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Integrated Drainwater Management in Irrigated Agriculture

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Abstract

Drainwater management strategies include source control, reuse, treatment, and evaporation ponds; questions of interest are efficient management, policy instruments, and sustainability. A high level of source control is indicated absent reuse due to the relatively high cost of evaporation ponds; this is accomplished largely through high uniformity/high cost irrigation systems. With reuse, the primary form of source control is reduction in land area devoted to freshwater production; the released land goes to reuse production. Reuse appears as an economically promising solution to the drainage problem. A high level of net returns is achieved while maintaining overall hydrologic balance in the system.

Economic efficiency and hydrologic balance may be attained through pricing or market schemes. With pricing, growers are charged for deep percolations flows, while reuse and evaporation pond operators are paid for extractions. With markets, permit supply is generated by extractions from the water table, while permit demand is generated by deep percolation. Competitive equilibrium exists, is efficient, and implies hydrologic balance. The analysis suggests that a high level of agricultural production may be possible for some period of time while still maintaining environmental quality.

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Introduction

Deep percolation flows are an inevitable consequence of irrigated agriculture. While some flow below the root zone is desired to leach salts away from the roots, most flows are a product of a field's nonuniform infiltration rate. In the presence of impermeable strata underlying the irrigated field, these flows can build up and encroach into a crop's root zone resulting in decreased yields and possibly eliminating production. The threat of such production losses to irrigated agriculture is present in California's San Joaquin Valley (SJV), a region consisting of nearly 5.6 million irrigated acres above an impervious clay layer. Early efforts to solve this problem involved installing a system of drains that transported the saline water near the rootzone to streams or other water bodies. Unfortunately, the drainage resulted in environmental damages, such as the bird deformities and fish kills at the Kesterson Reservoir in 1985, which subsequently lead to out-of-region discharge restrictions. Currently, irrigated agriculture in this region is operating as a semi-closed basin; surface water is imported for irrigation but external drainage is either not allowed or is greatly restricted.

Finding a solution to this drainage problem, a solution that maintains both agricultural productivity and environmental quality, requires consideration of a broad array of biophysical management options. These options will likely include some combination of source control, drain water reuse, and in-region disposal methods. Examples of source control options include more uniform irrigation systems and crop-switching. Reusing the drainage water for crop production is another option, similar to source control, which can reduce waste emissions and conserve scarce freshwater supplies. Finally, in-region disposal methods include options such as evaporation ponds and solar evaporators. An understanding of both the relationships that exist between the options themselves and their impact on production and the environment is required, though, to find the efficient solution among these various combinations.

Numerous studies have investigated the impact of these options on production, drainage flows, and water use. Dinar et al (1985) Caswell, Lichtenberg, and Zilberman (1990), and Dinar and Zilberman (1991), for example, investigated the implications of source control at the field-level, while Dinar, Hatchett and Loehman (1991) and Posnikoff and Knapp (1996) evaluated source control at the farm and regional level. Knapp et al. (1990*b*) and Shah, Zilberman, and Lichtenberg (1995) evaluated source control while accounting for the potential dynamics associated with the water table. Studies that have investigated irrigation with saline water and/or reuse include (among many others) Feinerman (1983), Bresler, Yaron, and Segev (1983), Feinerman and Yaron (1983), Knapp and Dinar (1984), and Feinerman and Vaux (1984) at the field and farm-level within a static framework, and Yaron and Olian (1973), Yaron et al. (1980), Dinar and Knapp (1986), Dinar, Aillery, and Moore, and Wichelns (1999) within a dynamic framework.

Studies using an integrated analysis of multiple strategies including source control, reuse, and disposal are much less numerous. Knapp, Dinar, and Letey (1986) consider source control and reuse with evaporation ponds, yet irrigation technology is treated as exogenous. Posnikoff and Knapp (1996) evaluate source control, reuse with agroforestry production, and evaporation ponds. However, agroforestry does not currently appear viable in the SJV (Oster et al). Hatchett, Horner, and Howitt (1991) develop a detailed simulation model for drainage in the SJV. Their model includes various source control methods and reuse, but not other in-region disposal options such as evaporation ponds. Research investigating the ability of policy to address the irrigated agricultural drainage problem includes Wicheln's (1991) evaluation of tiered pricing, Weinberg, Kling, and Wilen's (1993) consideration of water markets, and Weinberg and Kling's (1996) attention to cross-policy effects.

The purpose of this paper is to analyze the regional agricultural drainage problem. In contrast to much of the work in this area, the analysis here simultaneously considers the major management strategies of source control, reuse, and disposal along with substitution possibilities that exist among them.[1] A stylized theoretical model is developed to identify conditions when freshwater crop production, reuse, and evaporation ponds are viable options. Circumstances that determine the choice of reuse or evaporation ponds as the preferred disposal method are also investigated. Sensitivity of these options to changes in water management and environmental concerns is performed.

Two policy schemes are then evaluated with respect to their potential impact on the market solution. One scheme consists of charging or compensating growers for additions to or extractions from the water table, respectively. The second scheme consists of a permit system where permit supply and demand is generated by extractions from and additions to the water table, respectively. Both schemes are shown to result in a competitive equilibrium and hydrologic balance. These results suggest that a high level of agricultural production may be possible for some period of time while still maintaining environmental quality. It should be noted that the novelty of our policy analysis within the environmental economics literature is the endogeneity of the emissions and permit supply beyond just the allocation across emitters.[2]

Finally, an empirical analysis is conducted for a region of the SJV, a region that is currently heavily impacted by drainage problems. The intention of including the empirical section is not

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[1] The few available previous regional/integrated studies are empirical and primarily concern efficient management.

[2] It is often the case that policy options (e.g., surface water pricing) are specified exogenously.

to provide an all-encompassing analysis of the theoretical results, but rather illustrate the importance of accounting for each of the major management options – source control, reuse, and in-region disposal – so as to accurately reflect the problem, substitution possibilities, and consequences confronts growers and policy makers. Our findings indicate that overlooking any of these options, and the substitution opportunities that exist among them, can have a substantial impact on the results and, henceforth, the conclusions one can drawn about the relative attractiveness and efficiency of any particular policy scheme.

Model

Consider a region with irrigated agricultural production overlying a shallow, saline water table and no facilities for external drainage. Agricultural production is modeled consisting of three sectors: freshwater crop production, reuse production, and drainage disposal via evaporation ponds. Within the theoretical framework, land allocation and water applications are variable; the empirical analysis includes alternate irrigation systems and crop mix as additional choice variables. Land and water allocations are chosen to maximize regional net benefits subject to both land and hydrologic balance constraints. The latter constraint requires that flows to the water table are balanced by flows from the water table, an important assumption that eliminates the possibility of the water table rising to levels that damage crop or eliminate production.

Regional net benefits, Π (\$/yr), are given by

$$\Pi = (p_1^c y_1 - g_1)x_1 - p_1^w w_1 x_1 + (p_2^c y_2 - g_2)x_2 - \bar{g}_2 x_2^{\,2} - p_2^w w_2 x_2 - g_3 x_3 \qquad (1)$$

where w_i = applied water depth (ft/yr), $x_i =$ land area (acres), y_i = annual crop yield (per acre), and i = 1, 2, 3 denotes crop production, reuse and evaporation ponds, respectively. Parameters

p_i^j are defined for crops, *c*, and water, *w*, for *i* = {1,2}. g_1 and g_2 are annual per acre production costs, $\bar{g}_2 x_2^2$ are other costs associated with reuse, and g_3 represents evaporation pond costs ($/ac-ft). Other reuse costs may include additional production costs, land quality effects, or risk and uncertainty factors associated with experience growing reuse crops. The quadratic specification follows along the insight of Howitt (1995) who suggests that for most crops, profit functions might be modeled as nonlinear in land to capture a decreasing gross margin per acre.

The crop-water production functions are given by

$$y_i = f_i(w_i) \text{ and } d_i = g_i(w_i) \tag{2}$$

where d_i are deep percolation flows (ft/yr) for i = 1,2, implying crop yield and deep percolation flows are a function of applied water depth. The land constraint is

$$x_1 + x_2 + x_3 \leq 1 \tag{3}$$

where a unit regional area is assumed for convenience. To maintain hydrologic balance in the region, the following condition is assumed:

$$d_1 x_1 + d_2 x_2 - w_2 x_2 \leq e^p x_3 \tag{4}$$

where e^p is the pond evaporation rate (ft/yr). This implies that deep percolation flows below the rootzone must be less than disposals through reuse or evaporation in the pond.

Optimal management and shadow values

In this section, the first-order conditions associated with maximizing regional net benefits are identified. Particular attention is given to the importance of all three management options in achieving efficiency. To keep the analysis tractable, the choice variables are land acreage devoted to each activity (source control, reuse, and in-region disposal) given fixed levels of water application for both crop production and reuse. A succeeding section will analyze variable water applications.

Let $p_1 = p_1^c y_1 - g_1 - p_1^w\ w_1$ and $p_2 = p_2^c y_2 - g_2 - p_2^w w_2$ be the annual net returns per acre from crop and reuse production respectively before drainage and land costs. Let l_l (\$/ac-ft) and l_d (\$/ac-ft) denote the Lagrange multipliers associated with the land constraint (3) and the hydrologic balance constraint (4), respectively. Forming the Lagrangian and differentiating yields

$$p_1 \leq d_1 l_d + l_l \tag{5}$$

$$p_2 - 2\bar{g}_2 x_2 + l_d w_2 \leq l_d d_2 + l_l \tag{6}$$

$$l_d \leq \frac{g_3 + l_1}{e^p} \tag{7}$$

as the first-order conditions associated with x_1, x_2 , and x_3 respectively. Each of these conditions must hold with equality when the associated land variable is positive. Furthermore, the shadow values must be non-negative (Sydsaeter, Strom, Berck 2000).

The first two conditions imply that crop and reuse production are carried out to the point where the marginal net returns are equal to the marginal costs of drainage plus land opportunity costs. As shown in equation (6), part of the benefit of reuse is associated with the water extractions, which are valued by l_d. Equation (7) implies that drainage disposal by evaporation ponds is produced to the point where the marginal benefits of disposal equal the marginal costs; the latter including both pond construction and environmental costs along with the opportunity cost of land.

Assuming crop production is sufficiently profitable to be grown, condition (5) implies that the shadow value of land equals crop revenue less all other costs including drainage. Condition (6) implies

$$l_d \leq \frac{-(p_2 - 2\bar{g}_2 x_2) + l_l}{w_2 - d_2} \qquad (8)$$

where (w_2–d_2) is the evaporation rate of the reuse area. Thus the shadow price of drainage consists of production costs net of crop returns (if any) and a land opportunity cost. For any positive x_1, equation (7) or (8) must hold with equality to meet the disposal requirements associated with the deep percolation flows, d_1x_1.

A comparison of equations (7) and (8), for instance, illustrates the importance of recognizing all three management options in efforts to identify an efficient solution. Assuming w_2-d_2 < e^p, as will typically be the case, implies that the shadow prices associated with the two disposal methods will depend on the shadow value of land. This comparison is depicted in Figure 1. Under the assumed conditions, reuse is the less costly disposal option when land values are low while the evaporation pond is preferable when land values are high. This tradeoff arises because while reuse may be less costly per-acre than evaporation ponds (and quite possibly have positive returns), it also disposes of less water per acre than evaporation ponds. Hence, choice of disposal method depends in part on the profitability of crop production with freshwater, something which might otherwise have appeared independent.

Land Allocations

Under what circumstances might positive levels of x_1, x_2, and x_3 be observed? First, consider the necessary conditions for x_1 >0. From (5) and the non-negativity of shadow value on land, it must be the case that

$$p_1 \geq d_1 l_d \tag{9}$$

As mentioned above, positive crop production requires some drainage disposal via reuse, evaporation pond, or both. If the reuse area, $x_{2,}$ is positive, then equation (6) and a non-negative l_l imply that

$$l_d \geq \frac{-p_2}{w_2 - d_2} \tag{10}$$

For analogous reasoning, a positive evaporation pond area, x_3, implies

$$l_d \geq \frac{g_3}{e^p} \tag{11}$$

Combining equations (9)-(11) suggests that

$$p_1 \geq d_1 Min\left[\frac{g_3}{e^p}, \frac{-p_2}{w_2 - d_2}\right] \tag{12}$$

when crop production is positive. If p_1 is less than this amount, any positive x_1 would be inefficient.

Assuming a positive level of x_1, under what conditions might $x_2 > 0$? Efficiency requirements for positive levels of x_1 and x_2 require equations (5) and (6) hold with equality. From equations (6) and (7) it follows that

$$\frac{-(p_2 - 2\bar{g}_2 x_2)}{w_2 - d_2} \leq \frac{g_3}{e^p} + l_l\left(\frac{1}{e^p} - \frac{1}{w_2 - d_2}\right) \tag{13}$$

again assuming $e^p > w_2 - d_2$. This and the non-negativity of $\bar{g}_2$ yield

$$\frac{-p_2}{w_2 - d_2} < \frac{g_3}{e^p} \tag{14}$$

as a necessary condition for a positive x_2. If this condition is not satisfied, that is, if the cost per acre-ft of disposal using reuse is greater than the cost per acre-ft using the evaporation pond, than reuse cannot be socially efficient. Note that this is only a minimally necessary condition; sufficiency also requires a relatively small land value as previously illustrated.

Analogously, if crop production is positive, when would we observe $x_3 > 0$? Here both (5) and (7) must hold as equalities. These imply

$$\frac{g_3 + p_1}{e^p + d_1} = l_d \tag{15}$$

The first-order condition (6) and the shadow value of land from (5) result in

$$l_d \leq \frac{p_2 - 2\bar{g}_2 x_2 - p_1}{-d_1 - (w_2 - d_2)} \tag{16}$$

as an upper bound on the shadow value of drainage. Combining these two results yields

$$\frac{g_3 + p_1}{e^p + d_1} \leq \frac{p_1 - (p_2 - 2\bar{g}_2)}{d_1 + w_2 - d_2} \tag{17}$$

as a necessary condition for $x_3 > 0$. If this condition is violated, evaporation ponds are an economically inferior disposal strategy relative to reuse.

Hence, the above analysis illustrates that efforts to find an efficient solution to irrigated drainage problem in a region such as the SJV require recognition of the intricate links that exist between source control, reuse, and in-region disposal. Analyses that overlook any one of these factors are likely to lead to either environmentally and economically unsustainable practices or inefficient outcomes.

Environmental hazards of evaporation ponds

Having identified necessary conditions for observing positive levels of x_1, x_2, and x_3, sensitivity of these activities to changes in relevant parameters is now considered. Recently, in-region disposal in the SJV has garnered statewide attention given the potential environmental hazards associated with evaporation ponds. Drainage flows leach highly toxic trace elements from the soil profile. The concentration of these elements in evaporation ponds may build up over time as the water evaporates. Within the western U.S., evidence of increases in selenium levels within these ponds has been documented. Selenium is extremely toxic to birds and other wildlife. The deformities associated with chicks in the SJV were linked to selenium and ultimately prompted the closure of the Kesterson Reservoir as a drainage disposal area.

To investigate the impact of a change in in-region disposal requirements, the effect of a change in g_3 on x_i is evaluated. Increases in g_3 might arise from requiring netting on the ponds, and/or requiring additional compensating habitat for every acre of evaporation pond.[3] In the following analysis, we assume positive amounts of crop production, reuse, and evaporation pond are efficient, and that the land and drainage constraints (3) and (4) are both binding. These two constraints can be solved for x_2 and x_3 as functions of x_1 and then substituted into (1) leaving net benefits as a function of x_1. Differentiating with respect to x_1 yields the respective first-order condition. Differentiating with respect to γ_3 and solving yields

$$\frac{\partial x_1}{\partial g_3} = -\frac{(w_2 + d_1 - d_2)\,(e^p - w_2 + d_2)}{2\bar{g}_2 (e^p + d_1)^2} < 0 \tag{18}$$

under the likely assumptions that $w_2 > d_2$ and $e^p > w_2 - d_2$. Using definitions for x_2 and x_3 derived from the land and drainage constraints, it follows that

$$\frac{\partial x_2}{\partial g_3} = -\frac{(e^p + d_1)\,\dfrac{\partial x_1}{\partial g_3}}{e^p - w_2 + d_2} > 0 \tag{19}$$

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[3] Current regulations require compensating habitat at a ratio of 1:1 with respect to evaporation pond acreage.

$$\frac{\partial x_3}{\partial g_3} = \frac{(w_2 + d_1 - d_2)\,\frac{\partial x_1}{\partial g_3}}{e^p - w_2 + d_2} < 0 \qquad (20)$$

assuming, again, the likely conditions that $w_2 > d_2$ and $e^p > w_2 - d_2$.

An increase in the environmental costs associated with evaporation ponds results in a smaller pond area. Reuse area must expand to compensate. Since reuse typically disposes less water per unit area than evaporation ponds, more total land area is required for disposal and hence primary crop production must decline. Sensitivity analysis can be conducted for other parameters in an analogous manner. Clearly, different net outcomes may occur when other factors such as applied water rates, irrigation systems, and crop type are allowed to vary. Empirically, which factors vary will be application specific. In the empirical model below, all of these factors are choice variables.

Water applications and environmental hazards

This section identifies the efficiency requirements associated with freshwater and reuse water applications, both of which are now considered choice variables. Following the identification of the first order efficiency conditions, we briefly investigate the implications on water use of changes in the costs of in-region disposal.

From equations (1) - (4), the first-order conditions for water applications are

$$p_1^c f_1'(w_1) = p_1^w + l_d g_1'(w_1) \qquad (21)$$

$$p_2^c f_2'(w_2) + l_d = p_2^w + l_d g_2'(w_2) \qquad (22)$$

for w_1 and w_2, respectively. The first-order conditions for the land allocations and the shadow values for land and drainage disposal are defined in equations (5) – (8). Given a positive amount of crop production and drainage reuse, water applications are assumed to be strictly positive.

In equation (21), w_1 has the usual interpretation that water is applied to the point where the marginal value in production equals the marginal cost, which includes both water and drainage costs. In the case of reuse, equation (22), the marginal benefit of water applications includes both the value of crop production and drainage reduction. For efficiency, reuse water is applied (and extracted) until these marginal benefits equal the marginal costs of the water itself, p_2^w, and the corresponding deep percolation flows, $l_d g_2'(w_2)$.

Given these efficiency conditions, consider again a change in the cost of in-region disposal that might come about through efforts to reduce the environmental hazards associated with evaporations ponds. For tractability purposes, we suppose $x_2 = 0$. With the land and drainage constraints holding with equality, land areas x_1 and x_3 can be rewritten as functions of w_1. Rewriting equation (1) in terms of w_1 and differentiating yields

$$p_1^c f_1'(w_1) = p_1^w + \frac{g_3 g_1'(w_1)}{e^p} \tag{23}$$

as a first-order condition for w_1. Totally differentiating equation (23) and solving for $\frac{dw_1}{dg_3}$:

$$\frac{\partial w_1}{\partial g_3} = \frac{g_1'(w_1)}{e^p p_1^c f_1''(w_1) - g_3 g_1''(w_1)} \tag{24}$$

which is less than zero under the (realistic) assumption that drainage flows are convex in applied water (i.e., $g_1'(w_1) > 0$). Applying this to the land area relations implies that the land areas x_1 and x_3 are increasing and decreasing, respectively, in pond costs.[4]

Policy

In regions with high water tables, deep percolation flows from one field may have negative impacts on production or the environment elsewhere in the region, perhaps even imposing additional disposal costs on others growers. Conversely, extractions from the high water table may lead to substantial benefits elsewhere in the system. Absent regulation, these costs and benefits may be largely or entirely borne by other users of the resource; hence unregulated use is likely inefficient.

One possible regulatory strategy is to price flows to and from the water table. Consider a market consisting of three types of agents: crop producers who use freshwater, crop producers who reuse water via extractions from the watertable, and pond operators who provide disposal services. Freshwater crop producers maximize profits, $\prod_1$, subject to a charge on emissions,

$$\Pi_1 = \left(p_1^c y_1 - g_1\right)x_1 - p_l x_1 - p_1^w w_1 x_1 - p_d d_1 x_1 \qquad (25)$$

where p_d (\$/ft) is the regulatory price charged to producers for deep percolation flows and paid to producers for disposal of these flows, and p_l (\$/acre) is the land rental rate. Reusers also maximize profits, $\prod_2$, subject to the charge on additions to the watertable, but also receive payments for extractions from the water table,

[4] It should also be mentioned that changes in environmental costs brought about by changes in land requirements (e.g., requirement a compensating habitat) will add additional complexity to the theoretical model by essentially influencing both the land and hydrological balance constraints. This issue goes beyond the scope of the currently theoretical model.

$$\Pi_2 = \left(p_2^c y_2 - g_{21}\right)x_2 - \bar{g}_2 x_2^2 - p_l x_2 + \left(p_d - p_2^w\right)w_2 x_2 - p_d d_2 x_2 \qquad (26)$$

Finally, pond operators are paid for water table extractions implying

$$\Pi_3 = (p_d e^p - g_3)x_3 - p_l x_3 \qquad (27)$$

for their regional profits. If we let $p_d = l_d$ and $p_l = l_l$, then the private-optimum first-order conditions derived from equations (25) - (27) are identical to the social optima first-order conditions derived earlier. With many operators, land prices will be determined in a competitive market. Given the regulator sets the efficient water charge, p_d, the correct land value will automatically emerge.

An alternative to a pricing scheme is to establish a market for the unpriced services. Under marketable permit system, reusers and evaporation pond operators supply permits, while emissions to the water table must be covered by a permit. As illustrated in Figure 2, a competitive equilibrium will occur where the quantity of permits supplied equals quantity demanded. Such an outcome achieves hydrologic balance. Assuming that $p_d = l_d$ and $p_l = l_l$, it is straightforward to show that the conditions for equilibrium implied by equations (25) – (27), along with the market clearing conditions in both the permit market and the land market, will be identical to the social optimal conditions. Hence, an economically efficient competitive equilibrium exists with the permit system.

The novelty of these approaches as compared to the standard emission charge and TDP market schemes in environmental economics is that in the above example, the level of emissions and permit supply are endogenous. In the standard approach, an overall level of environmental quality would be specified and this level would determine a fixed level of aggregate pollution control that would be achieved with either an emissions charge or a marketable permit scheme.

While the regulator does specify the level of environmental quality in terms of maintaining a hydrologic balance in the present scenario, the actual total level of emissions is not targeted.

Empirical analysis

The empirical analysis focuses on the Westlands Water District (WWD) within California's Central Valley. WWD consists of approximately 600,000 acres located in the agriculturally rich San Joaquin Valley and is subject to an in-region drainage disposal requirement. A large portion of WWD confronts a high water table, the result of continued deep percolation flows from irrigation accumulating over time on top of the relatively impermeable Corcoran clay layer. Selected parameter values are described in Table 1. For a complete description of the model, parameters, and estimation procedures, see Kan, Schwabe, and Knapp (2002).

The model includes cotton, processing tomatoes, wheat, alfalfa, and lettuce as both freshwater crops and reuse water crops. Bermuda grass is an additional reuse crop. The irrigation systems and their respective Christensen Uniformity Coefficient (CUC) are furrow 0.5 mile (CUC=70), furrow 0.25 mile (CUC=75), linear move sprinklers (CUC=85), sprinkler (CUC=80), low-energy precise application system (CUC=90), and subsurface drip (CUC=90).[5]

Crop-water production functions are specified as

$$y = y_1(e - \underline{e}) + y_2(e - \underline{e})^2$$

$$e = \frac{\bar{e}}{1 + \acute{a}_1\left(c + \acute{a}_2 w^{\acute{a}_3}\right)^{\acute{a}_4}} \qquad (28)$$

$$d = w - e$$

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[5] A measure of the uniformity of water application for an irrigation system is its Christensen Uniformity Coefficient (CUC). The greater the CUC, the more uniform the water application.

where e (ft/yr) denotes evapotranspiration, $\bar{e}$ (ft/yr) is the maximum evapotranspiration under non-stressed conditions, $\underline{e}$ represents the minimum evapotranspiration level required for yield production, y is yield (tons/acre), and d (ft/y) is deep percolation flows. y*'s* and a*'s* are scalars, while w (ft/yr) and c (ds/m) are irrigation depth and salt concentration. This system is estimated for each crop-irrigation system combination. Data for yield, evapotranspiration, and deep-percolation flows given irrigation depth and salt concentration are generated using the Letey et al. (1985) plant-level model and assuming water is distributed over the field according to a lognormal distribution. Plant-level parameter values for the model are generally from Letey and Dinar (1986); distribution moments depend on irrigation system uniformity. The production function system was fit to the data using nonlinear regression analysis.

Non-water production costs and market prices for each cropping system are derived from UC Cooperative Extension Service (2000) crop budgets and Fresno County Crop Report (2000). The costs of irrigation include amortized capital costs along with maintenance and operating costs. Surface water costs are a weighted-average of water prices in WWD. Constraints are imposed to maintain acreages of individual crops within historical ranges observed in the 1990's.

Evaporation pond construction and maintenance costs are \$117.40 ac^{-1} yr^{-1} and the evaporation rate is 5.32 ft/yr (Posnikoff and Knapp 1997). In-region disposal consists of evaporation ponds and their requisite compensating habitat. Given the potential environmental damages associated with evaporation ponds, in particular the danger to birds from selenium buildup in the ponds, the state of California requires pond owners provide additional freshwater (compensating) habitat at a 1:1 ratio to evaporation pond acreage. Furthermore, various bird hazing techniques must be used on the evaporation ponds to discourage birds from feeding and nesting there. Compensating habitat costs are estimated as \$1,504 ac^{-1} yr^{-1}; however, the mandated 1:1 ratio imposed in 1995 has been questioned as perhaps going beyond what is needed to protect wildlife (Evaporation Ponds Technical Committee 1999).

The first column in Table 2 reports results with no constraints on net flows to the water table. This serves as a baseline for the hydrologic balance analysis and also to help verify the model. In effect, it represents the situation in WWD prior to 1985 when growers were allowed to discharge their drainage into nearby streams, rivers, or canals. As the results indicate, traditional irrigation systems are selected, there is no reuse, and deep percolation flows average slightly over 1 ft/yr. Interestingly, deep percolation flows of 1 ft/yr are generally considered to be the historical average in the region over the period time during which the current drainage problem developed.

The second column in Table 2 enforces the hydrologic balance constraint but with no reuse. This scenario mimics the WWD after the in-region disposal requirement but before the compensating habitat and hazing mandates imposed in 1995. The results suggest that efficient management entails both a substantial level of source control as well as in-region disposal of deep percolation flows to evaporation ponds. Total crop area declines to accommodate the evaporation ponds. Irrigation systems switch from traditional systems (furrow with ½ mile runs) to more uniform systems. Average deep percolation flows decline by almost 60% due to both improvements in irrigation efficiency as well as reductions in applied water for a given system. The pond area amounts to 7% of the regional area. While the results show that significant returns to land and management can be sustained while maintaining hydrologic balance, social net benefits (SNB) decline by 17% compared to the unconstrained case.

In column three, the compensating habitat requirement is introduced intended to mimic regulations in the WWD post-1995. As shown, there is a dramatic shift to more uniform irrigation systems that lead to a pronounced reduction in deep percolation flows by 12% as compared to the unconstrained case. Pond acreage has been reduced by 5%, some of which was needed for the compensating habitat. While still positive, SNB decrease by nearly 37% as compared to column one.

The last column of Table 2 allows growers the choice of evaporation ponds (including compensating habitats) and/or reuse as a drainage disposal option. The results suggest that drainwater reuse offers great promise in maintaining agricultural production and hydrologic balance in the region. As shown, the area devoted to crop production with freshwater is reduced quite substantially to allow for reuse production. Compared to the baseline solution, reuse opportunities require little source control from growers. There is a 5% reduction only in the use of the less uniform irrigation systems and, surprisingly, deep percolation flows increase slightly.

While the details of the crop mix for freshwater crops is not shown, column three does illustrate that most of the drainwater reuse is applied to cotton. The constraint on total cotton acreage was binding at the upper bound of its observed historical levels, implying that additional acreage would lead to even larger gains. Cotton as a reuse crop is practical since it is both profitable and moderately salt tolerant (Mass and Hoffman 1977). In the presence of the reuse option, no evaporation ponds where chosen. Most noteworthy, though, is that with reuse the net returns to land and management are not only positive – implying that agriculture can be sustained in the region for some time - but are only 5% below the unconstrained case.

The last row in Table 2 reports the shadow values on drainage disposal, l_d. These vary widely depending on the assumed conditions; however, the most realistic estimate at the present time would be that with reuse ($19/ac-ft). This would be the emission charge imposed by the regulator on deep percolation flows, and the payment to reuse and evaporation pond operators for extractions from the water table. For crop production, this would imply a payment of $23/ac-yr given average deep percolation flows of 1.21/ft-yr. This shadow value could also serve as an initial estimate to initialize grower planning under a permit market. Linking these results to the theory, and specifically equations (7) and (8) and Figure 1, we might expect that since reuse is the preferable disposal method the opportunity cost of land is low. These results are driven, in part, by the profits from using reuse water on cotton, a profitable alternative that lowers the opportunity cost of foregoing freshwater crops.

Conclusions

A variety of drainage disposal options are available for agricultural drainwater management in semi-closed basins; the broad categories include source control, reuse, and disposal in evaporation ponds or other means. The theoretical analysis demonstrates that the efficient choice of these options depends on a variety of parameter values and will undoubtedly vary from one locale to another. Furthermore, the choice of management strategies is interrelated and so, in principle, an integrated analysis as developed here is necessary.

Some level of source control is efficient since deep percolation flows generate disposal costs and/or environmental damages. Absent reuse, a very high level of source control is efficient due to the relatively high cost associated with evaporation ponds. This is accomplished largely through adoption of highly uniform/high-cost irrigation systems. With reuse allowed, the primary form of source control is reduction in land area devoted to freshwater production; the released land goes into reuse production.

Maintaining hydrologic balance, and hence sustainability, requires that deep percolation flows from production be reused or disposed of in an evaporation pond. The theoretical analysis demonstrates the trade-offs involved in choosing between these two strategies. Reuse may generate positive net returns per acre of production. Yet even if reuse production generates negative returns per acre, the costs per acre will typically be less than that of a pond. Additionally, the environmental implications are likely to be less costly with reuse. However, evaporation ponds are likely to generate more net drainage disposal per-acre than reuse thus making the opportunity cost of land in freshwater crop production a critical component driving the efficient choice of disposal. As equations (7) and (8) along with Figure 1 illustrated, when the opportunity cost of land is high, ponds have a comparative advantage relative to reuse. Alternatively, low opportunity costs favor reuse.

In the empirical analysis, reuse appears to be an extremely promising solution to the drainage problem. Maximizing regional net benefits while maintaining hydrologic balance seems best achieved with reuse and minimal source control thereby avoiding the expense and environmental implications associated with evaporation ponds. This strategy, though, requires a reduction in freshwater crop acreage for reuse production. Given the profitability of cotton as a reuse crop capable of enduring moderately high salt concentrations clearly reduces the opportunity costs of foregone freshwater crop production.

One facet of the empirical results that should be emphasized is that potentially large net returns can be achieved while maintaining overall hydrologic balance in the system with the reuse strategy. These are promising results that may help better inform growers within the region who are confronting ever-increasing costs of disposal and policy makers searching for more efficient solutions that are both sustainable and environmentally friendly. These conclusions, though, are conditioned in part on the existing salt concentration of the water table. Salt concentrations will likely vary between regions and evolve over time depending on the nature of the large-scale hydrologic regime. Furthermore, real-world outcomes will also depend on such elements as land quality, crop rotations, risk, grower knowledge, and a variety of other factors not considered here.

Whether agricultural production can be sustainable in a semi-closed basin while maintaining adequate levels of environmental quality is probably best answered with a dynamic analysis that is well beyond the scope of this study. The dynamics involve groundwater hydrology, including possible further increases in salt concentration, as well as possible buildup of human and physical capital, which might substitute in full or part for hydrologic degradation. The empirical analysis does suggest, though, that a high level of agricultural production may be possible for some period of time while still maintaining environmental quality.

From a policy perspective, the common property nature of the drainage problem in the SJV seems suitable for some sort of collective action. One possibility is a pricing scheme. Under this scheme, growers are charged for deep percolations flows to the water table, while reusers and pond operators are compensated for extractions from the water table. Setting the charge at the correct level will induce hydrologic balance; this also implies revenue-neutrality. For the empirical example considered here, the estimated drainage price was $19/af, a relatively modest amount. This shadow value was shown to be quite sensitive to the disposal options. Given the heavy reliance on reuse in the efficient solution, and the risk and uncertainties surrounding this strategy, it is likely that the true value is somewhat higher.

The other policy we briefly discussed was a marketable permit system. As in standard environmental economics, emissions to the water table need to be covered by a permit and the permits are freely tradable. A novelty of the scheme here, however, is that permit supply is generated endogenously by operators extracting from the water table. Equilibrium in this market implies hydrologic balance. Under competitive conditions in both the permit and land markets, an efficient equilibrium will exist in the market.

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Table 1. Price, Cost, and Production Data

Crop prices & harvest costs	***Cotton***	***Tomato***	***Lettuce***	***Wheat***	***Alfalfa***	***Bermuda -grass***
Output Prices ($/ton)[a]	*1489.7*	*55.2*	*596.5*	*133.3*	*109.3*	*75.2*
General harvest costs ($/ac)	*61.0*	*54.9*	*0.0*	*0.0*	*95.0*	*131.2*
Yield related costs ($/ton)	*0.04*	*12.7*	*232.6*	*29*	*13.3*	*15.0*
Revenue related costs	0.5	0.0	0.0	0.0	0.0	0.0
Irrigation System[b]	**Furrow 0.5**	**Furrow 0.25**	**Sprinkler**	**LEPA**	**Linear**	**Drip**
Christensen Uniformity Coefficient	70	75	80	85	90	90
Pressure head (ft)	10	10	150	50	80	50
Capital Recovery Costs ($/ac/yr)	21.9	28.8	42.7	81.7	81.8	178.1
O & M Costs ($/ac/yr)	2.9	3.8	20.0	38.3	38.4	60.0
Fixed energy costs ($/ac/yr)	1.0	1.0	1.5	1.0	1.2	1.0
Pressurization cost ($/ac-ft)	1.1	1.1	16.5	5.5	8.8	5.5
Nonwater production costs[c]						
Cotton ($/ac/yr)	607.8	628.1	678.5	683.1	680.3	744.9
Tomato ($/ac/yr)	636.8	661.2	718.8	704.9	701.5	751.2
Lettuce ($/ac/yr)	1652.1	1683.4	1729.6	1717.8	1700.5	1661.3
Wheat ($/ac/yr)	194.8	204.5	235.5	288.6	286.9	390.9
Alfalfa ($/ac/yr)	396.8	409.9	434.6	492.3	483.2	538.6
Bermudagrass ($/ac/yr)	507.1	541.6	609.8	557.3	548.8	627.2

[a] Average price per ton of cotton lint and tomatoes in Westlands Water District, California 1997-1999.

[b] University of California Committee of Consultants (1988), and Posnikoff and Knapp. All costs are in 1999 dollars. Capital recovery costs assume a 5% interest rate. Furrow and drip irrigation systems are assumed to have a 5 and 8 years life expectancy, respectively.

[c] Non-water production costs include costs associated with seed, land preparation, planting, machinery, fertilizer, etc. Opportunity cost of land and cash overhead is not included. Data come from University of California Cooperative Extension Crop Budgets for Cotton and Tomatoes (1999, 2000).

Table 2. Regional Drain Water Management: Economic Efficiency

	Historical	*No Reuse*		*Reuse*
		No CH	CH	
Crop Production				
Area (acres)	0.83	0.762	0.789	0.514
Furrow 0.5 miles (%)	95			90
Furrow 0.25 miles (%)		75	22	
Linear move sprinklers (%)		20	73	
Drip (%)	5	5	5	10
Surface water (ft/yr)	3.23	2.44	1.99	3.17
Deep percolations (ft/yr)	1.17	0.48	0.14	1.21
Reuse				
Area (acres)	0	0	0	0.32
Crop / Irrigation system				Cotton / F4[a]
				Wheat / F4
Ground water (ft/yr)				3.81
Deep percolations (ft/yr)				1.87
Land Disposal				
Evaporation pond (acres)	0	0.07	0.02	0
Compensation Habitat (acres)			0.02	
Region				
Social Net Benefits ($/yr)	311	258	196	294
Drainage shadow value ($/ac-ft)	0	80.68	393.86	18.69

[a] F4 = furrow 0.25 miles

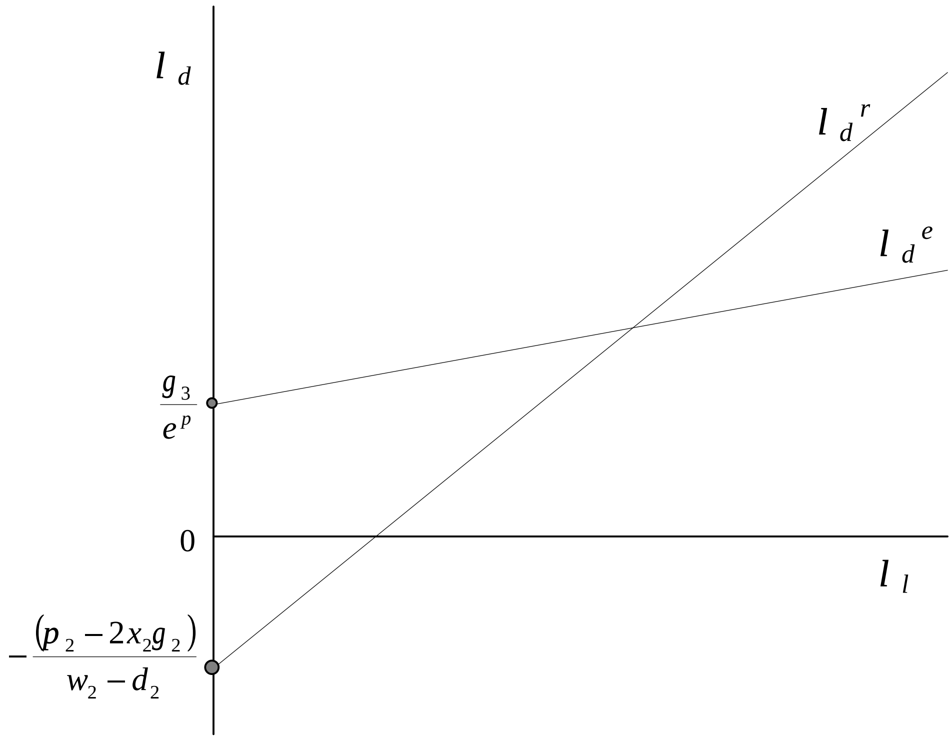

Figure 1 - Shadow value of drainage water as influenced by land value.

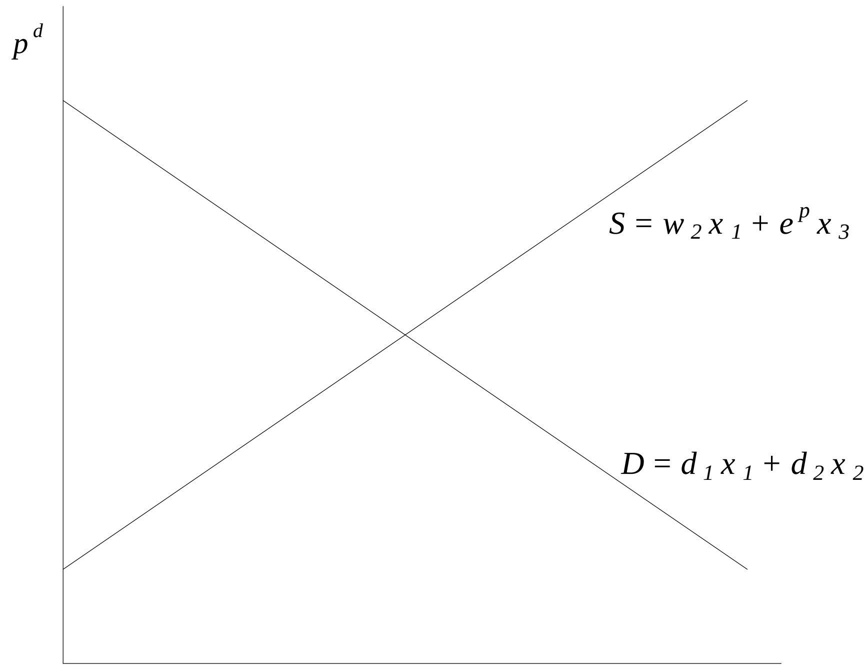

Figure 2- Drainage permit market with endogenous supply and demand.