time analyses. In the dimensionless variables expression used by *Jury* [1975] for travel time examinations, the solution for the stream function, μ, is:

$$\bar{\mu}(X,Y) = 1 - \frac{2}{\pi}\sum_{m=1}^{\infty}\frac{\sin(m\pi X)\sinh[m\pi(1-\pi Y)/\eta]}{m\sinh(m\pi/\eta)},$$

where $X = \xi A$ is the dimensionless lateral distance from the tile line; $Y = \psi/A$ is the dimensionless depth below the tile; $\eta = A/B$ denotes the ratio of half spacing to depth; $\bar{\mu} = \mu/Ad = \mu/\mu_{\max}$, where d is a steady rate of deep percolation into the aquifer per surface area, μ_{max} is the total amount of water reaching the tile from one side and μ is the water quantity percolating in the segment $[0, \xi]$. Also, it is assumed in this analysis that lateral flows can be neglected. Figure 2 shows two profiles of saturated zones of drained groundwater systems under a steady state, where ξ and ψ are the lateral and vertical distances from the tile line, respectively. B (=200 ft (1 foot = 0.3048 m) in both cases) denotes the depth from the water table to an impermeable barrier, and A (=200 and 50 ft in Figures 2a and 2b, respectively) is the half distance between tile lines (see also Figure 1). Each streamline, $\bar{\mu}$, represents the path of a percolating fluid-particle from the point it meets the water table (ξ feet from the tile) through the saturated zone and into the tile line. The "tube"-shaped space between every two streamlines (highlighted for $\bar{\mu} = 80; \bar{\mu} = 90$) therefore has a constant volume. The pores' volume of each tube equals the tube's volume multiplied by the soil porosity, ϕ.

[11] A portion of a particular deep-percolation volume that meets the water table in a certain year and enters a certain tube would cross the whole tube and be discharged into the tile line only after pushing out water volumes that had entered the tube in earlier years. Hence the travel time of this piece of deep percolation depends on the volume of the tube into which it is penetrating, the deep-percolation volume itself and the volumes of deep percolations entering the tube during following years. This implies an inter-temporal dependency between various periods. Because there is a variety of tube volumes, in each year a range of deep-percolation volumes originated in various previous years arrives at the tile line. Since the salinity levels of deep percolations vary in time, computing the drainage salinity in a certain year, θ_t, requires calculating the distribution of deep-percolation

volumes that cross the tubes and appear in the tile during that year. Appendix A presents a set of logical functions used for calculating θ_t.

[12] Note that the tubes' volume distribution, and hence the drainage salinity, depends on the tile spacing, A; this is illustrated in Figure 2. Section 5 discusses the tiles' density effect on the agricultural management.

2.3. Data and Computation

[13] The model is applied using data from the SJV. The salinity of the groundwater in this region is about 10 dS/m, the depth to an impermeable barrier (B) is commonly about 200 ft and the porosity (ϕ) is 0.5. The base year for the analysis is 1999. An interest rate of 4% is used for capitalization of prices and costs and as a discounting rate for net-present-value calculations; all data are reported on a per acre basis.

[14] Responses of yield, y_t (ton/yr), and deep-percolation flows, d_t (ft/yr), to water applications, w_t (ft/yr), and applied-water salinity levels, q_t (dS/m), are incorporated into the model by using four equations based on field-level steady state conditions [*Kan et al.*, 2002]:

$$e_t = \frac{\bar{e}}{1 + \alpha_1 (q_t + \alpha_2 w_t^{\alpha_3})^{\alpha_4}}, \tag{7}$$

$$y_t = \delta_1 [e_t - \underline{e}] + \delta_2 [e_t - \underline{e}]^2, \tag{8}$$

$$d_t = w_t - e_t, \tag{9}$$

$$\chi_t = \frac{w_t q_t}{d_t}, \tag{10}$$

where e_t (ft/yr) represents annual evapotranspiration (ET), $\bar{e}$ is maximum available ET, $\underline{e}$ denotes the minimal ET needed for crop production, $\alpha_1 - \alpha_4$, δ_1 and δ_2 are scalars, and χ_t is the concentration of the deep-percolation flows. Equation (10) is an outcome of the assumed steady state conditions within the root zone, implying that all of the salts applied annually to a field are leached down into the groundwater. This eliminates the dynamics of soil salinity from the present analysis. (Comparing steady state and transient-state models, *Letey and Knapp* [1995] concluded that convergence to a steady state happens after a few years and frequently even after only 1 year. This implies that introducing soil salinity as a factor in the model would cause a delay of a few years in the same paths calculated while excluding it.) Since the water table depth is also stable, dynamics is left only with respect to drainage salinity.

[15] Tomato and cotton are considered, representing moderate salt-sensitive and salt-tolerant crops, respectively [*Maas and Hoffman*, 1977]. The irrigation system is a furrow half mile run with a Christiansen Uniformity Coefficient of 70. This is the most common system in the SJV for these two crops. Corresponding response-function parameters and economical data are reported in Table 1. Also reported are data with respect to evaporation ponds and their associated compensation habitats. The price of drainage application, $p^{g}(q_t(^{r})$($/ac-ft) is given by:

$$p^{g}\left(q_t^{r}\right) = \beta_1 + \beta_2 q_t^{r}, \tag{11}$$

where β_1 is the pumping and pressurization costs and β_2 stands for the effect of salinity on the gypsum application required for soil-structure maintenance. The limit on water application in the reuse sector, $\bar{w}$, is set at 4 ft/yr.

[16] The model is built on an Excel worksheet and run by a Visual Basic code, using the Excel Solver instrument for solving the problem by a nonlinear optimization method. The solving procedure applies a quasi-Newton method based on quadratic extrapolation, where central differencing is used to estimate partial derivatives. For purposes of tractability, the time period of the analysis, T, is divided into 10 subperiods, each of which can include several years; the annual agricultural activities in years from the same subperiod are assumed to be identical.

[17] As aforementioned, state variables are calculated by the use of logical inter-temporal relationships. Because of this, however, the program could not converge into feasible long-term optimal management solutions. The model hence runs on the basis of year-by-year optimization: given the drainage salinity in a certain year, equation (1) is maximized subject to equations (2) through (6); then the program calculates the consequent drainage salinity for the next year and runs again. Nevertheless, even in this reduced optimization mode there is high sensitivity to decision-variables' starting values. This is attributed to the nonconcavity/convexity of the ET function, e_t (equation (7)), which in turn affects the yield, y_t, the volume of deep percolations, d_t, and thereby the deep-percolations' salinity, χ_t. That is, the objective function is not concave and the constraint set is not convex. To reduce the risk associated with missing global maximums, the program was run for each subperiod based on 16 different combinations of decision-variable starting points.

[18] An additional simplification due to computational considerations was applied with respect to the association between land allocation and the hydrological situation below the plots. For example, when a certain piece of land devoted to crop production is turned into a reuse area, and vice versa, the hydrological history in the groundwater underneath should be composed of the consequences of these two different agricultural activities. However, here the hydrological history of each sector was calculated without considering land allocation changes. This inconsistency appeared to be minor, since relatively small changes were found in land allocations. (A more advanced analysis might be exercised by dividing the land into many subplots, and allowing for each of them to be devoted to crop production, reuse or evaporation pond, while separately recording the hydrological history under each subplot.)

3. Optimal Management

[19] The maximization problem above was solved for a period of 50 years. The first, second and tenth subperiods included 1, 4, and 10 years, respectively, and all other subperiods represented 5 years each. Cotton was the only crop considered for growing in the reuse sector due to its

Table 1. Response Function Coefficients, Prices, and Evaporation Pond Data (1999)

Parameter	Cotton	Tomato
ET response function coefficients		
Maximum ET $\bar{e}$	2.39	1.97
α_1	1.3×10^{-5}	1.1×10^{-3}
α_2	47.06	21.85
α_3	−0.99	−1.46
α_4	3.14	2.37
Yield response function coefficients		
δ_1	0.60	37.38
δ_2	−0.12	0
Minimal ET for crop production $\underline{e}$	0.47	0.66
Prices and costs		
Output price p^c, p^r,[a] \$/ton	1586.2	43.2
Nonwater cost γ^c, γ^r,[b] \$/ac-yr	759.6	664. 8
Surface water price p^s,[c] \$/ac-ft	42.4	42.4
Groundwater cost coefficients p^g, \$/ac-ft		
β_1[d], \$/ac-ft	2.4	2.4
β_2[e], \$/ac-ft-dS/m	1.7	1.7
Evaporation pond data[f]		
Costs γ^p, \$/ac-yr	498.6	498.6
Evaporation rate e^p, ft/yr	4.0	4.0
Compensation habitat costs, \$/ac-yr	1504.2	1504.2

[a] Average price per ton of cotton lint and tomatoes in Westlands Water District, California, 1997–1999 minus harvest and other yield-related costs [*University of California Cooperative Extension*, 2000].

[b] Data include capital recovery, O&M [*University of California Committee of Consultants on Drainage Water Reduction*, 1988], seed, land preparation, planting, machinery, fertilization and harvest per acre costs [*University of California Cooperative Extension*, 2000]; land opportunity costs and cash overhead are omitted; based on A = 200 feet.

[c] Weighted average price per ac-ft in Westland Waters District 1997–1999 plus pressurization costs.

[d] Includes pumping and pressurization costs.

[e] Based on gypsum requirements and costs [*Posnikoff and Knapp*, 1996].

[f] Data are from *U.S. Bureau of Reclamation* [2001] and *San Joaquin Valley Drainage Implementation Program and University of California Salinity Drainage Program* [1999].

high salt tolerance. In the crop production area, two cropping scenarios were examined: cotton and tomato. Though tomato shows moderate salt sensitivity, it is a more attractive crop for growing with surface water due to its higher per acre profit.

[20] A comparison between the features of the two scenarios is presented in Figure 3, based on a drainage system with A = 200 ft and B = 200 ft, as presented in Figure 2a. This can be considered the typical case for the SJV (D. M. May, University of California, Davis, CA, personal communication, 2002; B. R. Hanson, University of California, Davis, personal communication, 2002; D. Birkle, University of California Center for Water Resources, Riverside, personal communication, 2002).

[21] The paths of optimal annual management across the 10 analyzed subperiods differ significantly with respect to the application timing of drainage-disposal methods. While evaporation ponds are applied from the onset in the case of tomato (x^p in Figure 3, plot a2), their construction in the cotton scenario appears to be optimal only after 10 years (Figure 3, plot a1). During this period (in the cotton case), salt accumulates in the groundwater under the reuse sector. This is reflected by the increase in the concentration of the deep percolations, χ^r, and of the drainage flows, θ^r (Figure 3, plot c1). In order to meet condition (3) (and (4)), drainage to the reuse area is applied from both the crop production and reuse areas (Figure 3, plot b1). Once evaporation ponds are constructed, the two cropping scenarios show very similar paths with respect to land allocation and water applications. Land devoted to crop production, x^c, is slightly decreased and turned into reuse, x^r. Surface water is applied only for crop production (i.e., $s^r = 0$, Figure 3, plots b1 and b2) and increases with time, while the drainage generated in this area is entirely disposed of by reuse ($D^c = G^r_c$, condition (3); not shown). At the same time, all the drainage from the reuse area is disposed of by evaporation ponds ($g^r_{rt} = 0$ and $D^r = G^p_r$, not shown). Total annual profit, Π_t, increases with time. This is mostly due to the increase in profit from the reuse area, Π^r_t, while profit from crop production, Π^c_t, and costs of evaporation ponds, Π^p_t, show mixed trends.

[22] Figure 3c shows that the system in both cases converges into a special situation, in which the concentration levels of the deep percolations and drainage flows are similar. In the tomato scenario (Figure 3, plot c2), χ^r and θ^r become almost equal after 30 years and from then on, both decrease. This situation, which involves drainage disposal by both reuse and evaporation ponds, is sustainable. (Using a noneconomic simulation model of a similar agricultural-hydrological system, *Letey et al.* [2003] illustrated a very similar sustainable solution.) This is because it possesses hydrological balance and an outlet for the salts: surface water entering the system vanishes via evapotranspiration in the crop production and reuse sectors, and through evaporation in the evaporation ponds; the salts imported with the surface water accumulate in the evaporation pond after

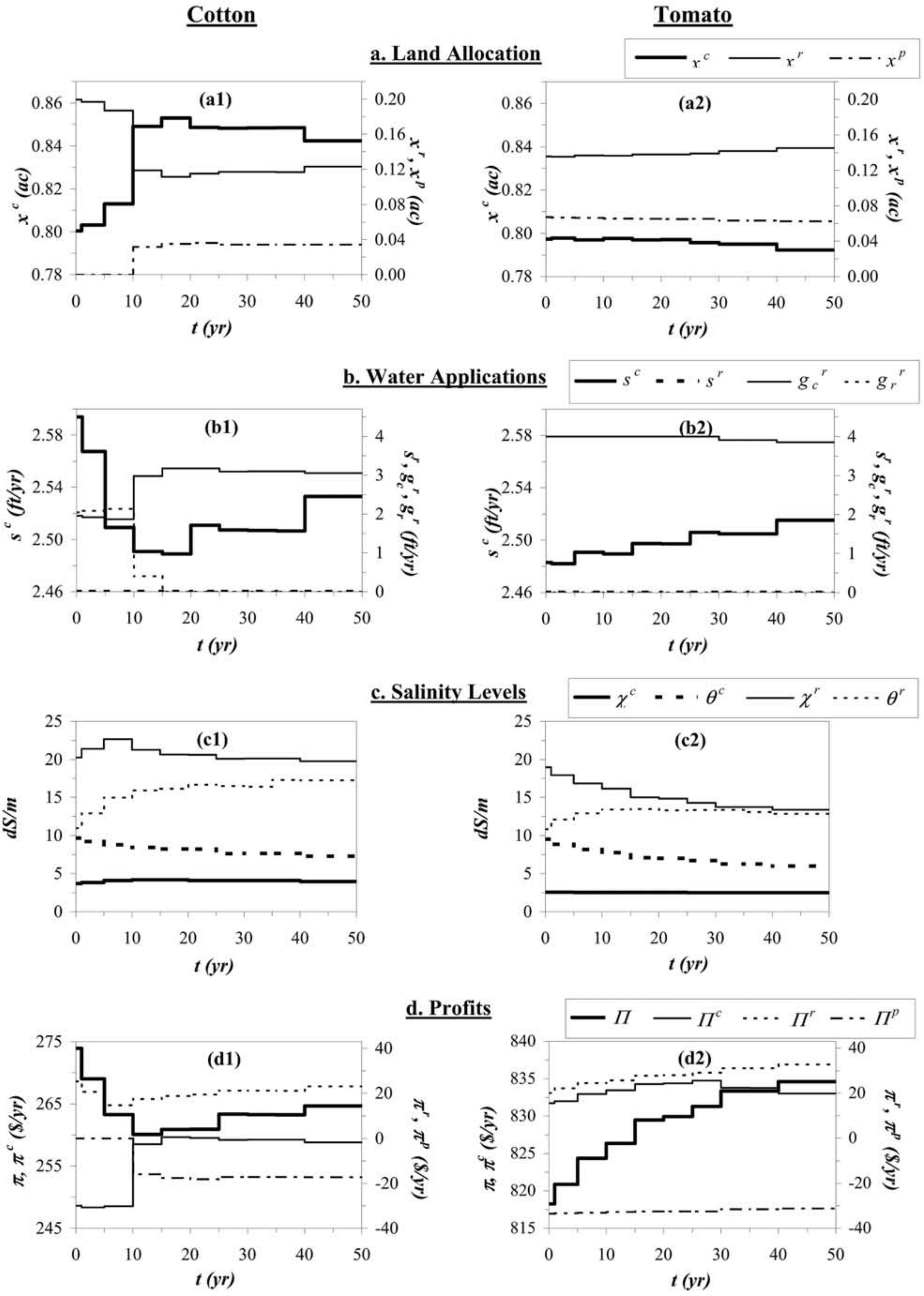

Figure 3. Paths of optimal land allocation, water applications, salinity levels and profits for a period of 50 years according to the cotton (plots a1–d1) and tomato (plots a2–d2) crop area scenarios, based on A = 200 feet.

traversing the hydrological systems below the crop production and reuse areas. Following this specific management strategy, the system is asymptotically approaching a steady state, in which both hydrological and salt balances exist: the annual quantity of imported salts is equal to the amount reaching the evaporation pond.

[23] To explain the distinction between the paths characterizing the cotton and tomato scenarios, one should consider the differences in water-plant relationships and per acre profits of these two crops, as well as the costs of evaporation ponds and reuse as two alternative drainage-disposal means. The total cost of each disposal method includes the cost of applying the disposal process itself and the opportunity cost of the land devoted to it, which is equal to the per acre profit of the crop production area. Evaporation ponds are more efficient in terms of land consumption per a given volume of disposed drainage, hence entail lower opportunity cost, but their operation is associated with expenses; reuse requires a larger area, but can yield a positive profit. This profit depends on the drainage salinity.

[24] Deep-percolation flows from the crop production area are averaged to 0.69 ft/yr and 0.44 ft/yr for tomato and cotton, respectively, implying that the drainage volume under the tomato scenario is 1.5 times larger than that of cotton. This means that tomato needs a larger area for drainage disposal. The per acre profit associated with irrigating tomatoes with fresh water is about three times higher than that of cotton; i.e., the opportunity cost of land devoted to drainage disposal under the tomato alternative is much higher. The combination of larger losses of crop production lands and a higher opportunity cost with tomatoes supports construction of evaporation ponds from the onset. In contrast, in the cotton scenario the opportunity cost and the drainage volumes are lower, that is, crop production land losses are lower; this makes devoting land to evaporation ponds unfavorable under the starting drainage salinity level, 10 dS/m. The appearance of evaporation ponds is postponed until the drainage salinity reduces the reuse profit (Π_t^r) to a level at which it cannot offset the land opportunity cost; only then does the alternative drainage disposal strategy, a combination of reuse and evaporation pond, become optimal.

[25] We are now in a position to compare the solute-movement theory to the immediate-homogeneous blending hypothesis with respect to paths of optimal management. Running the model based on the blending approach reveals a significant change in these paths. In the case of cotton, there is no construction of evaporation ponds during the entire 50-year period; drainage disposal by circulation in the reuse plot is possible because the build-up of the drainage salinity in the groundwater below that plot is much slower. The salinity in the 50th year is about 14.6 dS/m, a level reached after 10 years under the solute-movement approach. The tomato scenario shows a completely different strategy. In a first phase, only evaporation ponds are used; after 40 years, a combination of reuse and evaporation ponds is applied. The reason for this path is that the reduction in the salinity of the drainage created in the crop production sector is much slower; it is 9.1 dS/m after 40 years compared to 8.8 dS/m after five years with the solute-movement theory. Therefore the homogeneous-blending assumption predicts a long process of salt washing from the crop production hydrology system into the evaporation pond until the drainage salinity decreases to a level under which the profit associated with reuse is large enough to offset the land opportunity cost. In the solute-movement theory this happens during the first year.

4. Tile Spacing

[26] Subsurface drainage was first demonstrated in the SJV in 1909 [*San Joaquin Valley Interagency Drainage Program* (*SJVIDP*), 1979] following the discovery of water logging problems about 20 years earlier [*Hilgard*, 1890]. Nevertheless, most of the drainage systems were installed in the valley in the 1960s through early 1980s. During this period, groundwater pumping was replaced by the import of substantial amounts of surface water, causing an elevation in the water table and extending the salinity-affected area to about one-third of the valley by the late 1980s (850,000 acres [*San Joaquin Valley Drainage Program* (*SJVDP*), 1990]). (Areas with a water-table depth of less than 5 ft below the surface are considered affected.) The subsurface drained area was expanded from 34,000 acres in 1968 [*Fitz et al.*, 1980] to about 84,000 in 1984 [*U.S. Bureau of Reclamation*, 1984]. Tiles were installed at various distances, the most common appearing to be 400 ft ($A = 200$ ft). Spacing ranged from 100 ft to 1000 ft, depending upon soil, depth and money availability at the time of installation. Older systems were typically deeper (7.5–9.5 ft) and wider (500–1000 ft). In recent years, regulations related to drainage disposal and selenium contents have led to the favoring of shallower depths (5.5–7.0 ft) and narrower spacing. In some areas in California, such as Imperial Valley, a distance of 50 ft between tiles can be found.

[27] This section investigates the effect of tile spacing on the course of optimal irrigation management. As illustrated in Figure 2, narrowing the distance between drains from 200 ft to 50 ft causes most of the streamlines to be shallower and shorter and decreases the tubes' volumes. Consequently, a given schedule of deep-percolation flows would shove the tubes in the $A = 50$ ft situation faster than in the $A = 200$ ft case. Note that this phenomenon cannot be represented under the immediate homogeneous-blending assumption, since it is indifferent to tile spacing.

[28] Running the economic model based on $A = 50$ ft reveals that the influence of tile distance is on the rate at which the same processes occur. When $A = 50$ ft, everything happens faster relative to the $A = 200$ ft situation. In the cotton case, construction of evaporation ponds occurs after 5 years instead of 10 under $A = 200$ ft. Moreover, the total profit begins to climb after 5 years versus 15 years in the $A = 200$ ft case. The difference between the rates is prominent in the salinity routes, especially in the tomato scenario. The aforedescribed special sustainable situation, in which the levels of the deep-percolation concentration, χ^r, and the drainage salinity, θ^r, are equalized, appears in the 10th year in the $A = 50$ ft case, compared to the 30th year when $A = 200$ ft.

[29] The faster rate characterizing the $A = 50$ ft scenario implies that the increase in profits occurs sooner. Nevertheless, the profits are lower than those under $A = 200$ ft because of the higher installation and maintenance costs associated with narrower spacing. Hence, considering prof-

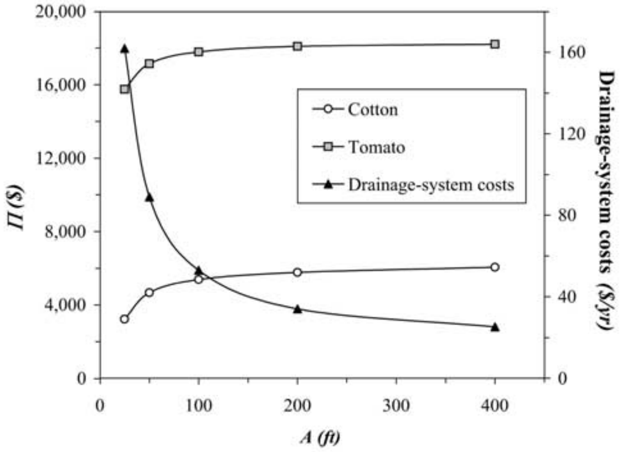

Figure 4. Effect of tile spacing, A, on the sum of present values of profits over 50 years, Π, in the cotton and tomato scenarios and on drainage system costs.

its during a T-years period, the rate and costs have contrasting effects. In order to judge which of the two is the dominant one should examine the sum of present values of the farm's net profits, Π:

$$\Pi = \sum_{t=1}^{T} \frac{\Pi_t}{(1+r)^t}, \tag{12}$$

where r is the discounting interest rate. (This is not the optimization's objective function, but an ex post calculated value.) Figure 4 shows the variation in Π (r = 4%/yr, T = 50 yr) with the spacing variable, A, for the cotton and the tomato scenarios. Also shown is the associated change in drainage-system costs. (Calculated costs are based on field dimensions of 1000 ft × 4000 feet (92 acres), tile (4") and general line (8") installation costs of 2.2 and \$5.7/ft, respectively, and high-pressure cleaning every 5 years at \$0.2/ft (D. Cohee, La Bolsa Corporation, personal communication, 2002). It is well recognized that in both cropping scenarios, narrowing the tile distance decreases Π; i.e., the effect of construction costs is dominant. The relationship between A and Π appears to have a concave nature. The increase in Π due to an increase in A from 200 ft (the common distance) to 400 ft, is \$290 and \$112 for cotton and tomato, respectively. These are equivalent to increases of 5.0% and 0.6%, respectively.

[30] Hence, according to the long-term effects of the drainage salinity and the drainage-system costs, a distance larger than the typical one in SJV should be favorable. However, there are at least two additional aspects that should be considered with respect to tile spacing, which are, however, beyond the scope of the present study. The first one is the spatial distribution of water table depths between tiles and the associated damage to the root zone. On the basis of yield reduction, installation costs and risks associated with a future need for installing additional tiles, *Fitz et al.* [1980] concluded that the optimal distance ($2A$) and depth of drains in the SJV is approximately 300 ft (A = 150 ft) and 8 ft, respectively. The second aspect is the potential relationship between selenium concentrations in the drain water and the spacing. Selenium is discharged from the aquifer matrix and begins to appear in the groundwater with time; hence it is expected that faster movement of drainage through the saturated zone and shoving of lower volumes of groundwater per tile, as is the case with higher tile density, would reduce selenium concentrations. The effect of high selenium concentrations is associated with environmental regulations; these are analyzed in the following section.

5. Environmental Regulations

[31] High selenium concentrations in the drainage water in the SJV and the associated deformities and mortality of aquatic birds stimulated the implementation of environmental regulations on drainage-disposal applications. In-region disposal by evaporation ponds was enabled subject to strict mitigation requirements, the demand for construction of compensation habitats being perhaps the most severe. According to agricultural drainage instructions [*SJVDP*, 1990], a 1:1 acreage ratio of compensation habitat to evaporation pond is required to compensate for unavoidable waterfowl losses. This section analyzes the effect of this regulation on irrigation management and its significance with respect to agricultural profitability.

[32] In terms of our model, compliance with the compensation habitat regulation is equivalent to a decrease in the evaporation rate of the total area devoted to the evaporation pond plus compensation habitat, and an increase in the costs associated with that land. That is, e^p is decreased by 50% to 2 ft/yr, and γ^p is increased to \$1,002/ac-yr($= \frac{498.6+1{,}504.2}{2}$, see Table 1).

[33] On the basis of A = 200 feet, as in Figure 3, Figure 5 presents trajectories of the system's features under the compensation-habitat requirement over 200 years. During the first three decades, the associated increase in cost and decrease in per acre drainage-disposal performance turn the evaporation pond into an inferior strategy in both cropping scenarios; disposal is via reuse only. The consequence is a continuous shoving of salts from the crop production's groundwater and their accumulation in the saturated zone below the reuse area. Surface water application in the crop production area, s^c, is reduced in time and accordingly, the drainage directed from that area to reuse, g_c^r, is also decreased (Figure 5b). At the same time, reuse of drainage generated in the reuse area, g_r^r, increases. Consequently, the salinity of that drainage, θ^r, increases (Figure 5c). Profits gained from both agricultural areas are reduced (Figure 5d). After about 35 years in the case of tomato and 60 years with the cotton scenario, evaporation ponds (accompanied by the compensation habitats) are constructed (Figure 5a). This leads the system into the aforedescribed sustainable phase, in which θ^r and χ^r become equal, at about a century from the onset (Figure 5c). Simultaneously, the farm's annual total profit begins to increase with time. Note that with tomato, the reuse of drainage from the reuse sector, g_r^r, continues during the entire period and even increases after 120 years (Figure 5, plot b2).

[34] What is the economic significance of the compensation-habitat regulation? This question should be discussed in light of the overall impact of the need for on-farm drainage disposal. Table 2 presents sums of farm's net-present profits, Π (r = 4%/yr, T = 50 yr), associated with three scenarios: (1) external drainage-disposal services are

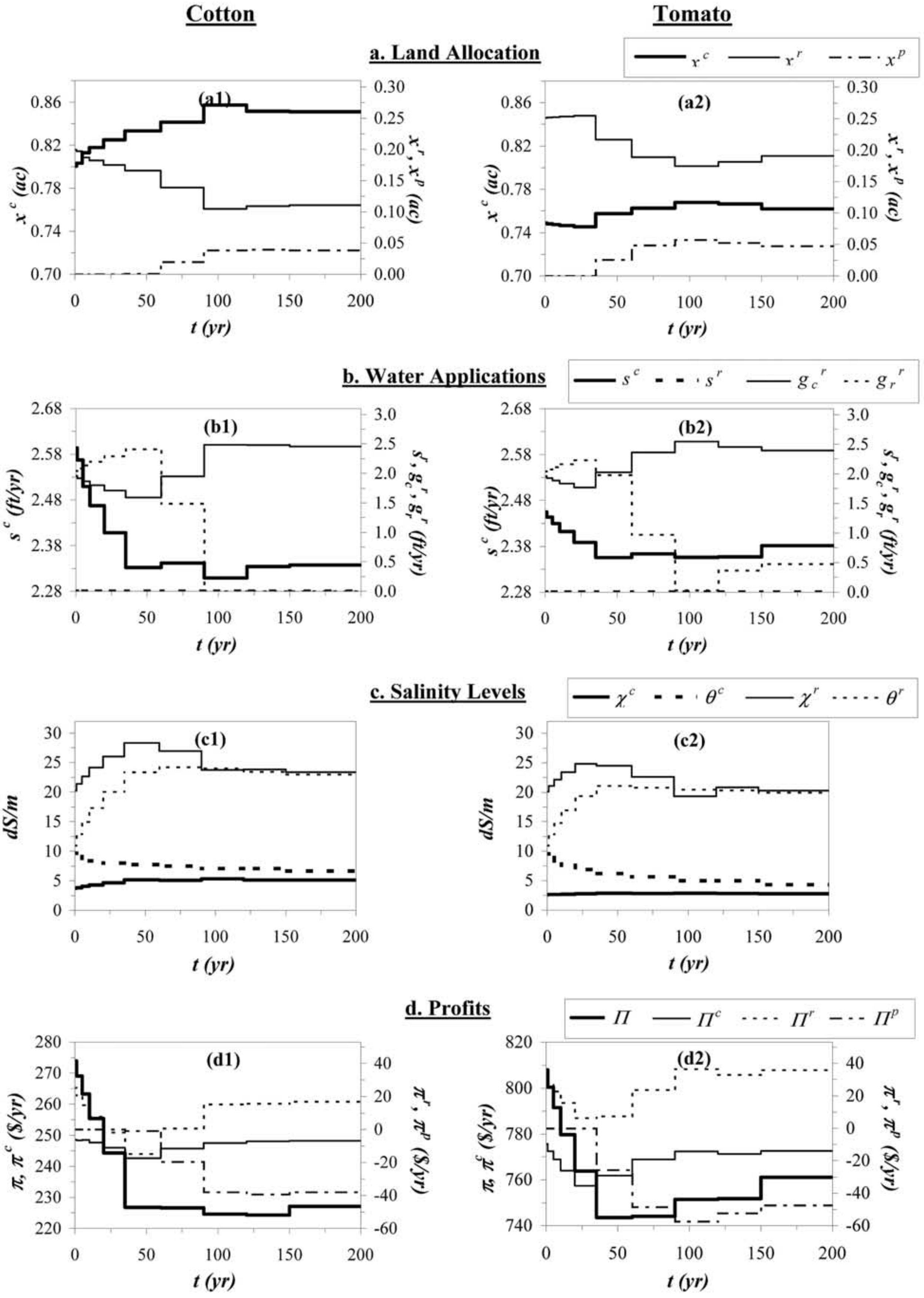

Figure 5. Trajectories of optimal features under the compensation habitat requirement for a period of 200 years according to A = 200 feet.

Table 2. Sums of Net Profit Present Values Π (4%/yr, 50 Years), According to Various Drainage Disposal Scenarios

	Cotton	Tomato	Weighted Average
Total area in Westlands Water District (average 1997–1999; acres)	226,500	87,400	
(1) Net present profit under free external drainage-disposal services ($/ac)	7,040	26,010	12,320
(2) Net present profit under on-farm drainage disposal ($/ac)	5,770	18,092	9,201
(3) Net present profit under on-farm drainage disposal + compensation habitat ($/ac)	5,563	17,032	8,756
(2)–(3) Value of the compensation habitat regulation ($/ac)	207	1,060	445
(1)–(3) Value of the external drainage disposal services ($/ac)	1,477	8,972	3,564

provided by the authorities free of charge, (2) drainage disposal is done on-farm, at the expense of the farmer, and (3) on-farm disposal is under the compensation habitat regulation. Weighted averages are calculated according to land allocation among cotton and tomato in the WWD; together both account for more than half of the district's area.

[35] The difference between scenarios (2) and (3) represents the additional costs imposed on farmers by the compensation habitat regulation: $445/acre on average. Applying for the 200,000 acres affected by high salinity in the WWD we get $89 million. Is this expenditure justifiable? It depends on the environmental benefits attached to the compensation habitats; i.e., compensating for unavoidable wildlife losses in the district during 50 years. Unfortunately, benefit estimations are as yet unavailable, preventing accomplishment of such a cost-benefit analysis.

[36] The difference between scenarios (1) and (3) is an estimate for the agricultural value of external drainage-disposal services. On average it amounts to $3,564/acre, about $4,000/acre in 2002 dollars. Regarding the aforementioned ongoing public debate with respect to governmental responsibility for drainage disposal services and the associated $4,088/acre buyout agreement, it appears that the authorities' payment is approximately equal to the agricultural value of the services they are supposed to provide; this should be compared to the cost of actually providing the services, which is unknown. However, what do farmers give in return? The answer can be found in Table 2, scenario 1: the weighted average value of the land retired by the farmers is worth about three times the compensation they get, $12,320/acre. On the basis of the available information it appears that accepting the payment as a reimbursement for applying the on-farm drainage disposal, with the compensation habitat, might be a favorable deal from the farmers' point of view.

[37] Evaluation from a social viewpoint requires additional information regarding the value of the retired land under alternative uses. If there is an economic justification for the compensation habitats, then, if a fallowed acre is worth more than $9,201 (Table 2, scenario 2), retirement is the socially preferred action; if compensation habitats cannot be economically justified, retirement is optimal only if the value attached to the alternative land use is higher than $8,756/acre (Table 2, scenario 3).

6. Concluding Remarks

[38] Drainage salinity evolution with time is analyzed with respect to its influence on farm-level irrigation management under on-farm drainage-disposal requirements and drainage-related agricultural regulations. The integration is based on a specific soil physics theory of solute-movement in a drained hydrological system; this is a modeling approach alternative to the immediate homogeneous-blending assumption used in previous long-term economic studies of similar agricultural systems. Under the approach described herein, the response of drainage salinity to changes in volumes and salt concentrations of past deep percolations is much faster; this affects the time-path of optimal irrigation management, particularly the timing of applying evaporation ponds and reuse as in-region drainage disposal tools.

[39] However, the relationship between the drainage salinity (the state variable) and historical features of deep-percolation flows is based on a set of logical functions. The involvement of such logical formulas dramatically reduces the performance of the empirical optimization analysis. In particular, computation of optimal long-run paths that take into account, in any given year, the effect of drainage-disposal strategies on drainage concentrations in subsequent years, yields nonfeasible outcomes. Extending the year-by-year optimization analysis presented in this paper to an examination of long-run optimization might require the development of a different formulation, one that does not rely on logical expressions.

Appendix A: Drainage Salinity Computation

[40] Let V_i be the volume of the pores in tube i, $i = 1\ldots I$. τ represents a certain year in which a particular volume of deep percolation enters the tube and N denotes a set of years. Let v_{iN} be the cumulative volume of deep percolations that entered the tube until the year N:

$$v_{iN} = \sum_{t=1}^{N} D_{it}, \tag{A1}$$

where D_{it} is the volume percolated into the tube in year t. Let $u_{i\tau N}$ be a variable representing the cumulative volumes of the deep percolations, which entered the tube in the year τ, and that are emitted from the tube until the year N (i.e., all or a part of the volume D_{it} for $\tau = t$). $\tau = 0$ represents the situation in the tube at the starting point. It is assumed that at the onset, the entire tube volume, V_i, is filled with groundwater of homogeneous concentration, χ^g. Until each year N, the cumulative volume of emitted groundwater, u_{i0N}, is given by:

$$u_{i0N} = \begin{cases} v_{iN} & \text{if } V_i \geq v_{iN} \\ V_i & \text{otherwise} \end{cases} \tag{A2}$$

The value of u_{i1N}, which is the cumulative volume of the deep percolations that enter the tube in $\tau = 1$ and emitted until the year N, is:

$$u_{i1N} = \begin{cases} 0 & \text{if } u_{i0N} \geq v_{iN} \\ D_{i1} & \text{if } v_{iN} - u_{i0N} > D_{i1}\,, \\ v_{iN} - u_{i0N} & \text{otherwise} \end{cases} \tag{A3}$$

where D_{i1} is the drainage that entered the tube in the year $\tau = 1$; and in general, for any $\tau > 0$ we get:

$$u_{i\tau N} = \begin{cases} 0 & \text{if } \sum\limits_{\tau=0}^{\tau-1} u_{i\tau N} \geq v_{iN} \\ D_{i\tau} & \text{if } v_{iN} - \sum\limits_{\tau=0}^{\tau-1} u_{i\tau N} > D_{i\tau}. \\ v_{iN} - \sum\limits_{\tau=0}^{\tau-1} u_{i\tau N} & \text{otherwise} \end{cases} \tag{A4}$$

[41] On the basis of the cumulative volumes, the drainage volume enters the tube in year τ, and emits in a particular year t, is

$$u_{i\tau t} = u_{i\tau N} - u_{i\tau N-1}, \tag{A5}$$

where $t = N$. Let $k_{i\tau t} = u_{i\tau t} \times \chi_\tau$ be the amount of salt that enters the tube in year τ, and emits from it in year t, where χ_τ is the concentration of the deep percolations in year τ. The amount of salt emitted from the tube in year t, k_{it}, is equal to $\sum_{\tau=1}^{T} k_{i\tau t}$. The concentration of the drainage water in year t, θ_t, is then:

$$\theta_t = \frac{\sum\limits_{i=1}^{I} k_{it}}{G_t}, \tag{A6}$$

where G_t is the volume of drainage (equal to that of the deep percolations, D_t) emitted from the I tubes during year t.

Notation

χ_t^c	salinity of deep percolations generated in the crop production plot at time t (dS/m).
χ_t^r	salinity of deep percolations generated in the reuse sector at time t (dS/m).
$d_t^c(s_t^c)$	deep percolations in the crop production sector as a function of the surface water applied in year t (ft/yr).
$d_t^r(w_t^r, q_t^r)$	deep percolations in the reuse area as a function of the quantity and quality of water applied in year t (ft/yr).
D_t^c	total deep percolations from the crop production area at time t (ac-ft/yr).
D_t^r	total deep percolations from the reuse plot at time t (ac-ft/yr).
e^p	annual evaporation rate in the evaporation pond; static (ft/yr).
e_t	annual evapotranspiration in year t (ft/yr).
g_{ct}^p	drainage from the crop production sector applied to the evaporation pond in year t (ft/yr).
g_{ct}^r	drainage from the crop production plot applied to the reuse parcel in year t (ft/yr).
g_{rt}^p	drainage from the reuse plot applied to the evaporation pond in year t (ft/yr).
g_{rt}^r	drainage from the reuse plot applied to the reuse sector in year t (ft/yr).
G_{ct}^p	total drainage from the crop production plot disposed of by evaporation pond in year t (ac-ft/yr).
G_{ct}^r	total drainage from the crop production area disposed of by reuse in year t (ac-ft/yr).
G_{rt}^p	total drainage from the reuse area disposed of by evaporation pond in year t (ac-ft/yr).
G_{rt}^r	total drainage from the reuse plot that is circulated back to be disposed of in the reuse plot in year t (ac-ft/yr).
γ^c	nonwater costs in the crop production plot; static (\$/ac).
γ^r	nonwater costs in the reuse sector; static (\$/ac).
γ^p	costs associated with evaporation pond; static (\$/ac).
p^c	yield price of crop grown in the crop production area; static (\$/ton).
$p^g(q_t^r)$	cost of drainage pumping and gypsum application in the reuse sector as a function of the reuse-water salinity level in year t (\$/ac-ft).
p^r	yield price of reuse-area crop; static (\$/ton).
p^s	surface water price; static (\$/ac-ft).
Π	sum of present values of the farm's net profits (\$).
Π_t	total farm's annual net profit at time t (\$/yr).
Π_t^c	annual net profit in the crop production sector in year t (\$/yr).
Π_t^r	annual net profit in the reuse sector in year t (\$/yr).
Π_t^p	annual costs associated with evaporation ponds in year t (\$/yr).
q_t^r	salinity of the water applied to the reuse plot at time t (dS/m).
θ_t^c	salinity of drainage forms in the crop production area at time t (dS/m).
θ_t^r	salinity of drainage generated in the reuse sector at time t (dS/m).
θ^s	salinity level of the surface water; static (dS/m).
s_t^c	surface water used for crop production at time t (ft/yr).
s_t^r	surface water applied in the reuse area in year t (ft/yr).
T	terminal time period (yr).
w_t^r	water applied to the reuse area in year t (ft/yr).
$\bar{w}$	upper bound on reuse water application (ft/yr).
x_t^c	crop production plot in year t (acres).
x_t^p	evaporation pond area at time t (acres).
x_t^r	reuse sector at time t (acres).
$y^c(s_t^c)$	yield at the crop production sector as a function of surface water applied in year t (ton/ac-yr).
$y^r(w_t^r, q_t^r)$	yield in the reuse plot as a function of the quantity and quality of water applied in year t (ton/ac-yr).

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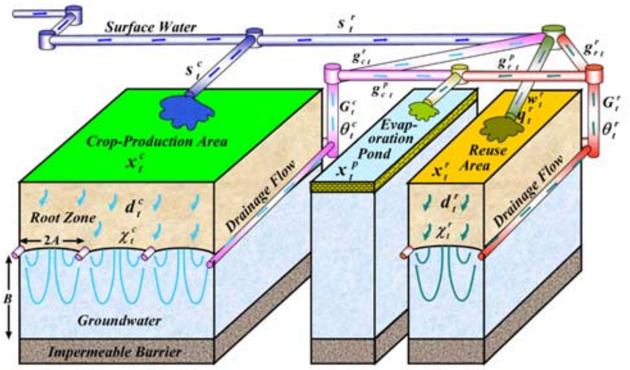

Figure 1. The agricultural-hydrological framework.