DRAINWATER MANAGEMENT FOR SALINITY MITIGATION IN IRRIGATED AGRICULTURE

KURT A. SCHWABE, IDDO KAN, AND KEITH C. KNAPP

Salinity and drainage management options include source control, reuse, and evaporation ponds. This article identifies efficient strategies to maintain hydrologic balance in closed drainage basins and evaluates their impact on regional agricultural profits. Theoretical analysis suggests that economic efficiency requires acknowledgment of the nonseparability between water use and land value. Empirically, our solution involves a modest amount of source control, a substantial amount of reuse, and the elimination of evaporation ponds often associated with large environmental damages, while maintaining grower income. Various policy instruments and options are introduced and discussed, including a system of drainwater charges, marketable permits, and land retirement.

Key words: irrigated agriculture, integrated drainwater management, mathematical programming, salinity.

Approximately one-third of the 260 million hectares of irrigated land worldwide, land that provides 40% of the global food production, are affected by salinization and are in need of drainage (United Nations). Historically, ancient societies in the Americas, China, and the Middle East have all had substantial bouts of salinity and drainage problems, the outcomes of which have ranged from yield reductions to land abandonment (Howitt 2000). Presently, countries such as Australia, Egypt, India, Pakistan, and the United States, all of which have substantial salinity and drainage problems affecting between 15 and 36% of their irrigated lands, are devoting substantial resources toward this problem. Australia, for example, recently adopted a $700 million initiative to combat the threat of salinity and rising water tables on nearly 6 million hectares of irrigated land.[1] Pakistan, with nearly 2 million hectares of irrigated lands suffering from severe salinity problems, has allocated over $785 million toward waterlogging and salinity problems (Chaudry, 2002). As evidenced in table 1, this problem is endemic throughout the world.

A common denominator across these regions is that they are located in arid and semiarid areas where evapotranspiration (ET), which is the amount of water evaporated and transpired by plants, is greater than precipitation. Over time, continued irrigation with water imports salts that eventually accumulate in the soil, thereby hindering crop-yields. In response to this accumulation, and because of nonuniform irrigation, water is applied in excess of plant requirements, for leaching purposes. If the area sits above a relatively impermeable geologic strata or an underlying groundwater table, the deep percolation flows from these excess water applications can encroach upon the root zone, resulting in reduced aeration, salinization, and consequently, yield losses. A common remedy involves installing tile lines in fields and collector drains throughout the region, ultimately discharging the drainage into some water body outside the region. However, exporting drainage water can be problematic and prohibitive, if, through the process of transport, or in the ultimate disposal of these waters, human- or environment-related damages arise.[2] Under

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[1] In this plan, regional communities are expected to draw up and implement their own integrated management plans. New South Wales, for example, has 70–80% of the irrigated land threatened by rising water tables and the associated salinity problems and is considering management plans consisting of source control, evaporation basin, and the use of highly salt-tolerant crops.

[2] Irrigation with saline water, referred to as secondary salinization, exacerbates this problem. Ribaudo (2001) cites annual damages of approximately $120 million to irrigated agriculture

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such circumstances, drainage restrictions are often imposed.

In reaction to these environmental threats and to the possibility of a closed basin, various strategies for reducing the quality and quantity of external drainage have been considered. One strategy, source control, includes measures such as changing crop mix, installing more uniform irrigation systems, and varying irrigation timing to meet plants' needs more closely. This strategy has undergone considerable analysis and adoption (e.g., Dinar, Letey, and Knapp, 1985; Dinar, Hatchett, and Loehman, 1991). A second category of drainage control is the reuse of drainage water on salt-tolerant crops. This category, which provides both drainage disposal and water conservation services, has received extensive scientific research, and yet has undergone relatively little economic analysis (e.g., Yaron and Olian, 1973; Feinerman and Yaron, 1983). Irrigated agriculture in the Nile Delta, for instance, incorporates widespread reuse as a strategy to meet the surface water shortfalls, address high water tables, and limit saline drainage flows back to the Nile. Two additional strategies include evaporation ponds and land retirement. Evaporation ponds, which are common worldwide wherever restrictions exist on disposal into natural sinks, serve as an in-region disposal option (Johnston, Tanji, and Burns, 1997); land retirement reduces the total amount of drainage by taking land, preferably with poor-quality soils, out of production.

While combinations of these strategies have been or are currently being implemented in most irrigated agricultural regions in response to the salinity and drainage problem, efforts to identify efficient drainage strategies among the myriad of possible combinations pose a significant challenge. Integrated analyses, which are necessary to identify shadow values, efficient combinations of strategies, and effective policy instruments, are somewhat limited. An early study by Knapp, Dinar, and Letey (1986) considers source control and reuse with evaporation ponds, yet irrigation technology is exogenous. Hatchett, Horner, and Howitt (1991) include source-control methods and reuse, but do not consider in-region disposal options. Notably, the authors account for multiple subareas and treat both water table levels and salt concentrations in a dynamic framework; yet policy options are specified exogenously. Posnikoff and Knapp (1996) empirically evaluate source control, reuse with agroforestry, and ponds. While many of these studies provide an empirical evaluation of both *extensive* margin (i.e., land allocation across freshwater crop acreage and reuse water crop acreage) and *intensive* margin (i.e., applied water rates and irrigation efficiencies, given a fixed land allocation) decisions, a comprehensive theoretical evaluation including both is absent.

This article extends the above research by providing (1) the first theoretical evaluation of the salinity and drainage problem at both the extensive and the intensive margins, (2) an empirical evaluation of this problem at the regional level where efficient responses at both margins are identified under alternative drainage options, and (3) a discussion of various policy options and instruments. While previous theoretical analyses (e.g., Caswell, Lichtenberg, and Zilberman, 1990; Weinberg, Kling, and Wilen, 1993) identify the necessary conditions on the intensive margin that guide efficient applied water rates or irrigation intensities, our analysis identifies necessary conditions on the extensive margin that guide land allocation decisions. As gleaned from table 1, both *margins* of analysis are important to solving this problem. Decisions about efficient water use are shown to be nonseparable from the drainage mechanism in that the efficient solution requires a combination of source control and reuse. Unique differences between the efficiency criteria for fresh and reuse water applications are identified.

Empirically, a programming model of regional agricultural production is developed to evaluate how changes in drainage options influence the efficient solution. After identifying a baseline solution with no drainage restrictions on deep percolation flows, a drainage restriction is imposed such that hydrologic balance is maintained. Efficient responses with and without the opportunity to engage in reuse are examined. The model allows for responses across three land-use sectors—surface water crop production, reuse crop production, and drainage disposal to an evaporation pond—and within the two production sectors via changes in crop types, irrigation strategy, and water application rates. The focus is on irrigated agriculture in the San Joaquin Valley (SJV), California, where out-of-region drainage services were terminated in the mid 1980s after the agricultural drainage of this region was linked to environmental damages.

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from secondary salinization, using Colorado River water. Approximately 37% of the measured salt concentrations in the Colorado River are from runoff from irrigation in the Upper Colorado Basin (Gardner and Young, 1988).

Table 1. Salinity- and Drainage-Affected Regions Worldwide

	Irrigated Acreage			Current Disposal Options		
Region	Total (Hectares)	% Affected by Salinity or Waterlogging	Drainage, Environmental, and Additional Irrigation Issues	Reuse	Evap. Ponds/ Basins	Other Management Options Considered
Murray–Darling River Basin[a]	2.1 million	70–80	Rising salinity levels in rivers and tributaries from agricultural drainage and shallow saline water table.	Yes	Yes	Land retirement; agroforestry; irrigation upgrades
Aral Sea Basin[b]	7.9 million	50	Aral Sea drying up because of increasing water use by agriculture. River water quality decreasing because of drainage discharge. Water shortages. Evaporation basin at capacity.	Yes	Yes	Land retirement; decrease cotton/increase rice production; irrigation canal upgrades
Nile Delta[c]	3 million	33	Saline drainage waters threatening fisheries in Northern Lakes. Water resources under severe stress. Projected water demand by 2025 cannot be met by new water source projections. Plan to increase reuse of agricultural drainage water from 4,400 million m^3 to 8,000 million m^3.	Yes	No	Revegetation with salt-tolerant crops; irrigation and drain upgrades
Indus Plain[d]	15.8 million	25	Pumping of groundwater may lead to seawater intrusion. Seepage from evaporation ponds affecting adjacent lands. Low water allowances for irrigation.	Yes	Yes	Irrigation canal upgrades; well additions; conjunctive use; source control; groundwater pumping
United States[e]	24 million		Increasing salinity in rivers due to seepage and return flows from irrigated agriculture (e.g., Pecos River, Arkansas River, Rio Grande, Yakima River, Snake River). Rising salinity levels in Colorado River and drainage disposal sites (e.g., Salton Sea), which threaten ecosystem health and wildlife.	Regional		Source control; reuse; conjunctive use
Great Basin	997,000	58		Yes	No	
Rio Grande	782,000	75		Yes	No	
Upper Colorado	651,000	41		Yes	No	
Lower Colorado	616,000	66		Yes	Yes	

[a] Focus is on regions in New South Wales, Australia (Tanji and Kielen, 2002).

[b] Focus is on regions in Uzbekistan and Kazakhstan (Tanji and Kielen, 2002; Ghassemi, Jakeman, and Nix, 1995).

[c] Focus is on Egypt (Tanji and Kielen, 2002; Ghassemi, Jakeman, and Nix, 1995).

[d] Focus is on Pakistan (Tanji and Kielen, 2002; Ghassemi, Jakeman, and Nix, 1995).

[e] Include only regions with considerable salinity/drainage problems (Postel, 1999; Tanji and Kielen, 2002).

Elements of this application, many of which are common to irrigated agriculture worldwide, provide a unique opportunity to investigate how integrated drainwater management can be used efficiently. Results show that agricultural production in a closed basin can be profitable, and yet highly dependent upon a combination of source control and reuse strategies. Furthermore, efficient responses at the intensive margin are largely dependent on the disposal mechanism.

The attractiveness of reuse as part of an efficient solution depends largely on its relative profitability versus the other alternatives; this profitability, in turn, is likely influenced by a wide variety of factors, both economic and biophysical. To better understand the ability of reuse to be a part of an efficient strategy, sensitivity analysis is performed on the price of the reuse crop and the salinity of the reuse water. Results indicate that reuse can play a critical role as part of an efficient drainage strategy. The common property nature of the drainage problem, though, suggests the need for collective action if efficiency is to be achieved. Various policy instruments such as a system of drainwater charges or marketable permits are introduced and discussed. The economic attractiveness of land retirement is also considered.

Agricultural Production in Closed Drainage Basins: Theoretical Framework

Consider a region with irrigated agricultural production, overlying a shallow, saline water table and no external drainage facilities. There are three distinct sectors in the model: freshwater crop production, reuse crop production from the saline groundwater source, and drainage disposal via evaporation ponds. Decision variables within the first two sectors include applied water rates and areas devoted to crop type and irrigation system; evaporation pond area is the decision variable in the third sector. These variables are chosen to maximize basin annual net benefits.

Table 2 lists two approaches to representing this problem mathematically. For tractability purposes, our theoretical evaluation employs the more simplified model consisting of a single crop and irrigation system for both production sectors. This framework allows us to evaluate decisions regarding water use for two sectors at the intensive margin, and land use for all three sectors at the extensive margin, the latter being somewhat novel to the irrigated agricultural economics literature. Characteristics of the efficient solution for alternative land-use choices and water application rates are identified (in this section), along with the efficient responses

Table 2. Theoretical and Empirical Modeling Framework

Category	Stylized Framework (Theoretical Analysis)	General Framework (Empirical Analysis)
Regional net benefits to land and management[a]	$\pi = \pi_1 x_1 - \pi_2 x_2 - \psi_2 x_2^2 - \eta_3 x_3$	$\pi = \sum_{i=1}^{2} \sum_{j=1}^{n_{ic}} \sum_{k=1}^{n_s} \pi_{ijk} x_{ijk} - \psi_1 x_1^T - \psi_2 x_2^T - \eta_3 x_3$ where $x_i^T = \sum_{j=1}^{n_{ic}} \sum_{k=1}^{n_s} x_{ijk}$
Profits/acre	$\pi_i = \left(p^c y_i - \eta - p_i^w w_i\right)$	$\pi_{ijk} = \left(p_j^c y_{ijk} - \eta_{jk} - p_i^w w_{ijk}\right)$
Land constraint[b]	$\sum_{i=1}^{2} x_i + x_3 \leq 1$	$\sum_{i=1}^{2} \sum_{j=1}^{n_{ic}} \sum_{k=1}^{n_s} x_{ijk} + x_3 \leq 1$
Hydrologic balance constraint	$d_1 x_1 \leq (w_2 - d_2) x_2 + e_3 x_3$	$\sum_{j=1}^{n_{2c}} \sum_{k=1}^{n_s} d_{1jk} x_{1jk} \leq \sum_{j=1}^{n_{2c}} \sum_{k=1}^{n_s} (w_{2jk} - d_{2jk}) x_{2jk} + e_3 x_3$
Deep percolation flows[c]	$d_i = g_i(w_i)$	$d_{ijk} = w_{ijk} - et_{ijk}$
Domain	$i = \{1, 2\}; n_{ic} = 1, n_s = 1$	$i = \{1, 2\}, j = \{1, n_{ic}\}, k = \{1, n_s\}$ where $n_{1c} = 5, n_{2c} = 6, n_s = 6$

Note: *i* stands for production sector; *j* stands for crop type; *k* stands for irrigation strategy.

[a] Ψ_i stands for calibration parameters.

[b] Upper and lower bounds are imposed on $x_j^T = \sum_{i=1}^{2} \sum_{k=1}^{ns} x_{ijk}$ based on historic crop acreage data.

[c] et_{ijk} stands for evapotranspiration for crop *j* using irrigation strategy *k* in sector *i*.

to changes in economic and biophysical parameters (in a latter section). These responses will be evaluated quantitatively with the more general, detailed model using a regional agricultural production model. Together, these models allow us to understand the problem from the dual vantage point of theory and empirics while avoiding the downsides of each.

The efficient solution to this regional drainage problem can be derived by maximizing regional net benefits subject to a variety of resource constraints. Mathematically, we maximize

$$(1)\qquad \pi = \sum_{i=1}^{2} \pi_i x_i - \psi_2 x_2^2 - \eta_3 x_3$$

where $\pi_i = (p^c y_i - \eta_i - p_i^w w_i)$, w_i is applied water depth, x_i is land area devoted to crop production, and y_i is crop-yield, where indices $i = \{1, 2\}$ represent freshwater and reuse crop production sectors, respectively, for a single crop and irrigation system. Applied water in the freshwater crop production sector (w_1) comes from a surface water source; water in the reuse sector (w_2) comes from a saline groundwater source. The variable x_3 is the area devoted to evaporation ponds. Parameters are p^c for crop price, p_1^w and p_2^w for fresh and saline water prices respectively, η_i for nonwater production costs, and η_3 for evaporation pond costs.

The expression $\psi_2 x_2^2$ reflects other costs associated with reuse crop production, including additional production costs, land quality effects, or risk and uncertainty associated with this less common production system. Following Howitt (1995), it is assumed that these costs are quadratic in acreage. Crop-yield and deep percolation flows for freshwater crops (d_1) and reuse crops (d_2) are defined as functions of applied water depths and specified as continuous functions with $y_i = f_i(w_i)$ and $d_i = g_i(w_i)$, where $f_i' > 0, f_i'' < 0, g_i' > 0$, and $g_i'' > 0$.

Land and hydrologic balance constraints are

$$(2)\qquad \sum_{i=1}^{2} x_i + x_3 \leq 1$$

$$(3)\qquad d_1 x_1 \leq (w_2 - d_2) x_2 + e_3 x_3$$

where a unit regional area is assumed for convenience. The hydrologic balance constraint implies that deep percolation flows below the root zone must be less than disposals via reuse or evaporation, represented by e_3, in the pond. Equation (3) thereby ensures that the water table level is conducive to crop production.

Efficiency at the Extensive and Intensive Margins

Using the theoretical model and its associated constraints (table 2), the first-order conditions for profit maximization with respect to x_1, x_2, and x_3 are

$$(4)\qquad \pi_1 \leq d_1 \lambda_d + \lambda_l$$

$$(5)\qquad \pi_2 - 2\psi_2 x_2 + \lambda_d w_2 \leq \lambda_d d_2 + \lambda_l$$

$$(6)\qquad \lambda_d \leq (\eta_3 + \lambda_l)/e_3$$

where λ_l and λ_d are the Lagrange multipliers associated with the land and drainage constraints. With positive shadow values, cropland allocation is carried out to the point where the marginal net benefit of agricultural production equals the resource cost. With reuse, drainage disposal services are part of the marginal benefits of production, implying that crop net returns can be negative even with positive reuse areas. For evaporation ponds, land is allocated to the point where the marginal disposal benefit equals the marginal cost, which consists of both land opportunity costs and evaporation pond costs.

Similarly, profit maximization with respect to w_1 and w_2 yields

$$(7)\qquad p^c f_1'(w_1) = p_1^w + \lambda_d g_1'(w_1)$$

$$(8)\qquad p^c f_2'(w_2) + \lambda_d = p_2^w + \lambda_d g_2'(w_2)$$

as the respective first-order conditions. Drainage-constrained regions imply positive drainage shadow values that suggest reduced water applications in crop production, relative to the unconstrained case. In the reuse sector, positive drainage shadow values will increase water applications, since reuse reduces the amount of deep percolation flows requiring disposal.[3] Hence, from a policy perspective, an optimal charge set equal to the shadow value of drainage would decrease freshwater applications and increase reuse water applications. Such a charge might be effective in a

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[3] Provided crop evapotranspiration is increasing in w, and $g_2' < 1$, two reasonable assumptions. Mass balance requires that plant evapotranspiration cannot be greater than applied water under steady-state conditions.

country such as Egypt, which intends to nearly double the amount of reuse water to combat freshwater scarcity and drainage-related damages to fish populations (table 1).

In some areas of the world, parts of the SJV, California, for instance, reuse is not used in any appreciable manner.[4] Growers often install evaporation ponds and engage in more water-conserving irrigation strategies. Assuming reuse is not feasible, a necessary condition for $x_1^* > 0$ is the existence of some level of water application such that net return per unit of deep percolation flow, π_1/d_1, is greater than or equal to the per unit *explicit* drainage disposal cost, η_3/e_3. The ability of source control (other than changing cropped area) to contribute to the efficient solution can be illustrated by substituting the shadow values on land and drainage from equations (4) and (6) into the water application first-order condition (equation (7)), giving

$$(9) \qquad p^c f_1'(w_1) = p_1^w + \frac{(\pi_1 + \eta_3)}{(e_3 + d_1)} g_1'(w_1).$$

In contrast to the usual first-order conditions for water use, this condition includes average per acre profits and pond construction costs. The benefits of applying more water is balanced against both the costs of surface water, p_1^w, and the opportunity costs of additional evaporation pond acreage, which consist of the foregone profits from the freshwater crop from a shift in acreage toward evaporation ponds as well as the direct costs of the pond itself.

Increasingly, though, reuse is being considered as a means of disposal. When reuse is a viable option, a necessary condition for $x_1^* > 0$ is a water application level satisfying

$$(10) \qquad \pi_1 \geq d_1 \,\mathrm{Min}\left[\frac{\eta_3}{e_3}, \frac{-\pi_2}{(w_2 - d_2)}\right]$$

where the second term within the brackets represents explicit drainage costs (i.e., no land opportunity costs) per unit area evaluated at a reuse area of zero.

Should one use evaporation ponds, reuse, or both in closed drainage basin management? Consider the first-order conditions involving reuse acreage:

$$(11) \qquad \lambda_d \leq \frac{-(\pi_2 - 2\psi_2 x_2) + \lambda_l}{w_2 - d_2}$$

where $w_2 - d_2$ is evapotranspiration associated with reuse. Equations (6) and (11) suggest that the shadow price on drainage (i.e., the opportunity cost of drainage) depends on the shadow value of land, λ_l, which is measured by the profit from an additional acreage of freshwater crop production. Whether reuse is more costly than ponds depends partly on the relative rate of disposal between reuse, $w_2 - d_2$, and ponds, e_3. Consider a scenario where reuse disposes of less water per unit area than ponds (i.e., $w_2 - d_2 < e_3$), a likely outcome in semiarid and arid regions. As figure 1 illustrates, reuse becomes relatively less costly compared to ponds for low land values and relatively more costly for high land values, since the slope of λ_d^r, the shadow value on drainage under reuse, is greater than λ_d^p, the shadow value under ponds. If $w_2 - d_2 > e_3$, the results are reversed. Thus, the choice of disposal method depends, in part, on the profitability of freshwater crop production and on the relative cost per acre of each strategy (i.e., $\pi_2 - 2\psi_2 x_2$ versus η_3). The more (less) profitable the reuse crop, the higher (lower) the intercept of λ_d^r relative to λ_d^p, thereby increasing (decreasing) the attractiveness of reuse, relative to ponds.

More explicitly, necessary conditions for $x_2^* > 0$ and $x_3^* > 0$ require, respectively

$$(12) \qquad \frac{-\pi_2}{w_2 - d_2} < \frac{\eta_3}{e_3}$$

$$(13) \qquad \frac{\eta_3 + \pi_1}{e_3 + d_1} \leq \frac{\pi_1 - (\pi_2 - 2\psi_2)}{d_1 + w_2 - d_2}$$

for positive crop production. The first condition compares the marginal costs of drainage

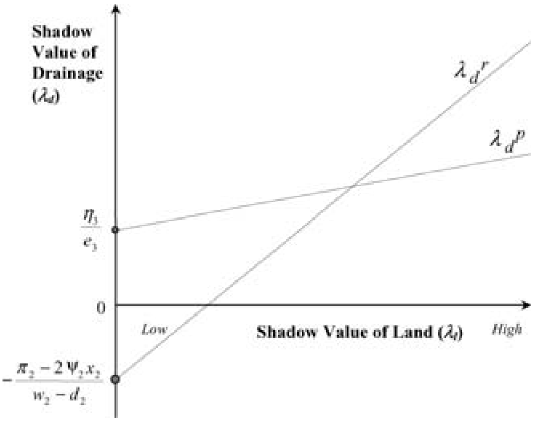

Figure 1. Shadow value of drainage water under reuse, *r*, and ponds, *p*, as influenced by land value

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[4] Reasons might include lack of technological knowledge or that prices do not accurately reflect resource scarcity.

disposal for reuse, at zero area, and evaporation ponds. Recalling the quadratic term in equation (1) (i.e., the marginal disposal costs of reuse increase as x_2 increases), for reuse to occur at all it is required that its costs at a zero area be less than the costs of the evaporation pond.

The interpretation of equation (13) is more involved. Suppose that reuse is disposing of all drainage and consider a small decrement in reuse area. The land and drainage constraints determine how the released land is split between freshwater crops and the evaporation pond, given the likely condition $w_2 - d_2 < e_3$. The marginal benefit is the profit from additional crop production in the freshwater sector; the marginal cost is lost reuse profits plus pond costs. Similar to figure 1, these comparisons suggest that ponds are more likely to be used if either their explicit costs are low, or freshwater crop profits are sufficiently high relative to reuse profits.

Empirical Focus: Application and Data

Our empirical focus is on agricultural practices in the SJV, with particular attention toward the 570,000 acres of irrigable farmland comprising the Westlands Water District [WWD] (2002). WWD has no natural drainage outlet, and many of the region's soils have very low permeability and high salinity. The amalgamation of these physical and chemical characteristics, coupled with increased reliance on surface water irrigation that is used partly to leach salts out of the root zone, results in a rising water table that threatens agricultural productivity throughout the region. While a drainage system was built in the early 1970s to export drainage out of the region, out-of-region environmental damages from the drainage forced its closure. Currently, the region is operating as a closed basin. Consequently, the amount of acreage having a shallow groundwater depth more than doubled between 1985 and 1998.

Growers responded to the cessation of drainage services by implementing various source-control strategies such as more uniform irrigation. Evaporation ponds were also built, requiring a fraction of land to be set aside for disposal alone. These evaporation ponds, though, became an attractive nuisance for avian species in search of sparse wetlands-like habitat. To mitigate these impacts on wildlife, mandates requiring the evaporation pond operators to provide alternative (*freshwater*) compensation habitat at a 1:1 ratio with evaporation pond acreage were enacted.

To evaluate the impacts of drainage restrictions on regional agricultural net benefits, as well as the ability of growers to respond to changes in critical economic and biophysical factors, a regional agricultural production model was developed that includes the major crops and irrigation systems found in the SJV. Choice variables, as identified in table 2 (General Framework), include freshwater and reuse crop production and irrigation system acreage, evaporation pond acreage, and applied water rates for both production sectors. Crops, available to both production sectors and accounting for over 80% of the region's cropped acreage, include cotton, tomatoes, lettuce, wheat, and alfalfa. Bermuda grass is considered for reuse only. Six possible irrigation systems are considered, including furrow on a $^1/_2$ mile run (FUR2), furrow on a $^1/_4$ mile run (FUR4), low-energy pressure application (LEPA), sprinkler, linear move (Linear), and drip irrigation. Neither LEPA nor sprinklers were chosen in any of our simulations.

Table 3 presents parameter and price information. Market prices for each cropping system are derived from county agricultural commissioner crop reports. Surface water costs are a weighted average of water prices in WWD (WWD, 2002). Salinity concentrations for both surface water sources and groundwater sources, measured in deci-Siemens per meter (dS/m), reflect actual salt concentrations in the region (Tanji and Karajeh, 1993). Nonwater production costs include costs for factors such as planting, land preparation, weed cultivation, fertilizer, and tile and drainage systems costs. Harvest costs include both a fixed per acre component and a yield-related variable component. Constraints are imposed to maintain acreages of individual crops within historical ranges observed during the 1990s. Annual pond construction and maintenance cost is \$117.40 per acre with an evaporation rate of 5.32 feet per year (Posnikoff and Knapp 1996). Annual compensating habitat (CH) cost is \$1,504 per acre.[5]

The crop-water production functions that describe the relationship between yield, evapotranspiration, salinity, and applied water are fully described in Kan, Schwabe, and Knapp, (1998).[6] These functions were developed for

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[5] Use of evaporation ponds requires compensating habitat, so they are lumped together.

[6] For an example of how increases in salinity affect evapotranspiration, and hence yield, see figure 1 in Kan, Schwabe, and Knapp

Table 3. Annual Price, Cost, and Production Data

Prices and Harvest Costs[a]	Cotton	Tomatoes	Lettuce	Wheat	Alfalfa	Bermuda
Output prices ($/ton)	1,489.7	55.2	596.5	133.3	109.3	75.2
Yield-related costs ($/ton)	12	11.95	232.6	29	13.3	15.0
Revenue-related costs	0.005	0.0	0.0	0.0	0.0	0.0
Irrigation system[b]	FUR2	FUR4	Sprinkler	LEPA	Linear	Drip
CUC	70	75	80	85	90	90
Pressure head (ft)	10	10	150	50	80	50
Capital recovery cost($/acre)	21.9	28.8	42.7	81.7	81.8	178.1
O & M costs ($/acre/year)	2.9	3.8	20.0	38.3	38.4	60.0
Fixed energy costs ($/acre)	1.0	1.0	1.5	1.0	1.2	1.0
Pressurization cost ($/af)	1.1	1.1	16.5	5.5	8.8	5.5
Production costs[c]	FUR2	FUR4	Sprinkler	LEPA	Linear	Drip
Cotton ($/acre)	668.8	689.1	739.5	744.1	741.3	805.9
Tomatoes ($/acre)	691.7	716.1	773.7	759.8	756.4	806.1
Lettuce ($/acre)	1,652.1	1,683.4	1,729.6	1,717.8	1,700.5	1,661.3
Wheat ($/acre)	204.8	214.5	245.5	298.6	296.9	400.9
Alfalfa ($/acre)	491.8	504.9	529.6	587.3	578.2	633.6
Bermuda grass ($/acre/year)	638.3	672.8	741.0	688.5	680.0	758.4

[a] Price and cost data are as per 1999 dollar rates. Capital recovery costs assume a 5% interest rate. Output prices are average price per ton in WWD, California, 1997–99. Cost data from UC Cooperative Extension crop budgets with adjustment for inflation and irrigation system type.

[b] Irrigation system data are generally from Posnikoff and Knapp (1997) with adjustment for inflation. FUR2 $\sim$ furrow with $^{1}/_{2}$ mile runs; FUR4 $\sim$ furrow with $^{1}/_{4}$ mile runs; LEPA $\sim$ Low-energy precision appication; Linear $\sim$ linear move; CUC $\sim$ Christensen uniformity coefficient (a measure of the uniformity of water application for an irrigation system, with larger numbers implying greater uniformity).

[c] Production costs include all production costs (seed, land preparation, machinery, fertilizer, harvest, etc.) except water, irrigation system, land, and cash overhead.

each crop-irrigation system, based on plant growth models developed in Letey, Dinar, and Knapp (1985), and evapotranspiration functions based on van Genuchten and Hoffman (1984), and van Genuchten (1987).[7] As these studies show, for a given level of applied water, increases in salinity lead to yield deficits. Finally, deep percolation flows equal applied water rates less evapotranspiration.

The constrained maximization problem is solved using a nonlinear optimization procedure from the GAMS/CONOPT solver system. Since it is not possible to capture all production factors and costs in computational models, several calibrations were performed so that the baseline solution under a no-drainage-restriction scenario would replicate historic conditions in terms of net returns to land and management and reuse acreage. In particular, additional costs ($31.50/acre) were added to reuse production so that the solution mimics observed historic conditions of no reuse. These costs capture effects such as specific-ion-related damages, or the risk and uncertainty associated with a new technology not explicitly modeled. To replicate historic returns to land and management, $296/acre was added to all production costs.

Results and Analysis

Efficient Drainage Management under Alternative Drainage Options

Column A in table 4, External Drains, presents the results for the baseline solution—net benefits are maximized subject to a land constraint but no drainage constraint. Traditional irrigation systems (FUR2) are selected, no land is allocated to reuse or evaporation ponds, and deep percolation flows average slightly over 1 ft/year, which is consistent with historical averages for regional deep percolation flows (Tanji and Karajeh, 1993). This solution replicates the drainage situation in WWD prior to 1985 when there were essentially no constraints on drainage disposal.

Columns B and C of table 4 illustrate the impacts of the drainage restriction under different drainage mechanisms. Column B, Evaporation Ponds Only, restricts disposal to evaporation ponds alone ($x_2 = 0$), similar to the situation observed in WWD post-1985 after the out-of-region disposal services

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(2002, p. 22). For a given level of applied water, increases in salinity decrease evapotranspiration and, hence, yield.

[7] Each crop-irrigation system production function relates yield to evapotranspiration, where evapotranspiration is a function of applied water and salinity concentration. The difference between the freshwater and reuse water production functions arises due to the salinity concentration parameter. All model details are available upon request.

Table 4. Drainwater Management under Alternative Drainage Scenarios

	A External Drains[a]	*B* Evaporation Ponds Only ($x_{2jk} = 0$)	*C* Reuse Allowed ($x_{2jk}, x_3 \geq 0$)
Freshwater Crop Production			
Area (acres of x_1^T)	0.83	0.75	0.51
Cotton (% of x_1^T)	58	53	37
Tomatoes (% of x_1^T)	24	27	39
Wheat (% of x_1^T)	4	4	–
Lettuce (% of x_1^T)	6	7	10
Alfalfa (% of x_1^T)	8	9	14
Water (acre-ft/acre/year)[b]			
Water use	3.28	2.05	3.18
Deep percolation	1.23	0.19	1.21
Irrigation[c]			
FUR2 (% of x_1^T)	94	–	90
FUR4 (% of x_1^T)	–	13	–
Linear (% of x_1^T)	–	80	–
Drip (% of x_1^T)	6	7	10
Reuse Production			
Area (acres of x_2^T)	–	–	0.32
Cotton (% of x_2^T)	–	–	91
Wheat (% of x_2^T)	–	–	9
Water(acre-ft/acre/year)[b]			
Water use	–	–	3.85
Deep percolation	–	–	1.89
Irrigation[c]			
FUR4 (% of x_2^T)	–	–	100
Land Disposal (*Acres*)			
Evaporation pond (x_3)	–	0.06	–
Welfare Measures			
Net benefits (in \$) $\sim \pi$	311	206	295
Drainage shadow value $\sim \lambda_d$ (\$/acre-ft)	–	305	19

Note: Land areas and social net benefits are per regional acre, with 17% of land devoted to trees and fallowing.

[a] External drains ~ no hydrologic balance constraint.

[b] Water variables are average depths over the cropped areas per acre in each respective sector.

[c] FUR2 and FUR4 are, respectively, irrigation with furrow 1/2 mile runs and irrigation with 1/4 mile runs.

were ceased. Growers responded with various forms of source control and the establishment of evaporation ponds; reuse was not practiced. As shown, the efficient solution to the drainage restriction entails construction of evaporation ponds and a substantial level of source control, including increasing irrigation efficiency by switching 80% of the irrigated acreage out of FUR2, and reducing applied water rates nearly 38%. Combined, these strategies reduce average deep percolation flows by approximately 85%. Since total cropped areas decrease by 6% to accommodate evaporation ponds, net benefits decline by 34% to \$206/acre.

Column C, alternatively, allows the model to allocate acreage to either evaporation ponds or reuse production, or to both, as a means of meeting the drainage restriction. The results suggest that reuse offers great promise in maintaining regional agricultural production and hydrologic balance. Net benefits decrease by only 5%, relative to the external drainage scenario, by devoting a substantial portion of freshwater cropland to reuse production, mostly in cotton. Cotton as a reuse crop is practical, since it is moderately salt tolerant (Maas and Hoffman, 1977) and, given the current groundwater salinity concentration, somewhat profitable. Note that with the reuse option, no acreage is allocated to evaporation ponds. Compared to the external drainage solution, reuse opportunities require little source control. There is a 4% reduction in irrigated acreage using the less uniform system (FUR2), and applied freshwater rates per acre decrease by a mere 3%. While total water applications across both production sectors, $\sum_{i=1}^{2} x_i w_i$, increase relative to the baseline scenario, total *freshwater* applications decrease.

What lessons can be learned by comparisons of columns B and C? First, the importance of both extensive and intensive margin responses is highlighted. Efficient responses entail crop switching, increases in irrigation efficiency, reductions in applied water use, and a shift in acreage toward the disposal sector that has the lowest shadow value of drainage (i.e., last row of table 4). The results also emphasize that the efficient level of water use or irrigation efficiency is nonseparable with the drainage disposal option. As highlighted in equation (7), the nonseparability arises through the shadow value of drainage, which depends on the shadow value of land. Hence, the benefits of additional freshwater applications must be balanced against the price of the water and the opportunity cost of transferring land out of freshwater production for disposal purposes. In our specific application, the opportunity costs of transferring land out of the freshwater sector and into the reuse sector is very low, given the profitability of the reuse sector crop—cotton. Yet, as shown in column B, if evaporation ponds are the only disposal strategy, the opportunity cost of disposing of additional water is the foregone profits on the transferred land. Finally, recalling figure 1, the results in table 4 show that the slope of λ_{d}^{r} is much steeper, and the intercept much lower, than those of λ_{d}^{p}.[8]

Reuse, Cotton Prices, and Efficiency

As shown above, net benefits are maximized when all disposal acreage is transferred to the reuse sector. There are many reasons to expect that reuse will become more attractive throughout the world, as is happening in Egypt and the Nile Delta, either because of its role as a substitute for increasingly scarce surface water supplies, or because of the lack of and temporary nature of evaporation basins and their potential for environmental damages. Hence, an understanding of how solutions that include reuse are impacted by changes in critical economic factors in the reuse sector would seem useful for policy design. In the WWD, for instance, there has been a downward trend in *upland* cotton prices by nearly 50% over the past eight years. While cotton acreage is slowly being allocated toward *pima* cotton, whose price is substantially higher and not trending downward, *upland* cotton still comprises over 70% of cropped cotton acreage.

For analytical evaluation, consider the theoretical model with reuse only (i.e., $x_3 = 0$), and take as given water applications in the reuse sector. This leaves source control as the driving variable after substituting for the land variables from the land and drainage constraints. In an unconstrained setting, higher output prices encourage additional water use as one moves further out along the production function. Higher cotton prices also increase profits in the reuse sector, in effect reducing *net* drainage costs and again, positively influencing water application rates. However, higher cotton prices imply higher land opportunity costs and, hence, higher drainage prices. These latter results tend to have a contrary effect on water depths and source control.

Because the second effect reinforces the first, we make the further simplification of fixing explicit net returns in reuse. With the land and drainage constraints holding with equality, land areas x_1 and x_2 can be rewritten as functions of w_1. Rewriting equation (1) in terms of w_1, differentiating with respect to w_1 yields the respective first-order condition. Totally differentiating this equation and rearranging yields the following:

$$(14) \quad \operatorname{sign}\left[\frac{\partial w_1}{\partial p^c}\right] \equiv \operatorname{sign}[(d_1 + w_2 - d_2) f_1'(w_1) - y_1 g_1'(w_1)].$$

The first multiplicative term on the right-hand side is the marginal productivity effect and is positive; the second term reflects the land opportunity cost effect and is negative. This is suggestive—but does not prove—that source-control sensitivity to cotton prices could have an ambiguous sign, depending on parameter values. A situation characterized by a low marginal product of water and a high marginal drainage product of water, perhaps arising from a large application volume, would likely give rise to a negative relationship between crop price and applied water rates.[9] This is a greatly simplified example, and

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[8] Note that the slope of λ_{d}^{p} is 1/5.32, while the slope of λ_{d}^{r} is 1/1.96.

[9] Numerical experimentation yielded examples of both positive and negative responses. The land opportunity cost effect can be sufficiently strong so as to outweigh the productivity effect so that declining cotton prices could actually increase applied water in the crop production sector.

Table 5. Sensitivity Analysis: Reuse and Changes in Cotton Prices

	Cotton Price ($/ton)			
	$P^C = \$1{,}560$		$P^C = \$1{,}140$	
	A External Drains[a]	*B* No External Drains	*C* External Drains	*D* No External Drains
Freshwater Crop Production				
Area (acres of x_1^T)	0.83	0.51	0.75	0.45
Cotton (% of x_1^T)	58	37	53	29
Tomatoes (% of x_1^T)	24	39	27	44
Wheat (% of x_1^T)	4	–	4	–
Lettuce (% of x_1^T)	6	10	7	11
Alfalfa (% of x_1^T)	8	14	9	16
Water (acre-ft/acre/year)[b]				
Water use	3.30	3.17	3.2	3.21
Deep percolation	1.24	1.2	1.18	1.27
Irrigation[c]				
FUR2 (% of x_1^T)	94	90	93	89
Drip (% of x_1^T)	6	10	7	11
Reuse Production				
Area (acres of x_2^T)	–	0.32	–	0.3
Cotton (% of x_2^T)	–	91	–	90
Wheat (% of x_2^T)	–	9	–	10
Water (acre-ft/acre/year)[b]				
Water use	–	3.86	–	3.85
Deep percolation	–	1.9	–	1.93
Irrigation[c]				
FUR2 (% of x_2^T)	–	9	–	100
FUR4 (% of x_2^T)	–	91	–	–
Land Disposal (Acres)				
Evaporation pond (x_3)	–	–	–	–
Welfare Measures				
Net benefits (in $) $\sim \pi$	334	317	216	204
Drainage shadow value $\sim \lambda_d$ ($/acre-ft)	–	19	–	15

Note: Land areas and social net benefits are per regional acre, with 17% of land devoted to trees and fallowing.

[a] External drains ~ no hydrologic balance constraint.

[b] Water variables are average depths over the cropped areas per acre in each respective sector.

[c] FUR2 and FUR4 are, respectively, irrigation with furrow 1/2 mile runs and irrigation with 1/4 mile runs.

a more complex adaptation is presented below. The central point, though, is that general equilibrium effects operating through land and drainage markets can yield results counter to those typically obtained in a partial equilibrium setting.

Table 5 presents results for the highest (columns A and B) and lowest (columns C and D) annual cotton price spanning the 1997 to 2001 seasons (California Agricultural Statistics, 2002).[10] In columns A and C, net benefits are maximized without maintaining hydrologic balance, whereas in columns B and D hydrologic balance is maintained. As illustrated, regardless of the drainage scenario, a reduction in cotton prices results in a nearly 36% decrease in profits. This is likely an upper bound on losses, given the bounds we imposed on individual crop acreage.

The effects on drainage management from this price change, however, are quite limited. In the absence of any drainage restrictions, the qualitative impacts of lower cotton prices are a reduction in crop production and a slight

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[10] The prices are calculated by using a weighted average of *pima* and *upland* cotton prices on the basis of their respective acreage as a percentage of the total harvested. The highest price is associated with the 1997 harvest year, while the lowest price is associated with the 2001 harvest year. Cotton is the most likely crop for reuse because, unlike tomatoes, it does not involve human digestion. Reuse water is often laden with salts and toxic trace elements and thus is less likely to be used on food crops.

decrease in applied water rates. Alternatively, when drainage is constrained, a lower price leads to a reduction in freshwater crop acreage (mostly cotton), a slight increase in applied water rates, and a shift to a less efficient irrigation strategy in the reuse sector. Notice that the level of applied freshwater ($w_i x_i$) decreases with the price reduction—an outcome highlighting the importance of accounting for changes at both the intensive and extensive margins.

Under either price scenario, though, the efficient management response to the drainage constraint is reuse, not evaporation ponds. The reduction in net benefits from the drainage constraint relative to the unconstrained solution is only 5%. The shadow value on drainage differs slightly, depending on the cotton price, but still is substantially lower than its value under evaporation ponds (table 4, column *B*, last row). Thus, while agriculture can be substantially impacted by changes in cotton prices, this general effect has little impact on drainage choice.

Reuse and Salinity Concentrations

A concern with using groundwater as a long-run irrigation source is the possible increase in aquifer salt concentration. Since ET is almost completely pure water and soil salinity has to be maintained at an appropriate level for crop production, reuse ultimately just recirculates salts in the basin, while surface water inflows import salts. Given no significant drainage outflows from the basin, the efficient reuse strategy will, in principle, increase groundwater salt concentrations over time. While a full analysis requires an explicit dynamic model, some informative calculations can be done with the static model developed here.

As before, general equilibrium effects complicate the analysis. An increase in groundwater salt concentration, c_2 (where $w_2 = w_2(c_2)$), decreases reuse profits and also decreases reuse ET, given reuse water depths. As reuse ET is the drainage disposal mechanism, both of these effects work to increase the explicit cost of drainage disposal, which tends to increase source control. However, this reduces crop profits and, consequently, the opportunity cost of disposal (shadow price of drainage), which in turn has a contrary effect on source control. Thus, while it might be reasonable to expect that an increase in groundwater salt concentration increases source control, a more formal analysis is warranted.

Consider the theoretical model with reuse only and fixed water applications in the reuse sector. While the latter is for analytical tractability, reuse quantities may well be limited by infiltration constraints (Oster, 1994). This is also consistent with the empirical analysis where reuse water applications are at their upper bound. Following similar procedures as used in equation (14), the sign of $\partial w_1/\partial c_2$ is being determined by

$$\text{(15)}\quad \operatorname{sign}\left[(d_1 + 2w_2 - 2d_2)\left(p_1^w - p^c f_1'(w_1)\right) - \left(p^c y_2 - p_2^w w_2 - \eta_1 - \left(p^c y_1 - p_1^w - \eta_1\right)\right)\right].$$

Applying the first-order condition for optimal w_1 (equation (7)) establishes that $\partial w_1/\partial c_2 < 0$ under the postulated conditions consistent with what might be expected in a partial equilibrium setting. Alternatively, with land and drainage constraints binding, we can rewrite x_2 as a function of x_1, which when entered into equation (1) and differentiated with respect to x_1, gives us the requisite first-order condition. After totally differentiating this first-order condition, the response of crop area to changes in aquifer salt concentration, $\partial x_1/\partial c_2$, is determined by

$$\text{(16)}\quad \operatorname{sign}\left[(d_2 - w_2) g_1'(w_1)\frac{\partial w_1}{\partial c_2} - d_1 \frac{\partial d_2}{\partial c_2}\right].$$

Since aquifer salt concentration increases reuse deep percolation as noted above, this expression has an ambiguous sign. While crop acreage would generally be expected to decline as reuse becomes less viable, the opposite could occur if the source control response is strong.

Table 6 evaluates grower net benefits for groundwater salt concentrations ranging from the current level of 10 dS/m to a higher level of 20 dS/m.[11] As salt concentrations increase, reuse acreage declines, and the remaining reuse acreage is reallocated toward wheat, another moderately salt-tolerant crop. This is efficient, since as salt concentrations rise, the opportunity costs of moving cotton out of freshwater production and into reuse production increases, relative to wheat.

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[11] Salinity concentrations in the SJV aquifer are unlikely to change in any appreciable manner in the short run, given its volume, as shown in Kan (2003) or Knapp (1998). Hence, this analysis can be thought of as addressing long-run issues as well as serving as an insight to other regions worldwide where such changes may happen on a shorter time scale.

Table 6. Sensitivity Analysis: Reuse and Changes in Salinity Concentration

	Groundwater Salinity Concentration (c_2) (dS/m)			
	A $c_2 = 10$	*B* $c_2 = 12$	*C* $c_2 = 15$	*D* $c_2 = 20$
Freshwater Crop Production				
Area (acres of x_1^T)	0.51	0.55	0.56	0.63
Cotton (% of x_1^T)	37	42	43	49
Tomatoes (% of x_1^T)	39	36	36	32
Lettuce (% of x_1^T)	10	9	9	8
Alfalfa (% of x_1^T)	14	13	13	11
Water (acre-ft/acre/year)[a]				
Water use	3.18	2.9	2.51	2.17
Deep percolation	1.21	0.93	0.57	0.27
Irrigation[b]				
FUR2 (% of x_1^T)	90	42	–	–
FUR4 (% of x_1^T)	–	49	55	11
Linear (% of x_1^T)	–	–	36	81
Drip (% of x_1^T)	10	9	9	8
Reuse Production				
Area (acres of x_2^T)	0.32	0.28	0.19	0.12
Cotton (% of x_2^T)	91	89	84	75
Wheat (% of x_2^T)	9	11	16	25
Water (acre-ft/acre/year)[a]				
Water use	3.85	3.85	3.79	3.73
Deep percolation	1.89	1.99	2.1	2.31
Irrigation[b]				
FUR2 (% of x_2^T)	–	11	16	25
FUR4 (% of x_2^T)	100	89	84	75
Land Disposal (Acres)				
Evaporation pond (x_3)	–	–	–	–
Welfare Measures				
Net benefits (in \$) $\sim \pi$	295	280	259	229
Drainage shadow value $\sim \lambda_d$ (\$/acre-ft)	19	39	83	210

Note: Land areas and social net benefits are per regional acre, with 17% of land fallowed.

[a] Water variables are average depths over the cropped areas per acre in each respective sector.

[b] FUR2 and FUR4 are, respectively, irrigation with furrow 1/2 mile runs and irrigation with 1/4 mile runs.

Concomitantly, freshwater application rates decrease and irrigation efficiency increases. Compared to the baseline in column A, there is a loss of \$66/acre when salt concentrations double; the shadow value on drainage also approaches that observed with evaporation ponds.

Policy Implications

From a policy perspective, our approach and results can be informative under a variety of situations. First, consider the issue of a government mandate to provide drainage services and the sort of compensation required to make growers indifferent between the provision of drainage services and no compensation versus the forfeiture of such services. Results suggest that growers make positive profits even in the absence of drainage services (column *C*, table 4). Assuming a 5% interest rate, a one-time payment of \$320 would be equivalent to the annual loss in net benefits in perpetuity, due to the lack of drainage services (net benefits in columns *A* versus *C*).

Second, what sort of compensation might be required to encourage growers to participate in a land buyout? Land retirement is being considered in many regions throughout the world, such as the Murray–Darling Basin or the Aral Sea. In California, WWD and the USDOI are considering a government buyout program of up to 200,000 acres in return for WWD relieving USDOI of its obligation to provide drainage services. WWD is requesting that the government payment offered to growers reflect the fair market price of the land as if drainage services were provided (WWD, 2003). In effect, WWD is requesting a payment that would reflect the situation we described in column A of table 4. Unfortunately, the net benefits in table 4 include returns to both land and management, not just land rents. If we assume that the management salary of an average farmer in this region can be represented by the average income earnings of an average sized farm in this region (U.S. Census Bureau), the annual profits per acre of \$158 at a 5% discount rate amounts to a one-time payment of \$3,160. Given reuse is an option, just compensation would be approximately \$2,840 (\$142 per acre at 5%). The higher payment of \$3,160 includes, in effect, a subsidy from taxpayers to WWD growers.[12]

Land retirement, though, is not always an attractive option for dealing with the drainage disposal problem. This is especially true in countries, such as Pakistan and India, engaged in efforts to improve or reinstate current acreage that is drainage or salinity impaired. In these situations, drainage disposal mechanisms are needed, be it reuse or evaporation ponds. Even in WWD, there will still be a need for drainage disposal for the remaining lands that are not retired.

From a policy perspective, though, the common property nature of the drainage problem suggests the need for collective action if efficiency is to be achieved. One possible regulatory strategy is to price the flows to and from the water table. Under such a scheme, freshwater and reuse crop producers are charged for emissions to the water table, while the latter and evaporation pond operators are paid for extractions from the water table. Define this charge/payment as p^d. Furthermore, define the land rental rate as p^l. If we let $p^d = \lambda_d$ and $p^l = \lambda_l$, where λ_l and λ_d are the shadow values on the land and drainage constraints defined above (equations (2) and (3)), then the solution to the private landowners' problem will be identical to the social optima derived earlier. With many operators, land prices will be determined in a competitive market. If the regulator sets the efficient water charge, then the correct land value will automatically emerge. For the empirical example here, the estimated drainage price is \$19/af, a relatively modest amount calculated as the shadow value on the hydrologic balance constraint in table 4 (column *C*). This shadow value, though, is sensitive to a number of assumptions. For example, given the heavy reliance on reuse in the efficient solution above, coupled with the risk and uncertainties surrounding this strategy, it is likely that the true shadow value of drainage with reuse is somewhat higher.

An alternative to a pricing scheme is to establish a market for the unpriced services. Here, reusers and evaporation pond operators supply permits credited upon water table withdrawals, while freshwater crop producers are to purchase permits to cover their emissions to the water table. A competitive equilibrium will occur where the quantity of permits supplied equals the quantity demanded, and hydrologic balance is maintained. If we again let $p^d = \lambda_d$ and $p^l = \lambda_l$, then it is straightforward to show, as in Spulber (1985), that the competitive equilibrium for the private landowners, along with the market clearing conditions in both the permit market and a competitive land market, will be identical to the social optima conditions. Thus, competitive equilibrium exists with the permit system. With this trading system, there is no initial allocation of permits. Also, under standard assumptions of complete financial and risk markets, separation theorems imply that production decisions are completely separated from consumption decisions so that income effects will not affect grower production management decisions. However, equity consequences can differ in practice among growers, depending on their ability to mitigate and dispose of deep percolation flows via reuse and evaporation ponds.

The novelty of this tradable permit scheme is that the level of emissions and permit supply is endogenous. Recall that under the standard approach, an overall level of environmental quality is specified, which in turn helps to determine a fixed level of aggregate pollution control permits. Here, while the regulator is specifying the level of environmental quality in terms of maintaining a hydrologic balance, the total level of emissions to achieve hydrologic balance is variable, as is the allocation across individual emitters/controllers (similar to the standard approach). From an implementation perspective, if tile drains are installed, monitoring could occur after the deep percolation flows have drained into the collection line and accumulated in a standpipe.

As with any permit system, there are limitations of the proposed approach. First, this

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[12] Considering economies of scale, this will likely be a lower bound if the land and/or drainage restrictions lead to a reduction in average farm size. This calculation takes as given the land buyout option. Note that the total subsidy could actually be larger because land retirement, as opposed to compensation, could imply an additional type of subsidy.

considers only drainage volumes and not salinity. However, as discussed earlier in the article, salinity buildup is not likely to be a problem for a relatively long time period because of the large aquifer capacity relative to annual flows. Second, spatial variability can influence performance of the market. When deep percolation flows are emitted, they cause an immediate buildup of the water table underlying the field. Horizontal flows then occur in response to differences in water table elevation, with the flow rate determined by the difference in water table levels and hydraulic conductivity. Hence, one potential source of spatial variability arises from variation in the natural terrain such that either the growers can be differentiably impacted by drainage problems even with a constant (over space) water table surface, or they differentiably respond in terms of source control and disposal. In principle, this type of variability can be addressed via trading zones (Montgomery, 1972) although, in practice, markets are subject to a variety of considerations such as market thinness and administrative efficacy (Hahn, 1989). Idiosyncratic grower responses are subject to at least some form of natural regulation. Because hydraulic conductivities are typically low in drainage-impacted regions, growers who choose no source control and no disposal will face higher underlying water tables on their land as off-farm drainage flows will be relatively slow. As a consequence, they will have extra incentive over time to regulate their own emissions.

Conclusions

There are a multitude of management strategies confronting irrigated agriculture when addressing restrictions on the agricultural drainage that it generates. This study identifies, theoretically and empirically, how the efficient solution consists of strategies requiring adjustment at both the extensive and the intensive margins. In particular, efficient land-use choices, irrigation efficiencies, and water application rates are shown to depend on the shadow value of drainage which, in turn, is a function of the shadow value of land. Hence, efficiency at the intensive margin, say water application rates, depends not only on the price of water but also on the opportunity cost of the additional land required to dispose of drainage flows from additional water applications. The nonseparability between water applications and land use identifies additional factors that contribute to the efficient solution beyond those typically identified in partial equilibrium frameworks. Furthermore, we show that the ability of growers to meet restrictions on agricultural drainage disposal is largely influenced by a combination of source-control (i.e., water applications, crop switching, irrigation-efficiency improvements) and disposal options. Our empirical results suggest that reuse, as a disposal option, is very promising in that net benefits of the drainage restriction are minimal compared to a no-restriction baseline.

As noted in table 1, reuse is being implemented and considered as a means of dealing with the salinity and drainage problem worldwide. Hence, an understanding of the factors that seem to influence its cost-effectiveness as a disposal strategy is useful. Our analysis suggests that because reuse typically disposes of less drainage water per unit of applied water than evaporation ponds, a characteristic of semi-arid and arid regions, the opportunity cost of using reuse relative to evaporation ponds is higher for those regions with high land values (figure 1). In our particular application, however, this opportunity cost is small, since the foregone profits associated with the reuse land if it were cropped with freshwater are not much greater than the profit incurred with cotton in the reuse sector; hence, reuse is a favorable disposal strategy.

Agriculture in the WWD, as well as many other areas, has long had relatively cheap access to natural resources and the waste-assimilative capacity of the environment. With population and economic growth, and continued degradation of environmental quality, irrigated agriculture is facing rapidly evolving circumstances. The response to resource scarcity in other industries, such as copper and mercury, has seen the use of increasingly sophisticated production methods, including substantial levels of recycling. Our results suggest that this is a very promising direction for irrigated agriculture in the SJV as well.

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