Water Markets and Water Quality

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Abstract

A non-linear programming model is developed to simulate grower response to water market scenarios. As a result of encouraging conservation through improvements in irrigation efficiency, significant reductions in drainage are achieved, indicating the potential role of water markets as a policy tool for addressing the environmental problems of irrigated agriculture.

Key Words

Water Markets, Water Quality

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1. Introduction

Many of the West's most valuable agricultural lands are naturally arid and have been made productive only through large-infrastructure water delivery systems. Increasingly, however, many of the regions are facing salinity and drainage problems. The 1983 discovery of toxic concentrations of selenium in waterfowl at Kesterson Reservoir in California underscored the complex pathways through which drainage from irrigated agriculture can concentrate in ecosystems both near the source and far away.

Coincident with increased concerns over agricultural pollution has been increased competition for limited water supplies between growing urban centers and surrounding agricultural areas. As development of new supplies becomes increasingly unlikely, water conserved from agriculture may be the best source for "new" water supplies. Heated debates have been conducted over allocation questions as well as means of creating supplies thorough conservation. Water markets are gaining increased attention for the potential to generate increased efficiency of use in the agricultural sector and to facilitate transfers to higher valued uses.[1]

A principle barrier to more rapid adoption of market schemes has been uncertainty about the details and consequences of implementation. The move towards water markets and away from current systems based on fixed allocations and low prices in agriculture is for many such a radical option with so many unknowns that a great deal of resistance exists among potentially affected parties. In this paper we attempt to project some of the impacts and responses that might be expected from implementing water markets in a particular region in California's San Joaquin

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1. For discussions on the properties and merits of water markets see e.g. Hartman and Seastone, Howe, et al., and Saliba and Bush. Institutional responses and impediments to creating and operating water markets have been examined by Gardner and Smith.

Valley. The case study is part of a drainage problem area contributing significant concentrations of selenium, molybdenum, boron, and salts to the San Joaquin River. The problem area and the agricultural setting are described in the next section. The simulation model is presented in section 3, and results and conclusions follow.

2. Problem Setting

The State of California has recently established a water quality standard for selenium in the San Joaquin River and is considering setting standards for other elements and salts (California, 1988). A 94,000 acre drainage study area on the westside of the San Joaquin Valley has been targeted as the major source of the trace elements and salts in the San Joaquin River. It has been estimated that the river quality standard could be met with approximately 30 percent reductions in drain flows from the drainage study area, and that these decreases are feasible with water conservation through improved management of irrigation applications (California, 1987). The means by which growers might be encouraged to adopt the changes necessary to achieve the recommended drain flow reductions have not yet been determined.

Drainage reduction policies under consideration range from voluntary implementation of recommended best management practices, to more stringent "command" type policies. Water charges, tiered water pricing schemes, and drain discharge permits have also been suggested as incentive based policy alternatives. Water markets are yet another alternative policy that may provide incentives to growers to reduce water applications and drainage production without the income reducing consequences or administrative requirements of tax or charge systems.

Cotton is grown on roughly half of the irrigated acreage in the area examined in this study. Tomatoes, sugarbeets, alfalfa hay, melons (cantaloupes), and wheat represent another 30 to 40 percent of irrigated acreage in the study area. Siphon tube furrow irrigation systems with half or quarter mile runs are most commonly used to irrigate cotton, tomatoes, sugarbeets and melons in the area, whereas wheat and alfalfa fields are generally irrigated with border check systems. Water districts in the drainage study area obtain their water supplies from the Bureau of Reclamation. Contracts specify volumes to be delivered and the price per acre foot. Prices and allocations vary by district, with prices charged to growers ranging from $0-36/acre foot, and allocations from approximately 2.3 to 4+ acre feet per acre (California, 1988). In contrast to the prices that growers pay, some urban water users in the state pay $270/acre foot (Willey and Graff, 1988).

3. Simulation Model

In order to examine some of the implications of introducing water markets to the drainage study area, an agricultural production model was constructed to simulate grower decision making. The model reflects regional economic conditions and agronomic characteristics. For modeling purposes the region is divided into physically homogenous cells. These cells are subdivided into areas corresponding to water district jurisdictions. Areas within a cell are thus homogenous with respect to soil and drainage conditions but differ from each other by institutionally set parameters. Two such subareas are selected for the analysis presented here. One subarea (subarea 1) represents a district with a sixteen dollar water price and an allotment of 3 acre feet per acre, while the second (subarea 2) is represented by a token charge of one dollar per acre foot and a four foot allotment.

Production of the six principle crops is modeled with quadratic crop-water production functions. Observations generated with the plant growth model derived by Letey and Dinar (1986) are used to estimate production functions for alfalfa hay (alf), cotton (cot), sugarbeets (sbt), tomatoes (tom), and wheat (wht). A production function for melons (mel) is derived from actual observations. Crop production ($Y_{a,c}$), where a and c refer to area and crop indeces respectively, is specified as a function of applied water, irrigation application efficiency and pan evaporation.

Output is adjusted to reflect variation in average yields achieved by the water districts represented in the model.

The key to reducing generation of subsurface drain water is to improve the infiltration uniformity and irrigation efficiency of applied water. Improvements in these characteristics can be realized by adopting more efficient irrigation technologies, or by improving irrigation management techniques. Examples of management activities and changes in irrigation practices that can increase application efficiency include shortening furrow runs, compacting soils, installing tail water return systems, and adopting pressurized irrigation systems.

Changes in irrigation practices can conserve water that can be made available for market sales and reduce drainage production, but will necessarily increase production costs. To incorporate this aspect of the problem, a frontier-estimation technique was used to estimate an irrigation technology cost-efficiency function from data on annualized capital, maintenance, and labor costs associated with various irrigation technologies, and the associated efficiency levels.[2] Because irrigation techniques, and thus irrigation costs, vary by crop type, crop specific cost functions were estimated. Irrigation technology costs ($ITC_{a,c}$) are specified as an increasing function of irrigation efficiency. The resulting functions thus describe the lowest cost at which a given irrigation efficiency level can be attained, on each crop, by an average farming operation in the area.

The objective of the model is to maximize the sum of grower returns to land and management in the subarea. Net returns to land and management are described as a function of crop revenues, harvest costs, pre-harvest costs, water and irrigation technology costs, water sales revenues and drain costs:

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[2] Irrigation efficiency is defined as the ratio of the depth of water beneficially used (plant needs plus minimum leaching fractions) to the average depth of applied water. This information was compiled by Davids and Gohring (1989) for 11 irrigation technologies, with three management levels for each technology.

$$(1)\quad NR_a = \Sigma_c([(P_c - HC_c) \cdot Y_{a,c} - PC_c] \cdot ACRES_{a,c} - [P_{w,a} \cdot AW_{a,c} - ITC_{a,c}] \cdot ACRES_{a,c}) + PM_w \cdot SW_a - DC \cdot DA_a$$

where:

$a = 1, 2 \equiv$ subarea index

$c = \{alf, cot, mel, sbt, tom, wht\} \equiv$ crop index

$ACRES_{a,c} \equiv$ acres of crop c planted in area a (acres)

$AW_{a,c} \equiv$ applied water (af/a)

$DA_a \equiv$ drained acres (acres)

$DC \equiv$ drain system costs (\$/acre)

$HC_c \equiv$ harvest costs (\$/ton)

$ITC_{a,c} \equiv$ annualized irrigation technology and application cost (\$/acre)

$P_c \equiv$ crop output price (\$/ton)

$P_{w,a} \equiv$ price of water in subarea a (\$/af)

$PC_c \equiv$ preharvest costs (\$/acre)

$PM_w \equiv$ market price of water (\$/af)

$SW_a \equiv$ volume of water sold in water market (af)

$Y_{a,c} \equiv$ yield of crop c attained in area a (tons/acre)

Crop budgets produced by California State Cooperative Extension form the basis for most production cost parameters. Average crop prices and yields for each district were obtained from the Bureau of Reclamation. Production parameters and crop prices are assumed to be constant throughout the area, while water prices, per acre water allocations, and average yields vary by district, and thus by subarea. All prices and costs are expressed in 1988 dollars.

The optimization problem is to choose cropping patterns ($ACRES_{a,c}$), irrigation technology cost ($ITC_{a,c}$) and efficiency, water applications ($AW_{a,c}$) and water sales (SW_a), to maximize (1) subject to the production and cost functions. In addition, upper bounds on crop acreage are imposed on tomatoes and sugarbeets to reflect limited contract availability due to market conditions

Could model solve
for water price
for given change?

and processor capacity in the area. A minimum percent of cropped acreage is constrained to be planted with wheat due to the rotational importance of the crop. Lastly, water and land constraints are specified to reflect the availability of these resources.

The volume of collected drain water that could be expected to result is determined as a function of water applications and irrigation efficiency on overlying fields, soil properties, and high water table conditions. This formulation was adapted from a similar one in the Westside Agricultural Drainage Economics Model (Horner and Dudek, and Hatchett, et al). Surface runoff and evaporation losses are assumed to be seven percent of total water applications.

4. Results and Analysis

The model described above is specified as a non-linear programming problem, and solved with a non-linear optimization algorithm. The results predict optimal response to water sale alternatives. The analysis was conducted for the two subareas to indicate the role of water costs and allocations on market supply response.

Base Case Results

The base run results are presented in Table 1. In the absence of a water market growers in subarea 1 plant 67% of their acres to cotton, and 15% to melons. The tomato and wheat constraints are binding at 8% and 10% of the acreage respectively. Crops with high water needs, alfalfa hay and sugarbeets, do not enter the optimal solution. This cropping pattern is depicted in Figure 1. Cotton is irrigated with 3.3 acre feet per acre and 3.38 feet are applied on the tomatoes. Water applications are 1.97 and 2.17 acre feet per acre (af/a) of melons and wheat respectively. Maximum yields are attained with these water applications by irrigating most crops at a 73-74 percent application efficiency level, i.e. one at which 74% of applied water is beneficially used by the plant.

The application efficiency on melons is lower (65%) than on the other crops. These results are consistent with data observed in the area.

In subarea 2 water is cheaper and more plentiful than in subarea 1. Under these conditions it is more profitable to grow sugarbeets than melons and the former is planted to 17% of the acreage while the latter does not enter the optimal solution. As in subarea 1, cotton is the dominant crop, occupying two thirds of the acreage. Tomatoes, the most profitable crop in the model, is restricted to 3% of the acreage, and the remaining 14% of the acres are reserved for wheat (Table 1, Figure 1). The higher water allocation is reflected in optimal water applications that are higher, and irrigation efficiencies that are lower than in subarea 1.

Larger water applications are expected to result in the generation of larger volumes of drain water and, in fact, subarea 1 is predicted to generate .89 af/a of drain water while 1.25 af/a are predicted for subarea 2. Net returns to land and management are also higher in subarea 2.

The application efficiencies predicted might be attained with well managed half mile furrow systems or medium management levels on quarter mile and border check systems in subarea 2. The higher efficiency levels predicted for subarea 1 might require tail water return systems coupled with the border checks used in wheat irrigations and higher management levels on quarter mile furrows for the other crops.

Water Market Simulation

A water "supply" curve was derived by varying the market price of water between 0 and 150 dollars per acre foot and is presented in Figure 2. Subarea 2 enters the market when the price is $40, while subarea 1 enters at a $70 price. As the opportunity cost of using water increases, water use is reduced on all crops. In many cases, improvements in irrigation efficiency compensate for reductions in applied water such that yields are unaffected. As water market prices rise, it becomes profitable to sacrifice some cotton and melon output, rather than incur the extra cost associated with increasing irrigation efficiency enough to compensate for further reductions in water applied on these crops.

In addition to changing irrigation practices, water may be conserved through changes in cropping patterns. When the marginal value of use in a given crop becomes less than the value of use in a crop with a lower consumptive use plus the market value of the difference in water use between the two crops, acreage is taken out of production in the first crop and transferred to the second. This switch occurs between sugarbeets and cotton in subarea 2, and between cotton and melons in both areas (see Figure 1). Eventually, as the market price of water continues to rise, it becomes profitable to take land out of production. It should be noted that a switch from crops that have high water needs to those with low consumptive requirements will free up water for sale but will not necessarily have a proportionate effect on drainage production since only that amount of water that is greater than plant needs becomes drainage.

Gradual reductions in consumptive water use result in incremental water supply response in a broad range of market prices. However, as the price approaches $140/af it becomes suboptimal to produce cotton and a sharp jump in water sales results as the cotton acreage comes out of production. The results from market prices of $80 and $120 are presented in Table 1. Optimal response to these prices is indicative of general market responsiveness.

At a market price of $80/AF, exactly one acre foot per acre is sold from subarea 2; the remaining allocation (3 af/a) is equal to the total allocation in subarea 1. Comparison of irrigation applications and efficiencies with base case results for subarea 1 demonstrates the equivalence of these situations. In contrast to the one foot sales from subarea 2, the $80 price invokes a supply response from subarea 1 of only .2 af/a. The difference in the initial water allocation is also reflected in the income realized in the two areas. Net revenues in subarea 2 increase by $24/acre over the base case, while the difference in subarea 1 is only $2/acre.

In subarea 1 optimal irrigation efficiencies are at least 10 percent higher when the market price for water is $120/af than in the base case, in order to conserve .5 af/a for sale. Water applications on cotton and melons are 11% lower than when $PM_W = \$80$, resulting in slight yield reductions. Water applications on tomatoes decreased by 8 percent in response to the $40 increase in the market price. Net returns increased by $18/acre, though returns from crop production fell by $45 per acre. In Subarea 2 water applications on cotton and wheat are reduced by 29 percent from base, and melon irrigations drop by 12 percent as the market price increases from $80 to $120. Water sales revenues of $163/acre easily offset $92/acre reductions in crop returns.

Environmental Implications

The volume of drain water estimated to be generated under the market price scenarios is illustrated in Figure 3. Water conservation in response to the water market is clearly reflected in drain flow reductions in both subareas. As expected, subarea 2 is predicted to generate more drain water than in subarea 1 in all cases, but greater water supply responsiveness results in proportional reductions that are greater than in subarea 1.

In subarea 2, collected drain water is reduced by 30% in response to a market price of $80/af. A market price approaching $60 is sufficient to elicit a 30% reduction in water percolating below the root zone, i.e. in that portion of drain flows that a grower has the most direct control over. In subarea 1, a 30% reduction in total drain flows (including grower contribution plus contribution from the high water table) is not achieved until the market price exceeds $130. A 30% reduction in deep percolation is realized when $PM_W = \$90$. These results reflect the fact that the contribution of the high water table as a percent of total drain flows is higher in subarea 1. The 30% drainage reductions are significant in that they represent the target established by the State for San Joaquin River quality goals (SWRCB, 1987).

5. Conclusions

Water markets may create an incentive to conserve water in agriculture, thus creating an important "new" water supply, and provide a flexible alternative to rigid drainage reduction policy instruments. This paper examines some of these potential benefits by modeling grower response to a range of water market price scenarios, and the drain water changes that would result.

Water supply responsiveness is predicted for two areas with different underlying structures. Irrigation application efficiencies are increased in each area to conserve water for sale without appreciably reducing yields or cropped acreage. The results indicate that significant reductions in total drain flows may be achieved as a by-product of a water market in which prices range from $80 to $130. These prices are in the range of those realized in western water markets (Willey and Graff, 1988). They are also well below water prices paid by urban areas in California, indicating a clear potential for a water transfer that is beneficial to agricultural and urban sectors, as well as to the environment.

The analysis also suggests that underlying institutional factors, such as historic water allocations and delivered-water prices, can be as important as economic and hydrologic factors in conditioning water market impacts. In one of the areas considered water allocations are relatively "tight" compared to the other, and agricultural crop decisions and irrigation practices in the base case reflect a higher shadow price of water. Participation in a water market, and expected drainage reductions, is thus more modest than in a neighboring area with a more abundant allocation. These types of efficiency/equity impacts need to be better understood in order to assess how water markets might best be designed to address both conservation and agricultural pollution goals.

Agricultural firms' decisions and management practices influence soil erosion, surface runoff, subsurface percolation, and irrigation return flows, and are often linked to the degradation of water quality through contributions of sediment, nutrients, salts and toxins to rivers and other aquatic systems. While the results of this study are specific to the western San Joaquin Valley, the conclusions are relevant in the search for policy alternatives to the range of environmental problems associated with irrigated agriculture.

TABLE 1. WATER MARKET SIMULATION RESULTS -
Optimal Response to Base Case Conditions and Two Water Market Price Scenarios

		Subarea 1			Subarea 2		
		Base	PMw = $80	PMw = $120	Base	PMw = $80	PMw = $120
Cotton	Acres (%)	67%	65%	65%	66%	76%	76%
	Applied Water (af/a)	3.30	3.09	2.74	4.01	3.25	2.84
	Irrigation Efficiency (%)	0.74	0.77	0.84	0.63	0.75	0.81
	Yield (tons/a)	0.72	0.72	0.71	0.70	0.69	0.68
Melons	Acres (%)	15%	17%	17%	0%	7%	7%
	Applied Water (af/a)	1.97	1.84	1.63	0.00	1.93	1.69
	Irrigation Efficiency (%)	0.65	0.68	0.73	0.00	0.65	0.71
	Yield (tons/a)	8.47	8.44	8.34	0.00	8.03	7.93
Sugarbeets	Acres (%)	0%	0%	0%	17%	0%	0%
	Applied Water (af/a)	0.00	0.00	0.00	5.04	0.00	0.00
	Irrigation Efficiency (%)	0.00	0.00	0.00	0.68	0.00	0.00
	Yield (tons/a)	0.00	0.00	0.00	29.62	0.00	0.00
Tomatoes	Acres (%)	8%	8%	8%	3%	3%	3%
	Applied Water (af/a)	3.38	3.21	2.94	3.97	3.34	3.03
	Irrigation Efficiency (%)	0.74	0.78	0.86	0.63	0.75	0.83
	Yield (tons/a)	33.48	33.48	33.48	31.81	31.81	31.81
Wheat	Acres (%)	10%	10%	10%	14%	14%	14%
	Applied Water (af/a)	2.17	2.04	1.83	2.69	2.14	1.90
	Irrigation Efficiency (%)	0.73	0.78	0.87	0.59	0.74	0.83
	Yield (tons/a)	3.13	3.13	3.13	3.13	3.13	3.13
Water Sales (af/a)		na	0.22	0.52	na	1.00	1.36
Drain Water (af/a)		0.89	0.81	0.67	1.25	0.87	0.72
Crop Returns ($/a)		415.82	400.65	370.86	460.05	404.49	368.39
Net Returns ($/a)		415.82	418.21	433.38	460.05	484.32	532.07

FIGURE 1. WATER MARKET SIMULATION— EFFECT ON CROPPING PATTERNS

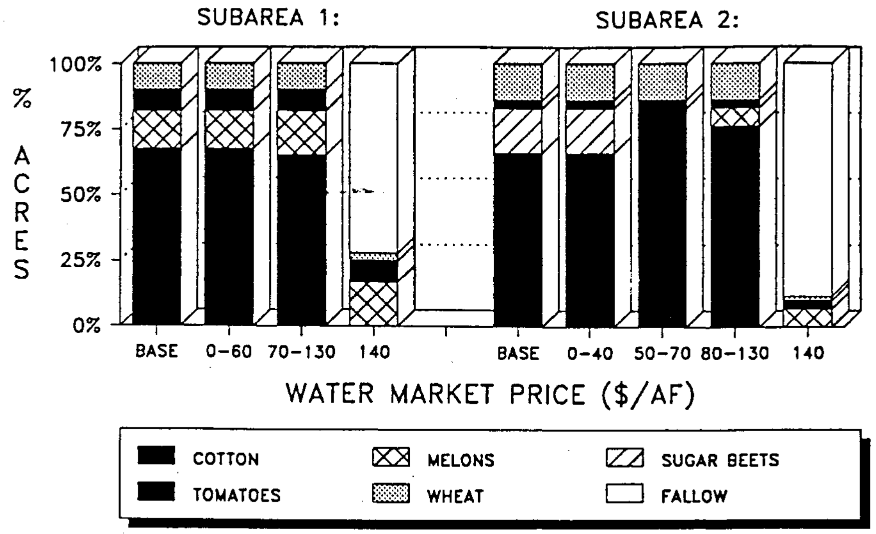


FIGURE 2. WATER MARKET SIMULATION — WATER SALES BY SUBAREA

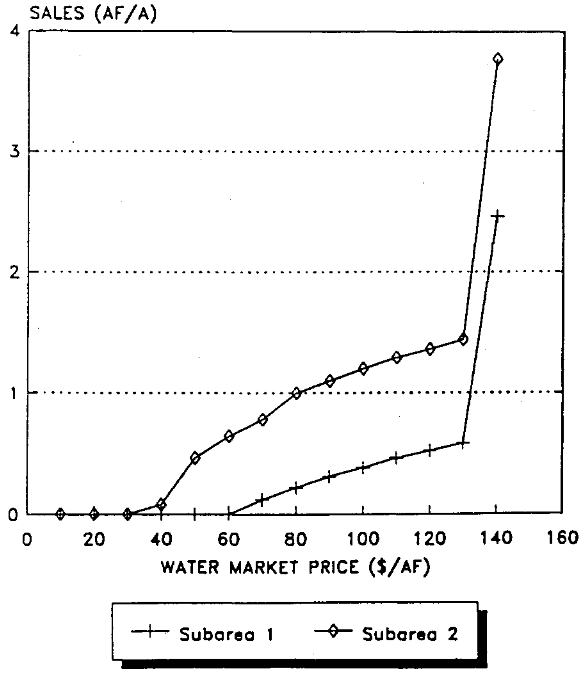
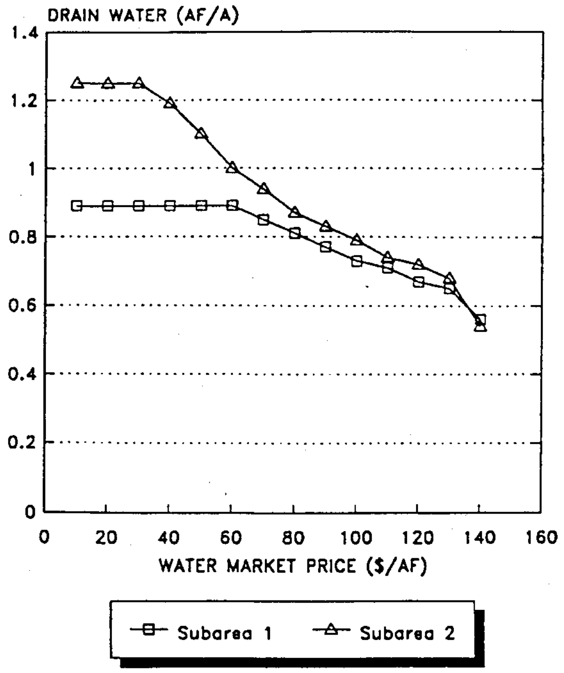


FIGURE 3. WATER MARKET SIMULATION — COLLECTED DRAIN WATER BY SUBAREA



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