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Regional Drainwater Management: Source Control, Agroforestry, and Evaporation Ponds

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Source control is one way to address salinity and drainage problems in irrigated agriculture, and reuse of drainage flows on salt-tolerant crops or trees in agroforestry production is another. A regional model of agricultural production with drainwater reuse and disposal is developed. Deep percolation flows are controlled through choice of crop areas, irrigation systems, and applied-water quantities. Crop drainwater may be reused in agroforestry production, and residual emissions are disposed of in an evaporation pond. A significant role for both source control and reuse is found. Sensitivity to various cost and revenue parameters is also analyzed.

Key words: agroforestry, drainage, irrigation, reuse, salinity, source control

Introduction

High water tables and associated drainage problems arise in irrigated agriculture when deep percolation flows accumulate on relatively impervious geologic strata. These water tables may cause damages through reduced aeration and/or increased salinization of the rootzone. In the past, drainage problems were often solved by publicly subsidized, physical solutions: tile drainage systems were installed in fields with effluent discharge to streams, lakes, or the ocean. However, it is now recognized that these drainage flows typically contain a variety of pollutants. Due primarily to environmental concerns over these flows and perhaps also due to fiscal constraints, traditional solutions are increasingly circumscribed, to the point where some regions are prohibited from explicitly exporting drainage flows (some water may escape through underground lateral flows). As a result, water districts are considering a range of alternate management policies such as source control, reuse of drainage water on salt-tolerant crops, treatment processes, and in-region disposal.

Recently, there has been a surge of interest on the part of agricultural economists in analyzing the drainage problems arising in irrigated agriculture (Dinar and Zilberman). The primary emphasis of this work has been source control, including reduced water applications, improved irrigation systems, and changes in cropping patterns. The existing literature analyzes efficient management strategies for achieving specified levels of source control, as well as the response of irrigators to various policies and the resulting impacts on drainage emissions. These analyses have been carried out at the field, farm, and regional level (e.g., Caswell, Lichtenberg, and Zilberman; Knapp, Dinar, and Nash; Dinar,

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Hatchett, and Loehman; Weinberg, Kling, and Wilen). While these studies investigate source control in detail, they do not consider reuse and in-region disposal options. Furthermore, they generally do not consider the overall efficient *level* of source control which is ultimately a balance between the costs of source control, remediation methods, and damages from the residual emissions.[1]

This article investigates economically efficient drainage management strategies for regions with no significant export facilities for drainage emissions. In contrast to previous work, the model developed here integrates the various source control methods with reuse and in-region disposal. Additionally, the model determines the overall efficient level of source control and emissions endogenously as opposed to meeting prespecified levels of source control or calculating the effects of prespecified policies such as water surcharges as in previous work. In general we find that a combination of source control, reuse, and disposal methods is efficient and that agricultural production can be maintained within the region even with the severe restriction of no drainage outflows. Since several of the underlying parameters are imperfectly known, we also consider sensitivity of the results to variations in these parameters.

The analysis here may also be of more general interest. Environmental economics has considered the economics of both source control and reuse for a variety of problems. However, these analyses are typically separate, that is very few studies integrate both source control and reuse in the same analysis.[2] In general, however, these two approaches to environmental problems are interdependent. The availability of reuse influences the optimal source control decision, while the level of source control influences the extent to which reuse can be practiced. The results here indicate that this interaction is significant. In particular, we show that the efficient amount of source control decreases when the possibility of reuse is considered.

Model

An agricultural region with a given land area is considered. Farms within the region can produce several different crops, using various irrigation systems. Some land may be used for agroforestry production to recycle drainage flows generated in crop production, while an evaporation pond provides final disposal for residual drainage flows from both crop and tree production. The evaporation pond size depends on deep percolation flows generated net of reuse and the atmospheric evaporation rate. Land allocations, choice of crops and irrigation systems, and water applications (including reuse) that maximize regional net benefits are determined in a static optimization model. Regional net benefits are defined as revenues less production costs, summed over various crops and irrigation systems and tree production. The disposal costs of deep percolation flows to the evaporation pond are also considered.

Net benefits from crop production are

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[1] Other pollutants in deep percolation and drainage from irrigated agriculture have also been considered in the literature (e.g., Pfeiffer and Whittlesey; Johnson, Adams, and Perry; Bernardo et al.). The focus here, however, is on drainage volumes and high water tables.

[2] Those that do integrate source control and reuse focus on household or municipal waste (e.g., Nestor; Dinan; Morris and Holthausen; Fullerton and Kinnaman).

$$(1) \quad \Pi^c = \sum_c \sum_i [p^c y_{ci} - \gamma_{ci} - \delta_i^v w_{ci}]x_{ci} - \sum_c (\nu_{c0} + \nu_{c1}x_c + \nu_{c2}x_c^2) - p^s s - b(g),$$

where x_{ci} is land area (acres), w_{ci} is applied-water depth (feet/year), and y_{ci} is yield (tons/year), for crop c and irrigation system i. Parameters are p^c, the market price for each crop ($/ton); γ_{ci}, which includes irrigation system operation and amortized capital costs, all harvest, postharvest, and nonwater production costs, and the annualized costs of both tile and collector drain lines ($/acre-year); and δ_i^v, the variable cost of pressurizing each irrigation system ($/ac.-ft.). Additional parameters include p^s ($/ac.-ft.), the cost of surface water supply s (ac.-ft./year), and the function $b(g)$, which gives the annual costs of groundwater usage g (ac.-ft./year).

Also subtracted from net crop revenue is a quadratic cost function that represents additional costs of increasing the acreage devoted to a particular crop, where x_c equals $\Sigma_i x_{ci}$. Acreage expansion typically requires using poorer quality land and consequently greater costs attached to crop production or the increased use of inputs only available in fixed quantities. As such, total profits or net benefits should not increase linearly with increased crop acreage (Howitt 1995a, p. 331). This is accounted for by including quadratic costs in the net benefit function.[3]

Crop yield and deep percolation (d_{ci}) are functions of applied water and effective annual rainfall r (the average amount of rainfall that can be used to support crop production) for each crop and irrigation system. Thus,

$$(2) \qquad y_{ci} = f_{ci}(w_{ci} + r),$$

and

$$(3) \qquad d_{ci} = g_{ci}(w_{ci} + r),$$

where both r and d_{ci} are measured in feet/year. Applied water for each crop is influenced by choice of irrigation system in that the greater the water application uniformity of the irrigation system, the less applied water needed for a specific yield and hence the less deep percolation that results. Total applied fresh water in the region is limited to the sum of surface and groundwater supplies:

$$(4) \qquad \sum_c \sum_i w_{ci} x_{ci} \leq s + g,$$

where surface water usage s is constrained to not exceed some fixed amount $\bar{s}$.

Crop production may also be subject to various crop constraints:

$$(5) \qquad \sum_i x_{ci} \leq \alpha_c \sum_c \sum_i x_{ci},$$

reflecting known rotational considerations or marketing constraints. These constraints allow each crop to split production across one or more irrigation systems with, however, the total land area per crop constrained to not exceed some fixed percentage α_c of the total cropped acreage. Historically land has also been fallowed for agronomic purposes such as pest control and soil nutrient renewal. We therefore assume that fallowed land area x_f is given by

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[3] In practice, this cost function may also be picking up other effects such as risk aversion, specialized knowledge, machinery constraints, and so on [see Howitt (1995a, b) for further discussion]. The interpretation here will primarily be land quality as the dominant factor.

$$x_f = \alpha_f \sum_c \sum_i x_{ci}, \tag{6}$$

where α_f denotes a constant fraction of cropped area.

The net benefits of agroforestry or tree production are

$$\Pi^a = [p^a y_a - \gamma_a - \delta^a w_r]x_a, \tag{7}$$

where x_a is the land area devoted to agroforestry production (acres); w_r is the amount of drainwater from crop production reused on the trees (ac.-ft./acre); and y_a is tree yield measured as bone-dry tons (bdt) per acre. Parameters are p^a, the market price for tree output net of harvest costs ($/bdt); γ_a, the annualized tree establishment costs and non-water production costs ($/acre); and δ^a, the application cost of water used on the trees ($/ac.-ft.), which is the cost of pumping crop drainage flows from the underlying water table.

Yield and deep percolation in the agroforestry sector, as in crop production, are functions of available water:

$$y_a = f_a(w_r + r), \tag{8}$$

and

$$d_a = g_a(w_r + r), \tag{9}$$

where the applied water for the trees comes from reuse of the crop drainage flows and is denoted w_r. The total amount of deep percolation generated in crop production is an upper bound on agroforestry reuse:

$$\sum_c \sum_i d_{ci} x_{ci} \geq w_r x_a. \tag{10}$$

A constant salt concentration for w_r is assumed. Effective rainfall also contributes to tree production as in crop production.

Residual deep percolation flows from crop and tree production are disposed in a regional evaporation pond of area x_p (acres). Pond costs are

$$\Pi^p = (\delta^p \beta + \gamma_p)x_p, \tag{11}$$

where δ^p is the cost of pumping the drainage flows to the pond ($/ac.-ft.); β is the atmospheric evaporation rate from the pond (feet/year); and γ_p are the annualized pond construction and operation costs ($/acre-year).[4]

Regional net benefits are then

$$\Pi = \Pi^c + \Pi^a - \Pi^p. \tag{12}$$

Land area is constrained by

$$\sum_c \sum_i x_{ci} + x_f + x_a + x_p \leq \bar{x}, \tag{13}$$

implying that the sum of all land uses (crop and tree production, fallowed land, and evaporation pond) must be less than or equal to the total regional land area $\bar{x}$.

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[4] Salts accumulate in the evaporation ponds over time and eventually need to be removed. Experience and calculations suggest that most evaporation ponds can remain operational for upwards of 30 years. A long-run solution to the drainage problem will eventually require pond cleaning and salt removal. These costs are omitted here as there is currently no accepted method for such a procedure.

There is an additional constraint on the amount of drainage that can be produced in the region. As noted above, in terms of reuse, drainage flows from crop production must be greater than or equal to what is reused on the trees. Since both the residual flows from crop production and drainage flows from the trees are ultimately disposed of in the evaporation pond, the pond's physical capacity also provides a constraint on the total drainage possible:

$$\sum_c \sum_i d_{ci} x_{ci} + d_a x_a + q^i \leq w_r x_a + \beta x_p + q^o. \tag{14}$$

The constraint implies that total drainage generated in the region from both crop and tree production and lateral inflows to the region q^i must be less than or equal to what leaves the pond through evaporation (a function of pond size and the evaporation rate β), lateral outflows q^o, and drainwater reuse.

The optimization problem is to maximize regional net benefits subject to the constraints (2)–(6), (8)–(10), and (13)–(14). Decision variables are choice of crops and irrigation systems, land devoted to crop production and agroforestry, evaporation pond size, water applications, and reuse. Nonnegativity must hold for the variables w_{ci}, w_r, x_{ci}, x_a, and x_p. This maximization problem is solved using a nonlinear optimization procedure from the GAMS/CONOPT solver system.

Data

The conceptual model of the previous section is applied to the drainage problem area in Westlands Water District (WWD), the largest water district in California's San Joaquin valley and an area with essentially no traditional drainage outlets. WWD is approximately 600,000 acres, while the drainage problem area consists of some 42,000 acres. WWD is served by the Central Valley Project and began receiving CVP water in the late 1960s. Situated on the west side of the San Joaquin valley, much of WWD is affected by a rising water table resulting from irrigating lands overlying the impermeable Corcoran clay layer. As the water table rises, not only does it create waterlogged soils, but it brings many toxic contaminants to the surface. Drainage relief was originally provided by tile drainage lines and disposal outside the region; however, this option has been foreclosed to the district since the 1980s due to environmental damages associated with those flows. All data are in 1992 dollars and reported on a per-acre basis unless otherwise noted, and an interest rate of 5% is used.

During the 1980s, the primary crops of WWD were cotton and tomatoes, with maximum observed acreage of 53% and 18%, respectively. Truck crops in the district are represented here by lettuce production with a maximum of 15% of the available acreage. Wheat is used to represent field crops (other than cotton), which compose up to 33% of the district acreage. Crop prices are an average of prices over the relevant period. Five irrigation systems differing in the uniformity with which water is applied are available for crop cultivation, ranging from a furrow half-mile run system with a Christensen uniformity coefficient (CUC) of 70, to a drip system with a CUC of 90.[5] The greater the water application uniformity (the higher the CUC), the less water necessary for a specific

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[5] The five irrigation systems in order of increasing water application uniformity are furrow with a half-mile run, furrow with a quarter-mile run, linear move sprinklers, a low-energy precise application system, and subsurface drip irrigation.

Table 1. Irrigation System Data and Crop Nonwater Production Costs

	Irrigation Systems[a]				
	Furrow 2	Furrow 4	Linear	LEPA	Drip
Christensen uniformity coefficient	70	75	85	90	90
Capital recovery costs ($/acre/year)	18.63	24.43	73.21	73.29	154.98
Operating and maintenance costs ($/acre/year)	2.63	3.43	34.36	34.39	53.71
Fixed energy costs ($/acre/year)	0.86	0.86	0.86	1.05	0.86
Pressure head (in feet)	10	10	50	80	50
Nonwater production costs ($/acre/year):[b]					
Cotton	485.69	494.84	466.20	475.02	427.73
Tomato	788.60	796.13	776.87	785.69	706.62
Wheat	197.27	202.78	189.25	198.07	186.01
Lettuce	1,081.79	1,123.03	1,007.05	1,015.87	988.37

Notes: Irrigation system data are from U.C. Committee of Consultants. Monetary amounts are 1992 dollars.

[a] Irrigation system definitions: Furrow 2 represents furrow with a half-mile run; Furrow 4 is furrow with a quarter-mile run; Linear is linear move sprinklers; LEPA represents a low-energy precise application system; and Drip is subsurface drip.

[b] Nonwater production costs include cultural costs such as planting, weeding, labor, and herbicide and pesticide applications; cash overhead costs such as office expenses; and annualized capital equipment replacement costs. Also included are the costs of the tile drain systems.

yield and therefore the less deep percolation and drainage. Water is assumed to be distributed lognormally over the field with a mean equal to the field-average applied-water depth (w_{ci}) and a standard deviation determined by the irrigation system CUC value. Plant-level production functions giving yield and deep percolation as a function of infiltrated water are from Letey and Dinar.

Table 1 gives installation and operation costs for each irrigation system; these increase as water application uniformity increases. Purchase costs are amortized payments over the life of each irrigation system reflecting both interest and depreciation. Taxes, maintenance, insurance, and the estimated repair costs are included in operating costs. These costs and the CUC numbers reflecting water application uniformities were obtained from University of California Committee of Consultants and Letey et al. Irrigation system pressurization costs consist of both a variable- and a fixed-energy cost component. Crop nonwater production costs in table 1 are derived from University of California Cooperative Extension crop budgets. These differ by irrigation system reflecting the different cultivation practices (primarily pesticide and herbicide applications) associated with each system. Nonwater production costs also include the costs of the tile drainage systems. Fallowed land is assumed to be 10% of the total cropped area; this approximates the historical average in WWD over the 1980s. For rotational reasons, tomato acreage is limited to one-half or less of the cotton acreage.

Parameter values for the land-quality cost function are reported in table 2. They were estimated by a calibration procedure generally following Howitt (1995a, b). In particular, values were selected so that the model solution matches historical crop acreage and estimated acreage response elasticities, and so that land-quality costs equal zero at the

Table 2. Coefficients for the Land-Quality Cost Function by Crop

	v_{c0}	v_{c1}	v_{c2}
Cotton	265.64	−1,266.13	1,469.70
Tomato	275.75	−6,694.51	39,369.80
Wheat	82.96	−946.07	2,624.00
Lettuce	430.09	−8,444.88	41,226.70

Note: v_{ci} is the coefficient associated with the x_c^i term in the land-quality cost function, where x_c is computed as a fraction of the regional land area.

observed historical crop areas implying that average production costs in the model match those reported in the Cooperative Extension crop budgets. Observed crop acreage was calculated as the average 1980s crop acreage in WWD, using various WWD crop production reports. Crop acreage response elasticities were obtained from data provided for crops grown in the Central Valley as reported in Central Valley Project Environmental Team. Howitt (1995a, b) provides an extensive discussion and rationale for calibration procedures.

Table 3 reports the economic data for cultivating eucalyptus trees (Lohr). The market price for eucalyptus wood, measured in terms of bone-dry tons (wood dried so that the moisture is removed), is based on an inflation-adjusted average of prices for various eucalyptus products as reported in Lohr. The trees are irrigated with water collected from crop drainage which incurs energy costs to pump the effluent from the tile drains to the area of tree production and also gypsum application costs. [Gypsum is applied as a soil amendment to counteract soil crusting and water penetration problems arising from irrigation with saline water (Rhoades, p. 19).] Annual gypsum application of 1–5 tons/acre is suggested. In this analysis, 3 tons/acre are used, at a cost of $40/ton (estimated gypsum costs range between $30 and $50/ton for purchase and application).

A dynamic micro-level analysis suggested that a 16-year rotation was optimal for

Table 3. Agroforestry and Evaporation Pond Data

Eucalyptus Trees		
p^a	Net market price for output	$62.49/bdt[a]
γ_a	Establishment and nonwater production costs	$166.31/acre[b]
δ^a	Water application costs (reuse of crop drainage)	$3.67/ac.-ft.
$y_a^{\max}$	Maximum yield (unstressed)	9.05 bdt/acre
Evaporation Pond		
δ^p	Pumping cost to pond	$0.85/ac.-ft.
β	Evaporation rate	5.32 feet/year
γ_p	Annualized construction costs	$104.02/acre

Notes: Monetary amounts are 1992 dollars. Eucalyptus output measured in "bdt" or bone-dry tons.

[a] Net market price is the market price ($84.49/bdt) less harvest costs ($22.00/bdt) for the eucalyptus output.

[b] Establishment and nonwater production costs reflect the sum of the annualized establishment costs of the trees and the annual cost of normal agronomic inputs such as fertilizer, pesticides, etc., except for water.

eucalyptus production, implying a total yield of 144.73 bdt/acre under nonstressed conditions. For the regional analysis here, we adapt a "fully-regulated forest" perspective (Howe), where equal areas are devoted to each age category starting with new plantings and ending at sixteen-year-old trees. This implies an even flow of wood over time and also reflects the fact that different growers plant trees at different times so that there will likely be a distribution of different-aged trees at each point in time. With this assumption, annual yield from agroforestry production under nonstressed conditions is 144.73/16 or 9.05 bdt/acre-year.

Maximum yields are not necessarily achieved because the drainage water used to grow the trees is saline and the volume of water applied is variable. Tree production functions are derived from agroforestry models in Letey and Knapp; these give yield and deep percolation as functions of applied-water volume and salinity. Applied water is assumed to have an electrical conductivity (salinity) of 10 decisiemens per meter (dS/m) approximating that of actual drainage flows in WWD (Tanji and Karajeh, p. 173).[6] The irrigation water is assumed to be uniformly applied, with the cost of the irrigation systems included in the production cost parameter γ_a. An upper bound of 5.5 ac.-ft./acre was placed on the applied water for eucalyptus production in recognition of soil infiltration capacities and deterioration resulting from irrigation with saline waters (Letey and Knapp).

For the evaporation pond, explicit costs are the energy needed to pump the residual drainage flows to the pond site and pond construction costs (see table 3). The greatest cost is, however, implicit: land used for an evaporation pond is land that can no longer be used to grow either crops or trees. Thus the primary cost of evaporation ponds is foregone profits on that acreage.

During the 1980s, the price of surface water provided to WWD averaged $22.89/ac.-ft. Over this time period, surface water availability was approximately 2.25 ac.-ft./acre. Farmers in the district can supplement surface water supplies with groundwater pumped from an aquifer below the confining Corcoran clay layer. The groundwater pumping cost formula used here reflects the energy costs of lifting the water, the difference between land height and the height of the water table, the recharge rate of the aquifer, and the area and storativity of the aquifer. (Details are available from the authors.) As pumping volumes deviate from recharge levels, the groundwater cost function allows for pumping lifts and hence costs to vary. Groundwater usage in the 1980s averaged 0.216 ac.-ft./acre, less than the long-run safe yield of the underlying aquifer (0.35 ac.-ft./acre as estimated from various WWD reports). Land height from sea level for the district was calibrated to 258 feet. Effective rainfall, the average amount of rainfall actually available to support crop production, is about 0.29 feet/year.

Regional Drainwater Management

Results are given in table 4 for alternative assumptions regarding drainage flows and management strategies. The historical results of table 4 replicate the drainage problem area in WWD in the 1980s before serious consideration was given to within-region

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[6] Salt concentration of the deep percolation effluent can be affected by irrigation volumes. While this can be included in a straightforward way, it seemed preferable not to do so here as the effluent flows undergo considerable mixing with the underlying water table whose volume is very large relative to the annual deep percolation flows. The salt concentration of the shallow water table (as well as typical deep percolation flows) is generally assumed to be 10 dS/m.

Table 4. Efficient Land Allocations, Irrigation Systems, and Water Applications under Alternate Drainage Conditions and Management Strategies

	Historic	Pond	SC + Pond	SC + Pond + Reuse
Crop Production:				
Cotton				
Land area (fraction of total)	0.49	0.43	0.44	0.42
Irrigation system	Furrow 2	Furrow 2	Furrow 4	Furrow 2
Tomatoes				
Land area (fraction of total)	0.10	0.09	0.10	0.10
Irrigation system	Furrow 2	Furrow 2	Furrow 4	Furrow 4
Wheat				
Land area (fraction of total)	0.20	0.18	0.18	0.16
Irrigation system	Furrow 2	Furrow 2	Furrow 4	Furrow 2/4
Lettuce				
Land area (fraction of total)	0.11	0.10	0.11	0.11
Irrigation system	Furrow 2	Furrow 2	Linear	Linear
Crop land area (fraction of total)	0.90	0.79	0.83	0.78
Applied water (ac.-ft./yr.)	2.30	2.01	1.78	1.80
Deep percolation (ac.-ft./yr.)	0.87	0.76	0.49	0.58
Agroforestry:				
Land area (fraction of total)	0.00	n/a	n/a	0.10
Reuse (ac.-ft./yr.)	0.00	n/a	n/a	0.58
Deep percolation (ac.-ft./yr.)	0.00	n/a	n/a	0.20
Evaporation pond:				
Land area (fraction of total)	0.00	0.13	0.09	0.04
Shadow price of drainage ($/ac.-ft.)	0.00	42.04	37.65	25.53
Regional net benefits ($/acre-year)	274.89	228.04	255.72	271.26

Notes: Results are for one acre of regional land area. Monetary amounts are 1992 dollars. Historic means free disposal of drainage outside of region; Pond means closed region, evaporation pond size sufficient to accommodate historic deep percolation flows; SC + Pond means closed region, source control (SC) and evaporation pond only; and SC + Pond + Reuse means closed region, source control, evaporation pond, and reuse. Irrigation systems are defined in table 1.

drainage disposal. This assumes costless disposal of drainage flows outside of the region. These results serve to verify the model and to provide a base of comparison for the management alternatives. With unlimited drainage flows, no source control is practiced (i.e., all crops are grown with the least efficient irrigation system), no trees are grown, and no land is set aside for evaporation pond use. Crop acreage matches the historical averages of the 1980s, with approximately 10% of the land fallowed. Applied water is equal to 2.30 ac.-ft./acre, with just over 2 ac.-ft./acre coming from surface water sources and 0.22 ac.-ft./acre from groundwater pumping. Deep percolation is 0.87 ac.-ft./acre and regional net benefits are $275/acre. Thus the model accurately reflects agricultural production in the drainage problem area of WWD absent active drainwater management.

The second case in table 4 assumes a closed region. In other words, given the same cropping patterns, irrigation systems, and water applications as in the historical case, if the drainage flows are now constrained to stay within the region, how much land would need to be set aside for evaporation ponds to store those flows? With deep percolation of 0.87 ac.-ft./acre, the evaporation pond area would have to equal 13% of the regional acreage, reducing regional net benefits.

The third case shown in table 4 also closes the region in terms of drainage flows but allows for changes in cropping patterns, irrigation systems, and water applications but not reuse. All four of the crops are now grown with a more uniform irrigation system. Water applications also decrease as do deep percolation flows. Due to increased source control and the corresponding reduction in deep percolation, the evaporation pond area also decreases to approximately 9% of the total acreage from the 13% necessary with an evaporation pond as the only strategy. Total cropped acreage increases as a result. Regional net benefits are considerably reduced from the historical case, reflecting the increased costs associated with source control, the reduced crop acreage, and the opportunity cost of allocating land to the evaporation ponds, but exceed those where the only response is construction of an evaporation pond.

The final case of table 4 considers all three management strategies and will be referred to as our "base case" results. In this scenario, within the closed drainage basin, we allow for source control, for land to be set aside for evaporation ponds, and for agroforestry production with reuse of the crop drainage flows. The results are interesting in that while both cotton and wheat acreage decrease, with most of that land going to agroforestry, less source control is practiced and more water is applied on the crops resulting in greater deep percolation than without the possibility of reuse. This is beneficial as the crop deep percolation is the applied-water source for the trees, and greater crop deep percolation implies more water available for tree production. Profits are also higher than in the no reuse case due to reduced source control.

As mentioned previously, the goal of cultivating eucalyptus trees in this situation is not for the net benefits of tree production but the opportunity to concentrate the crop deep percolation flows and reduce drainage volumes ultimately requiring disposal in the evaporation pond. This is accurately depicted by the model in that the trees are not grown until the region is closed in terms of drainage disposal. Agroforestry production is however an economically viable decision for farmers in the closed region in that its returns, while relatively low in comparison to most crops, are positive whereas relying solely on the evaporation ponds for disposal involves negative returns to that land, both explicitly and implicitly. As a result of the reuse decision, the evaporation pond area is reduced to approximately 4% of the region from slightly over 9% in the source control and evaporation pond–only situation. The goal of concentrating the drainage volume before disposal to the pond is achieved. Regional net benefits in this scenario differ by only a few dollars from those of the historical case of an open region with no constraints put on drainage disposal.[7]

Shadow prices for deep percolation emissions (table 4) show the value of providing external drainage facilities to the region. They can also be interpreted as the level of the emission charge to be imposed on deep percolation flows to induce economic efficiency, or as the efficiency-inducing subsidy for drainwater reuse on trees. The shadow price for the historical case is zero reflecting the unlimited drainage assumption of that case. The

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[7] Heterogeneity of soils is introduced in the land-quality cost function. This influences primarily the acreage variables; however, the water management variables are effectively being set based on average conditions in the region. For actual policy implementation, some of the results given here (e.g., recommended irrigation systems or applied-water levels) may need to be adjusted for farm-level differences that may exist.

Table 5. Surface Water Price Effects on Efficient Regional Drainwater Management

	Surface Water Price			
	$25/ac.-ft.	$50/ac.-ft.	$75/ac.-ft.	$100/ac.-ft.
Crop Production:				
Cotton				
Land area (fraction of total)	0.42	0.43	0.43	0.43
Irrigation system	Furrow 2	Furrow 4	Furrow 4	Furrow 4
Tomatoes				
Land area (fraction of total)	0.10	0.10	0.10	0.09
Irrigation system	Furrow 4	Furrow 4	Furrow 4	Furrow 4
Wheat				
Land area (fraction of total)	0.16	0.17	0.18	0.18
Irrigation system	Furrow 4	Furrow 4	Furrow 4	Furrow 4
Lettuce				
Land area (fraction of total)	0.11	0.11	0.11	0.11
Irrigation system	Linear	Linear	Linear	Linear
Crop land area (fraction of total)	0.78	0.80	0.81	0.81
Applied water				
Surface water (ac.-ft./yr.)	1.53	0.89	0.29	0.00
Groundwater (ac.-ft./yr.)	0.26	0.83	1.40	1.67
Total applied water (ac.-ft./yr.)	1.79	1.72	1.69	1.67
Deep percolation (ac.-ft./yr.)	0.57	0.47	0.44	0.43
Agroforestry:				
Land area (fraction of total)	0.10	0.09	0.08	0.08
Reuse (ac.-ft./yr.)	0.57	0.47	0.44	0.43
Deep percolation (ac.-ft./yr.)	0.19	0.16	0.15	0.14
Evaporation pond land area (fraction of total)	0.04	0.03	0.03	0.03
Regional net benefits ($/acre-year)	267.98	237.92	223.17	221.42

Notes: Results are for one acre of regional land area. Assumptions same as "base case" except for surface water price. Monetary amounts are 1992 dollars. Irrigation systems are defined in table 1.

shadow prices for the other cases range from $42.04/ac.-ft. to $25.53/ac.-ft., with the lower prices associated with increased opportunities for drainage reduction and disposal.

Irrigation Reform

With implementation of irrigation reform such as the Central Valley Project Improvement Act of 1992, surface water prices for farmers in the region under consideration have been and will be increasing. The "base case" results of the previous section are based on a surface water price of $22.89/ac.-ft., the average price paid for surface water in WWD over the 1980s. By 1992, surface water prices in WWD approximated $50/ac.-ft. and while further increases are expected, the extreme variability of prices in the early 1990s accompanied by quantity uncertainty prompted the initial analysis using data from a more stable period. The implications of higher surface water prices for both source control and agroforestry reuse are analyzed here.

As surface water price increases (table 5), surface water use decreases but groundwater use increases so that total applied water, while reduced, does not drastically decrease. Some source control takes place, but it takes place slowly and is not extreme. Except for lettuce, none of the crops switch from the furrow irrigation systems, even at surface water prices of $100/ac.-ft.. This result is driven by reuse where crop deep percolation generates positive returns with the trees before disposal to the evaporation pond. Deep percolation flows disposed of in the pond progressively decline as the surface water price increases, as expected given reduced crop water applications and reuse on the trees.

What is interesting about these results is the effect on crop acreage. The combined effects of increased source control and reuse work to actually increase the amount of acreage allocated to crop production from the base case situation as the surface water price increases. Since there is greater source control in crop production, less deep percolation is produced so less land area is devoted to the eucalyptus trees. Correspondingly, less drainage volume needs to be disposed of in the evaporation pond implying additional available land for crop cultivation. This appears to be somewhat nonintuitive initially (i.e., greater crop acreage with higher surface water prices), but follows from the interaction of source control and reuse.

With higher surface water prices, regional net benefits are reduced from the base case results due to the more expensive water, higher costs associated with the more uniform irrigation systems, and reduced yields resulting from some crop stressing. Increasing surface water prices from $22.89/ac.-ft. to $50/ac.-ft. reduces net benefits by a relatively small amount (less than $10/acre). As table 5 shows, it is only after surface water prices reach $75/ac.-ft. that net benefits decrease appreciably from the base case.

Eucalyptus Product Prices and Gypsum Costs

Since commercial cultivation of eucalyptus trees on a large scale in the San Joaquin valley is still a relatively untested proposition, estimation of the actual returns to and costs of agroforestry is rather uncertain. The data used for the trees in the model discussed above are based on averages of ranges of values, not actual market prices for trees produced and sold in WWD. As such, investigation of changes in tree prices on source control and reuse was made.

At a price of $84.49/bdt (as in the base case), agroforestry in WWD through the cultivation of eucalyptus trees is profitable enough to reuse and concentrate the crop drainage flows before disposal to the evaporation pond. That is not the case if the market price for the eucalyptus drops to $75 or below (see table 6). At those prices, the trees are no longer grown and the results are the same as those depicted in table 4 where for the closed region there is some source control and increased pond area but no tree production.

Once eucalyptus tree prices increase to $100/bdt and above, acreage devoted to crop production decreases as more land is devoted to the trees. This reduction primarily takes place in the cotton acreage, but wheat is also affected (both tomatoes and lettuce are reduced slightly). As tree prices increase, crop applied water increases even though crop acreage is decreasing with the greater deep percolation devoted to tree production. With greater crop deep percolation and increased tree cultivation, tree drainage increases so that the pond area also increases, but slightly. With applied water available only from reuse, the greatest contribution from agroforestry still appears to be concentrating crop drainage water before ultimate disposal to the pond.

Table 6. Eucalyptus Output Price Effects on Efficient Regional Drainwater Management

	Eucalyptus Output Prices[a]					
	$50/bdt	$75/bdt	$100/bdt	$125/bdt	$150/bdt	$200/bdt
Crop production:						
Land area (fraction of total)	0.83	0.83	0.77	0.74	0.73	0.71
Applied water (ac.-ft./yr.)	1.78	1.78	1.83	1.91	1.95	2.03
Deep percolation (ac.-ft./yr.)	0.49	0.49	0.63	0.74	0.79	0.91
Agroforestry:						
Land area (fraction of total)	0.00	0.00	0.11	0.13	0.14	0.17
Reuse (ac.-ft./yr.)	n/a	n/a	0.63	0.74	0.79	0.91
Deep percolation (ac.-ft./yr.)	n/a	n/a	0.21	0.25	0.27	0.31
Evaporation pond:						
Land area (fraction of total)	0.09	0.09	0.04	0.05	0.05	0.06
Crop DP to pond (ac.-ft./yr.)[b]	0.49	0.49	0.00	0.00	0.00	0.00
Tree DP to pond (ac.-ft./yr.)[b]	n/a	n/a	0.21	0.25	0.27	0.31
Regional net benefits ($/acre-year)	255.72	255.72	283.35	304.93	329.39	383.76

Notes: Results are for one acre of regional land area. Monetary amounts are 1992 dollars.
[a] Eucalyptus output is measured in terms of "bdt" or bone-dry tons.
[b] DP refers to deep percolation.

Gypsum amendments are required for agroforestry production to counteract the negative effects on soils of using highly saline irrigation water (e.g., Grattan and Rhoades; Tanji and Karajeh). The base case assumes gypsum applications of 3 tons/acre for agroforestry production, at a cost of $40/ton. These are only midpoints of estimated amounts to counteract soil degradation. Sensitivity of agroforestry to gypsum application rates and costs is analyzed here as little empirical evidence is available to provide more definitive numbers.

Table 7 details the effect on tree acreage of changing gypsum application rates and/or prices. The greatest tree acreage occurs when no gypsum is applied (11.5% of the region's acreage planted to eucalyptus). This percentage declines gradually as either more gypsum

Table 7. Sensitivity of Economically Efficient Agroforestry Land Area to Various Gypsum Application Quantities and Prices

Quantity Applied (tons/acre)	Gypsum Cost ($/ton)		
	30	40	50
0	0.115	0.115	0.115
1	0.113	0.113	0.112
2	0.112	0.111	0.110
3	0.110	0.105	0.098
4	0.105	0.000	0.000
5	0.098	0.000	0.000

Notes: Monetary amounts are 1992 dollars. Tabular values are agroforestry land area as a fraction of total acreage.

Table 8. Effects of Water Table Lateral Flows on Economically Efficient Land Allocation and Regional Net Benefits

Net Lateral Inflows[a] (ac.-ft./ acre-year)	Land Area as Fraction of Total			Regional Net Benefits[b] ($/acre/year)
	Crops	Trees	Pond	
0.00	0.78	0.10	0.04	271.26
0.10	0.78	0.10	0.05	265.94
0.20	0.77	0.09	0.07	260.57
0.25	0.76	0.08	0.08	257.78
0.30	0.79	0.00	0.13	242.87
0.40	0.78	0.00	0.15	237.98
0.50	0.76	0.00	0.16	232.69

[a] Net lateral inflows are defined as inflows minus outflows.
[b] Monetary amounts are 1992 dollars.

is applied or its cost increases. However, land area for the trees drops to zero when the cost per acre rises above approximately $150/acre. Therefore eucalyptus cultivation in the region under consideration appears sensitive to production costs and relatively small changes in those costs may be sufficient to preclude this as a means of coping with the drainage problem.

Lateral Flows

While WWD is prohibited from releasing drainage flows outside the district, underground flows of water move in and out of the drainage problem area, thus changing drainage disposal requirements. Our base case results assume that net lateral inflows are zero: inflows exactly balance outflows and therefore only the deep percolation flows actually generated within the drainage problem area require disposal. This may be unrealistic given the hydrogeology of this region of the San Joaquin valley so the model was rerun using various simulated lateral inflows.

Precise estimates of lateral underground flows are difficult to obtain, but some rough estimates can be made using Darcy's law (Freeze and Cherry). A one-mile wide, east-west transect in the drainage problem area was selected. This transect parallels the general direction of water table flows, thus only movements at the end points need be considered. Darcy's law may be expressed as

$$(15) \qquad q = -k\frac{dh}{dl}A^c,$$

where q is the flow rate, k is the hydraulic conductivity, dh/dl is the hydraulic gradient (water table slope), and A^c is the cross-sectional area of the water table aquifer. Using data in Belitz, Phillips, and Gronberg, we estimate the average volume of net lateral inflows (inflows minus outflows) as 0.08 ac.-ft./acre-year for the region under consideration. This is additional water which must be disposed of in the region to maintain the water table at acceptable levels.[8]

Simulated results for a range of net inflows are shown in table 8. Below a net inflow of approximately 0.3 ac.-ft./acre-year, there are only slight modifications to the base case results. As lateral inflows increase, greater disposal is necessary so land area set aside for the evaporation pond increases, taking away both crop and tree acreage. Greater source control is practiced on the crops. At 0.3 ac.-ft./acre-year and above, net lateral inflows are sufficient to require that land area devoted to the trees reverts to crop and pond acreage. As the net inflows further increase, more land goes to the pond and less to crop production.[9]

Conclusions

This study investigates the economics of source control and reuse as a means of coping with crop drainage flows. A model was developed to represent the prevailing conditions of a specific region with serious drainage problems. The model was calibrated to accurately reflect various historical cropping, irrigation system, applied water, and drainage patterns. It was then used to analyze the regional net benefits of introducing agroforestry, specifically eucalyptus production, as a means of concentrating crop drainage flows through reuse before long-term storage of the residual flows in an evaporation pond.

The results are quite encouraging in that, given a closed region in terms of drainage flows, agroforestry is a viable option for regional drainage management in terms of maximizing net benefits. The tree cultivation takes land that would otherwise be used for evaporation pond storage of the drainage flows, with implicit and explicit costs attached, and converts it to tree production which yields positive net returns. Since the drainage flows are now concentrated through reuse, less land area is necessary for the pond(s). Thus, the agroforestry option appears attractive in that regional production combining source control, reuse, and an evaporation pond within a closed region has regional net benefits which approximate those of unlimited drainage flows.

However, agroforestry production and reuse does appear to be fairly sensitive to the revenue and costs of tree production. While agroforestry is viable at an output price of $84.49/bdt, a price reduction to $75/bdt drops tree cultivation altogether. The results also suggest that while gypsum costs of $150/acre are feasible, $160/acre or more is sufficient to eliminate tree production. Thus costs and output prices are critical to the viability of drainwater reuse through agroforestry production.

Our empirical results also illustrate the interrelationship between source control and reuse. For example, higher surface water prices result in greater source control in the cropping decision (e.g., less applied water due to more uniform irrigation systems) which results in less crop drainage. Less water is thus available for reuse on the trees so that tree production and reuse are reduced as source control increases. Even so, the agrofo-

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[8] Hydraulic conductivity k is estimated at 6,300 feet/year, the hydraulic gradient dh/dl is estimated as 2.22×10^{-3} and 6.38×10^{-3} (unitless) at the west and east boundaries, respectively, and the vertical cross-sectional area A^C is estimated as 2.91×10^6 and 1.96×10^6 feet^2 for the same two boundaries.

[9] As net inflows increase, more land area is devoted to the evaporation pond for their disposal, reducing productive acreage. Less crop production means reduced land-quality costs (movement down the land-quality cost function) so that average profitability for the crops is increasing. Thus the crops become more profitable relative to the trees which therefore drop out of production.

restry decision is relatively insensitive to increasing surface water prices since tree production still provides a positive return as a reuse/drainage-reduction mechanism versus costly pond storage.

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