CAN WATER PRICING SOLVE THE WATER QUALITY PROBLEM?

by

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Paper presented to the Western Agricultural Economic Association Meeting July 19, 1976.

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The Federal Water Pollution Control Act Amendments of 1972 (PL 92-500) established the goal of restoring and maintaining the quality of the nation's waters (Section 101 a). The impact of this legislation on western agriculture is presently unknown, but it may be substantial if the states, which are charged with implementation and enforcement, interpret the law literally.[1/] Irrigated agriculture is one of the largest users of our water resources, and the irrigation return flows increase the nutrient, sediment, pesticide, and salinity content of receiving waters.

Probably the most serious and general water quality problem in the west is high salinity concentrations, which decrease the receiving waters reuse potential for crop production, wildlife habitat, outdoor recreation, industrial use, and human consumption (Skogerboe and Law). Improving the quality, or reducing the quantity of irrigation return flows, or both, can be achieved by increasing the efficiency of water delivery systems, improving on-farm water management, and treating return flows. Suggested policies to facilitate the improvement of water-use efficiencies at the district or farm level are generally based on mandating water-use performance standards, subsidizing the reduction or taxing the production of effluents, direct public investment in treatment facilities, or the taxation of externality producing inputs.

The objective of this paper is to project the changes in the quality and quantity of irrigation return flows as a result of two policies that could be adopted under Section 208 of PL 92-500. They are 1) implementing a $22.50 per acre-foot price for surface water and 2) requiring water management practices that increase water-use efficiency by 30 percent. These policies will be applied to a 700,000-acre region of the San Joaquin Valley.

Surface water in the west has been, and probably will be for a substantial period of time, allocated according to the doctrine of prior appropriation. Once the right to water is established, the user may divert all of the water right by incurring the diversion and distribution costs. In most western states, water rights are not transferred; but an attempt to discourage waste is made by limiting water use to "beneficial uses." The definition of "beneficial uses" is judicially determined, and this concept will differ by location. In most instances, the philosophy of "use it or lose it" predominates both agency and private water diversion decisions.

Water prices vary substantially because they are established by water agencies and districts to allocate diversion and distribution costs to individual water users.[2/] The U.S. Bureau of Reclamation covers the cost of water development and delivery by charging agricultural and municipal users, selling hydroelectric power, receiving federal and nonfederal payments of the cost of fish and wildlife benefits, and the federal payment of the cost of flood control benefits. Revenues generated from the sales of power and municipal water are used to reduce the cost of agricultural water. The cost of irrigation water is further reduced by eliminating the interest on the capital costs allocated to agriculture (California Department of Water Resources). The present pricing structure, based primarily on diversion costs, will generally result in more diversions, greater agricultural production, increased net farm incomes, and larger irrigation return flows in a specific area than would occur under higher water prices (California Department of Water Resources and Howe and Orr). Markets for the transfer of water rights and use would establish an opportunity cost of water, and it has been shown that water markets are feasible and can be expected to allocate water in an economically efficient manner (Hartman and Seastone; Gardner and Fullerton).[3/] However, markets for water do not generally exist, and conflicts among competing water users and environmentalists result.

The amount of water pollution resulting from past and present water use is no longer tolerable. Section 208 of PL 92-500 is an attempt to decrease the externalities of nonpoint sources of pollution by requiring the specification of methods to control runoff from agricultural and silvicultural practices. These controls will be a set of "best management practices" uniformly applied to achieve the water quality goals of PL 92-500. The best management practices being considered by the agencies conducting Section 208 analysis are specific soil and water-use management techniques and physical treatment structures. Changing water prices to achieve different water use patterns and environmental results have not been considered. The concern with identifying the physical pollution effects of changing irrigation practices and ignoring the effects of economic incentives is understandable. Many of these agencies do not favor pricing policies as pollution control alternatives because they are politically undesirable, and the income distribution and equity effects are largely unknown (California Department of Water Resources).

PRICING WATER DIVERSIONS FOR WATER QUALITY

Increasing the price of irrigation to reflect the externalities of irrigation return flows is suggested here as a surrogate effluent charge.

An effluent charge system is a method of internalizing the externalities of irrigation return flow disposal. However, monitoring, identifying, and determining the effect on the environment of each irrigator's return flow is expensive and not always possible. Therefore, less costly and more politically feasible incentives are required. Increasing the price of irrigation water in lieu of an effluent charge will probably result in the same amount of return flows if the diversions are proportional to salt load and social damage. Howe and Orr believe sufficient correlation exists, but argue that such a policy would promote excessive capital investment in equipment not related to reducing the salt load, and decrease agricultural production in the specific region. They conclude that a tax on water diversion to reflect the damages of return flows would be preferable to no internalization policy at all.

Surface water prices in the study area range from approximately $1.00 to $5.25 per acre-foot. The average price is $4.00 per acre-foot. Most of the water districts were established 25 to 50 years ago under U.S. Bureau of Reclamation projects or water exchange agreements. The cost of pumping ground water is approximately $7.00 per acre-foot.

The pricing policy evaluated a water price that is the approximate cost of developing new water supplies in the area, i.e., about $22.00 per acre-foot. This was done to determine the effects on return flows of a uniform price based on the marginal cost of water. It was assumed that the price increase would cause an increase in the water-use efficiency of 30 percent.[4/] It is not unreasonable to assume that the necessary investment would occur at the farm and district levels, and that water would be better managed as a result of the increased water price. Willardson concluded that application efficiencies of 80 percent can be achieved just by recovering runoff water. Application efficiencies for furrow irrigation, which is typical in this area, are 45 percent (Willardson). The water management policy presupposes that the pricing structure would remain intact; and that certain water management practices and water-saving investments, such as those being considered in the Section 208 plans of PL 92-500, would be mandated. These might include canal and lateral lining, minimum leaching, tailwater control, pressure irrigation delivery systems, irrigation scheduling, and other cultural practices. The resulting water-use efficiency was also assumed to increase by 30 percent. The cost of achieving the higher water-use efficiencies was not included in the water management policy alternative because they vary substantially for each practice, and the probability of public agencies sharing these costs is high.

THE ANALYTICAL MODEL

The analytical system consists of two specific models sequentially linked to simulate the agricultural production and environmental adjustments that occur as a result of an environmental policy. The first is a linear programming model that derives optimal cropping patterns, the use of ground and project water, and fertilizer in 40 specific subregions in the study area. The solution is constrained by the usual physical, institutional, and market restrictions. The results of the LP model serve as inputs to the physical model. The physical model is partitioned into three interdependent submodels that analyze the hydrology, salinity balances, and nitrogen concentrations. The submodels estimate the effects of irrigation water and fertilizer use on the water table depths and the quantity and quality of irrigation return flows. The costs for collection and disposal of return flows, and the costs for installing tile drainage to relieve high water tables, are calculated by the physical model; and the production costs of the LP model for the following year are adjusted accordingly. Solutions from the models are derived annually, and are iterated a sufficient number of times to simulate the environmental adjustments from a change in water-use as a result of alternative policies.

The Physical Model

The hydrology and water quality of the study area have changed dramatically in recent years, and are still changing rapidly. In particular, the area is still adjusting to the large scale importation of water through the California Aqueduct and the Delta Mendota Canal. During the coming decades, the volume of water lost to deep percolation will result in perched water tables, and more and more land will have drainage problems. The drainage water will contain relatively high concentrations of dissolved solids and nitrogen, reflecting farming practices that add nitrates and salts and leach additional dissolved solids from the soil. The primary function of the physical model is to predict the volume and quality of the agricultural return flows during the coming decades.

Natural inflows and outflows of water, diversions, rates of well pumpage, and water table levels were estimated for each subarea from the U.S. Soil Conservation Service, California Department of Water Resources, and U.S. Geological Service records. The entire area is underlain by a confined aquifer and an unconfined aquifer, which are separated by an impermeable clay layer. The water table in the unconfined or upper aquifer is rising rapidly as a result of the importation of irrigation water. Wells draw from both aquifers.

The hydrologic model generates predictions of the rates of deep percolation through the soil, subsurface drainage, surface runoff, rates of ground water flow among the 40 subareas, or nodes, and movement of the water table in the unconfined aquifer. The soil type, depth of water table, ground surface elevation, and depth to the impermeable layer are generally homogeneous throughout each node. In each node, the annual rate of deep percolation (Q_u) is computed as the sum of the components of water inputs and outputs at the surface. That is,

$$Q_u = Q_{DIV} + Q_R - R_{ET} - Q_{RO} \tag{1}$$

where Q_{DIV} = annual irrigation applications

Q_R = annual rainfall

Q_{ET} = annual consumptive use

Q_{RO} = annual surface runoff

Surface runoff was assumed to be 15 percent of all applied water, based on reasonable model performance and expert opinion.

Computation of subsurface drainage depends first of all upon whether a drainage system has been installed. In those nodes in which the water table is within 5 feet of the surface, a drainage system is assumed to be installed only if it is determined in the LP model as economically feasible. In a node where a drainage system has been installed, the rate of drainage (Q_D) is computed from the rate of deep percolation and the movement of the water table.

Movement by the water table is computed for each node by:

$$\Delta h_k = \frac{1}{A_k} \left[\frac{1}{S_k} (Q_{GI_k} + Q_{u_k} + \Sigma Q_{jk} - Q_{GO_k}) \right] \qquad (2)$$

in which Δh_k = change in water table depth in node k during a unit of time,

A_k = area of node k,

S_k = specific yield of the aquifer in node k,

Q_{GI_k} = ground water inflow to node k from the periphery of the study area,

Q_{GO_k} = ground water outflow from node k to the periphery of the study area, or through the impermeable clay layer,

Q_{P_k} = ground water pumped from the unconfined aquifer of node k,

Q_{j_k} = ground water flow between nodes j and k.

The annual rate of deep percolation will be zero, as a first approximation, for any subarea in which drainage is installed.

The ground water flow between nodes is computed by equation (3),

$$Q_{jk} = K \frac{\overline{\Delta h}_{jk}}{\Delta x_{jk}} \frac{\overline{h_j} + \overline{h_k}}{2} L_{jk} \overline{D}_{jk} \qquad (3)$$

where the bar over the h terms indicates a linear time average as defined by

$$\overline{h_j} = \frac{h_j(t_o) - h_j(t_1)}{2} \qquad (4)$$

and $h_j(t_o)$ = initial water table elevation at start of unit time,

$h_j(t_1)$ = final water table elevation at end of unit time,

Δh_{jk} = difference in water table elevation between nodes j and k,

Δx_{jk} = distance between centers of nodes j and k,

$\overline{D}_{jk}$ = average of the depths of the saturated zones (water table elevation minus impermeable layer elevation) of nodes j and k,

L_{jk} = length of common boundary between nodes j and k.

Equation (3) is therefore an approximate form of Darcy's Law in which spatial and temporal averages of water table depths are used to arrive at an average hydraulic gradient between the two nodes. A spatial average is used for the coefficient of permeability of the nodes, and the area through which the flow moves is equal to the product of the length of the common boundary and the time-averaged depth of the saturated zones.

One equation of the form of equation (2) may be written for each node, resulting in n equations for n nodes. By substituting equations (3) and (4) into equation (2) for each node, there remain only n unknowns, namely, the final water table depth for each of n nodes. This system of n equations is then solved by Gaussian elimination.

The quality changes taking place in the soil moisture are increased total dissolved solids (TDS) concentrations, due to evapotranspiration and chemical processes in the soil, and a change in nitrogen concentration due to the application of fertilizers and consumption of nitrogen.

Salt pickup in an irrigated soil is primarily a function of the chemical composition of the soil and of the applied water and the leaching fraction. Analysis of the total annual salt load carried by subsurface drains in the area suggests that the total annual salt load per acre in tile drains is approximately linearly related to the total volume of water carried by the drain. It was therefore assumed that the annual rate of salt pickup for each node can be approximated by a simple linear function having the form

$$SPU = \alpha + K\ L$$

where SPU = salt pickup in tons per acre per year,

α = an intercept,

L = volume of percolation water in acre-feet per acre,

K = constant of proportionality.

The constant (K) was determined from drainage data for those nodes where such data were available. For other nodes, the constant was based on the values used in other nodes with similar characteristics.

The major shortcoming of this approach is that it is based on current irrigation practices and the chemical composition of currently available water, both of which can be expected to change with time. An anticipated modification of the model will provide for the effects of changing irrigation practices and changing water quality.

The nitrogen model computes the increase or decrease in nitrogen in the soil solution on the basis of the nitrogen balance in the soil. Total nitrogen inputs (from fertilizers, irrigation, rain water, and atmospheric nitrogen) minus total nitrogen loss at the surface (as plant harvest, denitrification, and surface runoff) equals the net nitrogen input to the soil. The net input is assumed to be carried through the soil in the percolating water.

Water entering subsurface drains was assumed to have the same quality as the percolation water, since water quality in ground water is assumed to be stratified, with the water closest to the surface having the same characteristics as percolating water from the surface.

A weighted average of the quality components of ground water within a node is used to estimate the quality of water pumped from wells within the node, and the quality of water moving outward across the boundaries of the node. This assumes, in effect, that all strata contribute proportionate shares to flow from the aquifer. Although wells will generally draw water from certain specific strata more than from others, it would have been impractical either to differentiate between the various strata in every node or to determine the characteristics of every well in the study area. In addition, the gravel-pack wells used in the area result in some mixing between strata.

The quality of surface runoff was initially assumed to be the same as the quality of applied water. This approximation was justified by experience at various locations (Carter and English).

Calibration of the Model

The linear programming model derives a cropping pattern that maximizes returns to land and management in each of the 40 subregions, subject to the amount of surface and ground water available and the crop rotation requirements of the area. The locations of crops were specified in the base year, with the location of additional acreages of crops only being constrained by soil suitability. Water use in the base year approximated actual water-use reported by the area irrigation districts. Average commodity prices for 1970-75 are justified by constraining the LP crop production. These constraints were derived for the study area by the California Department of Water Resources and the USDA San Joaquin Valley River Basin Planning

Staffs. Fertilizer, labor, energy, machinery, and interest costs for 1972 were used in deriving the crop production budgets.

The hydrologic model was calibrated by adjusting ground water inflow and outflow and specific yield, for each node, until the movement of the water table predicted by the model matched the historical water table movement for a 12-year period -- 1958-1969.

Calibration of the TDS and nitrogen components of the model was not attempted. The difficulty of collecting and reducing the necessary data in a reasonable span of time and at a reasonable cost made such an effort impractical.

The sensitivity of the solution to changes in various assumptions was tested in the following manner:

a. The TDS concentrations of all surface runoff were increased by 50 ppm. The result was a 4.5 percent increase in total dissolved solids load in return flows predicted for 1977.

b. The salt pickup rate in water percolating through the soil column was increased by 20 percent, causing a 9.1 percent increase in the TDS load in 1977 return flows.

c. Nitrogen consumption by denitrification and plant uptake was decreased by 20 percent. This same amount of nitrogen was therefore added to deep percolation and return flows, causing a 62.9 percent increase in nitrogen load in 1977 return flows.

d. Surface runoff was reduced from 15 percent to 10 percent of total applied water and rainfall. The salt load increased by 57.3 percent, and the nitrogen load decreased 7.2 percent.

The results of the sensitivity analysis emphasize the importance of accurate estimates of surface runoff, and of the rates of nitrogen consumption.

RESULTS

The policy of increasing the surface water price to $22.00 per acre-foot was evaluated based on the supposition that this policy would generate a 30 percent increase in water-use efficiency. The water management policy assumes the present level, and requires water management practices that also assume an increase in water-use efficiency of 30 percent.

Production, Resource Use, and Returns

Crop acreage is expected to increase by 1985 to 475,000 if "no policy", or the water management policy, is adopted (Table 1). A surface water price of $22.00 will result in a decrease in the 1985 crop acreage of 360,000, because lower valued crops will not be economically feasible. These results rely on the assumption of equilibrium commodity price levels being relatively proportional to production costs.

Total water-use is expected to decrease under the surface water pricing policy from 1,474,000 acre-feet in 1976 to 920,000 acre-feet in 1985. The water management policy results in a reduction to 1,290,000 acre-feet. The change in total water use will affect the quantity of irrigation return flows, and the proportion of ground to surface water use will affect the salinity concentration of irrigation return flows. The cost of pumping ground water is cheaper than surface water under the pricing policy, and ground water is expected to increase to about 30 percent of the total water-use. This is contrasted to 10 percent in 1976, 15 percent under no policy, and 9 percent under the management policy. Salt concentration of

TABLE 1. Crop Production, Water and Fertilizer Use, and Returns by Policy, 1967 and 1985

Item	Unit	1976	1985		
			No policy	Pricing policy	Management policy
Crop production	1,000 acres	430	469	360	458
Nitrogen fertilizer use	million tons	17.5	19.1	14.6	19.1
Water use, total	1,000 acre-ft	1,470	1,560	920	1,290
ground	" " "	160	234	306	115
surface	" " "	1,310	1,326	614	1,175
Net returns to land & management	mil. dol.	140	151	139	154
Net returns per crop acre	dollars	319	320	390	337

ground water used for irrigation ranges from about 900 to 2,500 ppm, and project water is about 200 ppm. Ground water can be directly applied to some salt-tolerant crops or blended with surface water for use on more salt-sensitive crops.

Net returns will increase if surface water prices remain constant and water-use management policy is adopted. However, this ignores the costs of enforcing the use of the water management techniques. High surface water prices decrease the total net returns. But they increase the average net returns per acre because the lower value crops are no longer feasible, and the higher value crops are constrained to assume constant prices. However, the pricing policy should not require substantial implementation and enforcement costs.

Water Table Depths

Chronic water table depths less than 5 feet from the soil surface will usually decrease yields sufficiently to warrant the installation of subsurface tile drainage. Table 2 contains observed water table depth, acreages for 1970, and projected acreages for 1976 and 1985 under alternative policies. Sixty-five percent of the area may have drainage problems by 1985 if no policies are adopted. The pricing and management policies are expected to reduce the land affected by high water tables in 1985 by about 180,000 acres. The smaller area of land with subsurface drainage will result in higher quality return flows that have greater reuse potential and less environmental impact.

Irrigation Return Flows

High surface water prices reduced the amount of return flows and salt load, but the salt concentration remained about the same relative to

TABLE 2. Water Table Depths by Policy, 1970, 1976, and 1985

Item	1970	1976	1985		
			No policy	Pricing policy	Management policy
	1,000 acres				
Land with water table less than 5 feet	308	405	449	270	270
Land with water table 5 to 10 feet	146	114	95	188	188
Land with water table greater than 10 feet	239	168	150	236	236

the no-policy action (Table 3). Ground water was cheaper than surface supplies, therefore, a higher proportion of ground water was used and a high salt concentration in the percolation water resulted. However, this was offset in the total return flow salt concentration by a reduction in subsurface drainage relative to surface runoff. As discussed earlier, reduced water use results in lower water tables and reduced amounts of subsurface drainage.

The water management policy also decreases the return flows and salt load, and, in contrast to higher surface water prices, reduces the salt concentration. Since surface water prices remain unchanged, and increased water-use efficiency is required, the irrigation water will contain higher proportions of good quality surface water. This results in decreased return flows of better quality.

The nitrogen load in the return flows is highly correlated with the salinity load. The nitrogen concentrations of the total return flows (combined surface and subsurface drainage water) range from 1.8 ppm under the management policy to 4.4 ppm if no policy is enacted. These levels do not constitute a problem for reuse in irrigating crops or in meeting requirements for disposal to the San Joaquin River. Proposals are currently being formulated by the State of California to construct a concrete-lined drain to export just subsurface drainage water from the San Joaquin Valley. If constructed, the salt and nitrogen contents of the subsurface drainage will probably be too high to permit disposal into San Francisco Bay withour pretreatment, under the provisions of PL 92-500.

The potential reuse of return flows for irrigation in the study area depends largely on the TDS and boron content, and the ability of the district

TABLE 3. Quantity and Quality of Irrigation Return Flows by Policy, 1976 and 1985

Item	Unit	1976	1985		
			No policy	Pricing policy	Management policy
Surface return flows	1,000 acre-ft	296	312	200	271
Subsurface return flows	1,000 acre-ft	74	83	20	21
Total return flows	1,000 acre-ft	370	395	220	292
Salt load	1,000 tons	460	535	315	280
Nitrogen load	100 tons	13.3	15.0	12.3	11.6
Salt concentration	ppm	925	1,000	950	470

or farmer to mix return flows with good quality water (Tanji et al.). Since surface runoff is seldom collected or disposed of in separate facilities, the reuse potential of return flows may depend on using surface water supplies in a physically efficient manner to reduce the production of poor quality drainage water from subsurface drainage.

CONCLUSIONS

Section 208 of Public Law 92-500 establishes a planning activity to formulate policies to reduce the environmental impact of irrigation return flows. This paper presents estimates of the effect on return flows of raising water prices, and directly managing water-use efficiency. The water-pricing alternative is appealing because the associated implementation and enforcement costs are low, and the quantity of irrigation return flows is substantially decreased. However, the quality of return flows remains relatively constant.

The water management policy relies on institutional controls to require the water-use efficiency, through the specification of "best management practices", that could probably be achieved by administratively increasing the water price. However, this policy is attractive because the water quality goal can be achieved with the least amount of disruption to agricultural production and incomes. In other words, it is politically feasible, and probably will be adopted as the basis for the Section 208 plans. This approach has the disadvantage of requiring extremely high enforcement costs and large amounts of public investments in order to be effective. Another disadvantage is that this alternative will only provide for a least-cost solution if the production and damage functions for all water users are specified and incorporated into the set of controls. This would also require constant updating to account for changing input and commodity prices and technology.

A water pricing policy accounting for the opportunity cost of water, the social costs of use, and the conjunctive use of ground and surface sources is needed,but the institutional structure to implement such a plan does not exist in most areas. However, I believe that the idea of adjusting water prices to achieve socially desirable environmental goals should be considered in the Section 208 planning activity. Given the vague wording of the water quality goals of PL 92-500,and the lack of knowledge of the salt and nitrogen damage functions, it may be difficult to establish a pricing policy that would be acceptable to agriculture and environmentalists. These concerns would need to be addressed in further research.

This is an initial attempt to analyze alternative water quality policies. The model is a crude approximation of the economic, hydrological, and water quality parameters of the study area. However, it is flexible and disaggregated sufficiently to allow subroutines to be improved or added as additional information becomes available. The data requirements of the system are diversified and extensive. The San Joaquin River Basin staff provided most of the economic and physical data for this analysis. However, more detailed information on the variation of soil parameter values and ground water profiles is needed. The existing model presently provides a structure to formulate the irrigation return flow problem, with all of the complications and interdependencies,and provide usable results.

Increasing surface water prices should be considered as one policy alternative to reduce the environmental degradation caused by irrigation return flows. But without a conjunctive surface and ground water policy, and more knowledge of the return flow damage function, specific water management techniques and facilities will be required to achieve certain water quality goals.

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FOOTNOTES

1/ Water pollution control plans adopted by states are subject to approval by EPA. However, EPA can enforce its own regulations if states fail to do so, under default provisions in Section 303 (a)(3)(c) and 303 (b)(1).

2/ For example, the cost of water to a district serviced by the California Water Project is dependent upon the allocation to the district of costs of the Project facilities for conservation and transportation. The cost to the farmer will also include the cost of local conveyance systems for distribution of water.

3/ These markets may not derive the socially optimum allocation of water if significant temporal and externality effects are ignored.

4/ Water-use efficiency is defined as evapotranspiration divided by district water diversions.