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ECONOMIC ASPECTS OF SALINITY MANAGEMENT IN CALIFORNIA'S SAN JOAQUIN VALLEY: FARM-LEVEL AND REGIONAL CONSIDERATIONS

by

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Economic Aspects of Salinity Management
in California's San Joaquin Valley:
Farm-level and Regional Considerations

I. Introduction

Agricultural production in California's San Joaquin Valley is among the most efficient in the world. The Mediterranean climate provides an excellent environment for crop development. Rainfall occurs primarily in winter months and in magnitudes which are generally insufficient for supporting plant growth through the summer. Hence irrigation is an essential component of agricultural production in the region.

Over time, the salinity level of soils in many of the agricultural areas has increased. Salts are a natural component of most soils, arising from mineral decomposition. The rate at which this ongoing process produces various cations and anions generally poses no threat to plant productivity. However, irrigation water from both surface and groundwater sources contains varying levels of salts, depending on the quality of the particular water source. After each irrigation, the water is used by the plant or evaporated, while the salt component remains in the soil. If these salts are allowed to accumulate over time, their concentration may become deleterious to plant growth and productivity.

A. Farm-level Management

In order to maintain a soil salinity level which plants can tolerate, growers must apply water in excess of plant evapotranspiration requirements. This removes accumulated salts by leaching them through the soil profile. On soils which have poor hydraulic conductivity, various soil amendments can be applied to improve leachability. The combination of these practices has performed reasonably well where sufficient depth to the underlying water table has allowed for application of an appropriate leaching fraction of water.

In areas where impervious layers in the soil profile result in water tables being perched within several feet of the surface, the effectiveness of leaching may be diminished. Furthermore, if water tables are close to the surface, capillary action causes groundwater to move upward. If this water is saline, as is frequently the case in irrigated areas, this upward movement can contribute to salt accumulation in the root zone and diminish productivity of the land.

Where growers have been faced with both salinity and depth-to-groundwater problems, tile drainage or groundwater relief pumping has often been required in order to allow for adequate leaching. The common solution for a high water table is a subsurface drainage system consisting of perforated plastic pipe installed at regular intervals throughout a field at a depth of 5 to 7 feet. This system increases the subsurface drainage rate and controls water table depth. The quantity of drainage water collected must then be disposed.

Faced with soil salinity and depth-to-groundwater problems, growers have several options:

1. Not draining the land.
2. Draining the land and disposing of the drainage water into a proximal water course.
3. Draining the land and evaporating the drainage water in ponds constructed on the farm.

The first of these will result in diminished productivity of the land and possible removal from agricultural use over time. The second alternative allows the grower to maintain productivity but creates a disposal problem. The subsurface drainage water often contains quantities of salts and other chemicals which may not be desirable in rivers or irrigation delivery systems. As quantities of drainage water disposed into these receptacles have increased over time, regional authorities have become more aggressive in regulating these activities.

The third alternative is an internalization of the disposal problem. The grower sets aside a portion of land for use as an evaporation pond and collects the subsurface drainage water therein. The cost to the grower of implementing this option increases with the severity of the drainage problem. Acreage set aside in evaporation ponds will not provide agricultural output in the short-run and may require expensive reclamation activities for returning it to production in the long-run.

Additional alternatives include the improvement of irrigation water management techniques. This reduces the amount of drainage water discharged and thereby reduces the amount of evaporation acreage required, but the amount of salts being leached is only slightly reduced. The ultimate consideration is that of removing salts from the agricultural areas. Therefore, any long-term solution must include transport of the salts to a natural salt sink.

Researchers examining the farm-level salinity management problem have concentrated on practices such as leaching, the use of soil amendments, and the blending of irrigation waters of different quality (Feinerman and Yaron 1983, Llop 1978, Moore 1981). Results have described optimal strategies for dealing with water quality problems and their impact upon productivity. Dynamic analyses depicting the relative tradeoffs available for annual versus perennial crops have also been performed (Yaron and Voet). Optimal groundwater drainage strategies have also been examined (Fitz, Horner, and Snyder). Integrated analysis of the tradeoffs involved in the salinity/depth-to-groundwater problem has not been presented.

B. Regional Policy Questions

Several researchers have examined salinity and groundwater problems on regional or basin-wide levels. The concern is often one of optimally managing the quality and quantity of groundwater resources available over time (Cummings and McFarland, Howitt and Llop). Assumptions are generally made regarding farm-level response to salinity and groundwater conditions and to policies proposed by local or state authorities. In so doing, the important element of micro-level decision-making is virtually assumed away. This simplification can result in serious miscalculation of the actual outcome of policy implementation.

An example of this phenomenon pertaining to salinity and groundwater management is available in the San Joaquin Valley. The state of California and the U.S. Bureau of Reclamation have cooperated in constructing portions of a regional drainage water canal intended to provide disposal for growers in the region. Planners of the central drainage canal assumed that growers would be willing to pay expected costs of the system in order to dispose their drainage water into it. In actuality, most growers have elected not to commit themselves to the project, but rather have opted for evaporation ponds or changes in cropping patterns. A decision regarding completion of that facility is presently uncertain for these and other reasons.

Given this example and the nature of the salinity and groundwater problem, the necessity for consideration of micro-level responses when formulating regional policy is evident. The farm-level problem in dealing with salinity and groundwater depth is a dynamic one in which actions taken in one time period affect future yields and the effectiveness of actions taken in future periods. When a particular policy is implemented, growers will evaluate the relevant impacts and optimize over their farm-level alternatives. In response to policies, growers may elect to accept reduced yields, change cropping patterns, install drainage facilities or evaporation ponds, or discharge effluent into the water supply. Other management practices may also be employed.

In order to adequately evaluate regional salinity and groundwater problems, therefore, policy-makers require economic information at both the regional and farm levels. Optimal strategies selected by growers are necessary inputs in regional policy planning. Hence an integrated analysis to determine the economic tradeoffs between crop production and salinity management at the farm level is needed for policy analysis.

C. Externalities Present

Complicating the individual farmer's optimization problem are effects generated by farmers operating at higher elevations. The southern half of the San Joaquin Valley (the Tulare Hydrologic Subbasin) is a hydrologically closed basin. Both surface and underground flows of water tend to move from the edges of the subbasin to the center. As farmers at higher elevations within the subbasin irrigate their fields, water in excess of evapotranspiration requirements moves into the groundwater stock. This increases the flow of groundwater to areas of lower elevation in the subbasin. The result is a rising water table in areas of lowest elevation. As the water table rises in these areas, farmers have a more difficult task in leaching their fields to maintain productivity, since no natural outflow exists.

As lower elevation farmers attempt to deal with the rising water table, costs of production rise and net returns fall. As economic rents are dissipated, the ability of these growers to finance costly drainage projects is reduced even further. Economic theory suggests that these growers would be willing to pay the higher elevation farmers in order to avoid this loss of net returns. However, the transaction costs of estimating the magnitude of underground flows and identifying the responsible agents are formidable. Hence the market does not arise and an externality results.

II. Objectives

The objectives of this study were the following:

1. Develop a model for use in determining a farmer's optimal intertemporal strategy for managing soil salinity and groundwater resources.
2. Utilize the model to analyze representative situations in the San Joaquin Valley.
3. Examine the impact of intruding groundwater flows on a grower's optimal strategy.
4. Develop a conceptual model for use in describing the externalities present in the salinity and groundwater management problem.
5. Discuss regional policy implications.

III. The Farm-level Model

A. Conceptual Framework

Farm-level management of soil salinity and groundwater resources can be viewed in the context of manipulating the flow of services from durable inputs. In the case of salinity, these services are of negative value, while depth to groundwater provides both positive and negative effects. In situations where the groundwater depth is shallow and limiting to plant growth, increases in the depth would be of positive value. In other cases, increased costs of pumping groundwater for irrigation purposes may cause the value to be negative. In general, this would not apply to perched water tables, however, since the quality of water is often poor and unsuitable for irrigation purposes.

Given that these resources act as durable inputs, the dynamics involved in their generation and growth require consideration. In particular, salinity and groundwater can be regarded as stock resources, the levels of which may vary over time. The flow of services in any time period, then, is functionally related to the level of the stock. Factors influencing the rate at which these stocks change include exogenous physical relationships, management practices, and external effects. An individual farmer has direct control over management practices, takes physical relationships as given, and may be constrained by externalities generated by other growers.

1. The Physical Model

The farm-level optimization problem involves the management of these resource stocks over time so that the flow of services provided results in an optimal stream of income or wealth. A representation of the physical model governing the way in which these stocks change over time (equations of motion) is presented below. It is comprised of three principal equations pertaining to soil salinity, depth to the water table, and yield. This model acts as a constraint upon the intertemporal objective function discussed in the following section.

Soil Salinity

The level of salinity in the soil in any time period is a function of the previous salinity level and salts which have either entered or left the soil profile in the interim. Irrigation water introduces salts to the system, while leaching water can be applied to remove them. Soil amendments are applied to soils in order to improve the infiltration rate of water. The relationship can be posed as the following:

$$(1)\ SEC_t = \left[1 - \delta_1 k_1 (GW_t + SW_t + RF_{t-1}) - \delta_2 k_1 (1 + \gamma_1 SA_t) L_t\right] \cdot SEC_{t-1}$$

$$+ AEC\, k_2\, GW_t + SWS\, k_2\, SW_t + LEC\, k_2\, L_t + \gamma_2 SA_t$$

where:
SEC = salinity level of the soil extract (millimhos/cm)
GW = groundwater applied in irrigation (acre-feet/acre)
SW = surface water applied in irrigation (acre-feet/acre)
RF = annual rainfall (acre-feet)
L = leaching water applied for this purpose (a.f./acre)
SA = soil amendments applied (tons/acre)
GRP = groundwater relief pumping (acre-feet/acre)
AEC = salinity level of the groundwater
LEC = salinity level of the leaching water
SWS = salinity level of the surface water
δ_1, δ_2 = leaching parameters
k_1, k_2 = bio-linkage parameters (BLP's)
γ_1, γ_2 = soil amendment coefficients

The above equation depicts several important relationships. The bracketed term indicates the effect that physical quantities of water have upon the previous salinity level, by flushing salts through the soil profile. In addition, the interactive effect of soil amendments and leaching is represented. Soil amendments aid in reducing the salinity level of the soil only through their effect upon the leaching coefficient. In particular, soil amendments are generally applied in sodic situations in order to enhance soil pH and improve the infiltration rate of leaching water. Hence this variable is entered in an interactive fashion with leaching. The magnitude of the bracketed term will be less than one and its sign will be positive.

Remaining terms in equation (1) describe the manner in which the salt content of applied water and soil amendments adds to the salinity level in the current period. Values of the physical parameters were derived from existing models, where these were available.

Depth to the water table

The equation of motion describing current depth to the water table as a function of the previous level appears below. Applied water tends to bring the level closer to the surface, while groundwater relief pumping serves to move the level downward.

$$(2)\quad DWT_t = \alpha DWT_{t-1} - 5.0\,\delta_2(1+\gamma_1 SA_t)L_t + \rho GRP_t - 5.0\,\delta_1(GW_t + SW_t + RF_{t-1})$$

where: DWT = depth to the underlying water table (feet)
GRP = groundwater relief pumping (a.f./acre)
ρ = physical parameter linking acre-feet of groundwater pumped to increase in the depth to the water table

Externally generated impacts of lateral flows can be examined by varying the value of the GRP coefficient, rho, in equation (2). As a farm becomes more severely impacted by groundwater flowing from higher elevations, the value of rho will approach zero. This depicts the situation in which it becomes more difficult to alleviate a depth to water table problem and greater quantities of drain water are created in the process.

Yield

The third equation in the physical model describes the impact of soil salinity and depth to groundwater on yield in the current period. Parameters pertaining to salinity effects were obtained by fitting a quadratic function to linear relationships presented in Maas and Hoffman. Depth to water table coefficients were generated by fitting a general nonlinear function to data presented in Fitz, Horner, and Snyder. The resulting equation describes the percentage of total yield which can be achieved for a given soil salinity and depth to the water table. Inputs other than salinity management practices are held constant. This generates the following relationship:

$$(3) \quad y_t = \phi_1 - \phi_2 (SEC_t)^2 + \phi_3 (DWT_t)^{\phi_4}$$

where: y = percent of total yield expected in a situation not adversely affected by soil salinity or depth to groundwater problems

eg. barley: ϕ_1 = .02, ϕ_2 = .00125, ϕ_3 = 0.58, ϕ_4 = 0.35

cotton: ϕ_1 = .04, ϕ_2 = .00167, ϕ_3 = 0.60, ϕ_4 = 0.40

Implications of the physical model

Examination of final form equations (Kmenta) of the above model provides additional insight into the intertemporal nature of the problem. For example, recursive substitution of lagged salinity levels into equation (1) yields the following final form relationship:

$$(4)\quad SEC_t = a\sum_{i=0}^{t-1}\prod_{j=-1}^{i-1} bk_j + \prod_{j=0}^{t-1} bk_j\, SEC_0 + \sum_{i=0}^{t-1}\left(\prod_{j=-1}^{i-1} bk_j\right) LSA_i$$

where: $a = AEC\, k_2 GW + SWS\, k_2 SW$

$bk_j = 1 - \delta_1 k_1 (GW + RF + SW) - \delta_2 k_1 (1 + \gamma_1 SA_{t-j}) L_{t-j}$

$LSA_i = LEC\, k_2 L_{t-i} + \gamma_2 SA_{t-i}$

$bk_{-1} \equiv 1$

SEC_0 = *initial soil salinity*

Derivatives describing the change in soil salinity due to the use of leaching or soil amendments in any time period can then be described. Using the final form notation, a three period example is provided below:

$$\begin{aligned}(5)\quad SEC_3 = {} & a + a\, bk_0 + a\, bk_0\, bk_1 + bk_0\, bk_1\, bk_2\, SEC_0 \\ & + LEC\, k_2 L_3 + \gamma_2 SA_3 \\ & + bk_0 (LEC\, k_2 L_2 + \gamma_2 SA_2) \\ & + bk_0\, bk_1 (LEC\, k_2 L_1 + \gamma_2 SA_1)\end{aligned}$$

The current period derivative with respect to leaching is:

$$\begin{aligned}(6)\quad \frac{\partial SEC_3}{\partial L_3} = {} & -\delta_2 k_1 (1 + \gamma_1 SA_3)\Big[(a + a\, bk_1 + bk_1\, bk_2) SEC_0 \\ & + (LEC\, k_2 L_2 + \gamma_2 SA_2) + bk_1 (LEC\, k_2 L_1 + \gamma_2 SA_1)\Big] \\ & + LEC\, k_2\end{aligned}$$

Similarly, the current period derivative for the use of soil amendments is:

$$(7)\ \frac{\partial SEC_3}{\partial SA_3} = -\delta_2 k_1 \gamma_1 L_3 \Big[a + a\,bk_1 + bk_1\, bk_2\, SEC_0 + (LEC\, k_2 L_2 + \gamma_2 SA_2) + bk_1 (LEC\, k_2 L_1 + \gamma_2 SA_1) \Big] + \gamma_2$$

These relationships display the dynamic interactions between leaching and soil amendments as they affect soil salinity.

The final form equation for depth to the water table can be described in a similar fashion:

$$(8)\ DWT_t = \alpha^t DWT_0 - 5.0\,\delta_2 \sum_{i=0}^{t-1} \alpha^i (1 + \gamma_1 SA_{t-i}) L_{t-i} + \rho \sum_{i=0}^{t-1} \alpha^i GRP_{t-i} - 5.0\,\delta_1 \sum_{i=0}^{t-1} \alpha^i (GW_{t-i} + SW_{t-i} + RF_{t-1-i})$$

This relationship allows for description of the dynamic multipliers as follows:

$$(9)\ \frac{\partial DWT_t}{\partial L_s} = -5.0\,\delta_2 \alpha^{t-s} (1 + \gamma_1 SA_s)$$

$$(10)\ \frac{\partial DWT_t}{\partial SA_s} = -5.0\,\delta_2 \alpha^{t-s} \gamma_1 L_s$$

$$(11)\ \frac{\partial DWT_t}{\partial GRP_s} = \rho^{\alpha^{t-s}}$$

The final form equation for yield is obtained by simple substitution of equations (4) and (8) into (3). The derivatives of interest become:

$$(12)\ \frac{\partial y_t}{\partial L_a} = \frac{\partial y_t}{\partial SEC_t}\cdot\frac{\partial SEC_t}{\partial L_a} + \frac{\partial y_t}{\partial DWT_t}\cdot\frac{\partial DWT_t}{\partial L_a}$$

$$= \left(-2\phi_2\, SEC_t\right)\frac{\partial SEC_t}{\partial L_a} + \left(\phi_3\phi_4\left(DWT_t\right)^{\phi_4-1}\right)\frac{\partial DWT_t}{\partial L_a}$$

$$(13)\ \frac{\partial y_t}{\partial SA_a} = \left(-2\phi_2\, SEC_t\right)\frac{\partial SEC_t}{\partial SA_a} + \left(\phi_3\phi_4\left(DWT_t\right)^{\phi_4-1}\right)\frac{\partial DWT_t}{\partial SA_a}$$

$$(14)\ \frac{\partial y_t}{\partial GRP_a} = \frac{\partial y_t}{\partial DWT_t}\cdot\frac{\partial DWT_t}{\partial GRP_a} = \phi_3\phi_4\left(DWT_t\right)^{\phi_4-1}\cdot\frac{\partial DWT_t}{\partial GRP_a}$$

The signs of these derivatives will depend on signs and magnitudes of the individual components.

2. An Intertemporal Criterion

The objective function of the individual farmer can be described as maximization of the discounted stream of net revenues derived from crop production, subject to constraints imposed by the physical model. The continuous formulation of this criterion appears below:

$$(15)\qquad \max_{x}\ PV = \int_0^T e^{-rt} f(y_t, x_t, t)\,dt \qquad \text{subject to: } \dot{y} = g(y,x),\quad y(0) = y_0$$

where:
- PV = present value
- y = state variables (Y, SEC, DWT)
- x = control variables (L, SA, GRP)
- g = physical model containing the equations of motion for the states
- r = discount rate

This generates the following Hamiltonian function:

$$(16) \qquad H_t = e^{-rt} f(y_t, x_t) + \lambda_t g(y_t, x_t)$$

Invoking Pontryagin's maximum principle results in the following necessary conditions for an intertemporal optimum:

$$(17) \quad \frac{\partial H_t}{\partial x_t} = 0 \Rightarrow e^{-rt} \frac{\partial f(\cdot)}{\partial x_t} = -\lambda_t \frac{\partial g(\cdot)}{\partial x_t} \quad , \forall_t$$

$$(18) \quad -\frac{\partial H_t}{\partial y_t} = \dot{\lambda}_t \Rightarrow \dot{\lambda}_t = -e^{-rt} \frac{\partial f(\cdot)}{\partial y_t} - \lambda_t \frac{\partial g(\cdot)}{\partial y_t}$$

$$(19) \quad \frac{\partial H_t}{\partial \lambda_t} = \dot{y}_t \Rightarrow \dot{y}_t = g(y, x)$$

The intertemporal nature of the problem is fully embodied in these relationships. In particular, equation (17) implies that the current period marginal cost of a control must be equated to the discounted value of all future benefits provided by using that control in the present. Equation (18) describes how the marginal values of the groundwater and salinity stocks change over time. The first term on the right-hand-side of equation (18) displays the immediate payoff to current stock levels, while the second term reflects the marginal value of growth in these stocks. Equation (19) requires satisfaction of constraints implied by the equations of motion which comprise the physical model. The dynamic derivatives described above must be considered in determining the optimal path of controls and states over time.

B. Analysis

Given this intertemporal model of salinity and groundwater management, farm-level optimization can be analyzed in the context of optimal control theory. At the farm level, growers have available a set of instruments (L, SA, GRP) to use in achieving an optimal trajectory of state variables (SEC, DWT, Y) over time. The optimal path will vary given different initial conditions and physical parameters pertaining to different locations, but the conceptual framework will remain the same. Additionally, the impact of external groundwater pressures on a farmer's optimal strategy can be evaluated.

Initial calibration of the physical model presented above was performed. Given an initial soil salinity level of 7.0 mhos and a depth to the water table of 5 feet, the time path of states in the absence of controls is presented in Table 1. As irrigated farming continues over time, salinity increases, while the depth to water table decreases, resulting in yield reductions. It is this path of states which the grower attempts to avoid by selecting optimal values of the control variables.

The Hamiltonian formulation presented above is a general framework for examining intertemporal optimization problems. Maximization of discounted net returns is a valid economic criterion and is applicable to the situation at hand. For purposes of this study, however, a special case of objective function formulation was employed. In particular, quadratic tracking criteria were examined in order to exhibit dynamic properties of the physical model and derive implications for regional policy. In areas where resource degradation is a pressing concern, grower objective functions may actually include maintenance of productivity and the tracking of desired state variable levels.

Given this motivation, a six-period model was constructed using coefficients pertaining to barley production. The three state variables and three controls discussed above were included in the model. Three sets of analyses were selected for initial investigation:

A. Tracking yield, soil salinity, and water table depth

B. Tracking these three states, subject to instrument costs

C. Tracking yield only, subject to instrument costs

A Broyden-Fletcher-Goldfarb-Shanno (BFGS) symmetric update algorithm was interactively employed to obtain solutions to the nonlinear optimization problem. Desired levels of state variables were entered as 2.0 tons for yield, 7.0 mhos for soil salinity level, and 5.0 feet for depth to groundwater. The yield value was chosen to represent expected output in the absence of salinity and drainage problems. The salinity and groundwater levels reflect commonly perceived threshold levels for these variables. That is, at salinity levels less than 7.0 mhos and depth to groundwater greater than 5.0 feet, yield reductions are not expected. Convergence criteria were selected from those presented in Gill, Murray, and Wright (1981, p. 306).

1. Tracking yield, salinity, and water table depth

The first criterion examined in this analysis was that of minimizing the sum of squared deviations from desired paths for yield, soil salinity, and depth to the underlying water table. In particular, the following criterion was specified:

$$(19) \quad \min_{x} L = e'Qe$$

$$\text{subject to: } e = y^{*} - C(x)x$$

where:
- y^{*} = vector of desired levels of state variables after accounting for uncontrollable exogenous effects (18 x 1)
- x = vector of control variables (18 x 1)
- $C(x)$ = nonlinear function of the controls (18 x 18)
- Q = penalty matrix on the states (18 x 18)

This quadratic criterion describes a situation in which the grower desires to maintain productivity while holding salinity and water table depth at predetermined levels, irregardless of any instrument costs.

Results pertaining to the initial tracking problem appear in Tables 2 through 5. It is helpful to recall the importance of the parameter "rho" in this analysis. As noted above in equation (2), rho represents the effectiveness of groundwater pumping in alleviating a depth to water table problem. In general, one would expect that for every acre foot of groundwater pumped in this manner, depth to the underlying water table would increase by 4 to 5 feet. This is due to the way in which water is located throughout the soil profile. A rho value of 4.0 describes a situation in which one acre foot of groundwater relief pumping will result in a 4-foot increase in the depth to water table.

In a situation where lateral flows of groundwater contribute to the water table problem, the effectiveness of relief pumping may be diminished. For example, each acre foot removed may only increase the depth by two or three feet, as lateral flows move into the area. Basic hydrologic relationships determine this phenomenon. A rho value of 2.0 describes a situation in which an acre foot of groundwater relief pumping results in a 2-foot increase in depth to the water table.

In order to examine salinity management alternatives in situations unaffected by lateral flows of groundwater and those cases where the effectiveness of groundwater relief pumping is diminished in this manner, rho values of 4.0 and 2.0 were used, respectively.

Results pertaining to the initial tracking problem with a rho value of 4.0 appear in Table 2. The optimal level of groundwater relief pumping diminishes over time, while leaching rises in the first three years and then declines. Given this set of physical parameters, the use of soil amendments is not included in the optimal solution. This result verifies comments by Cooperative Extension Service specialists regarding the non-existence of infiltration problems in areas where groundwater intrusion occurs. These results reflect dynamic interactions in the model.

In order to examine a situation in which the grower is faced with more severe initial conditions, the starting soil salinity was increased to 9.0 mhos. Results of the tracking problem associated with this initial value appear in Table 3. Leaching in early periods is greatly increased in order to flush the high level of salts from the soil. Higher levels of groundwater relief pumping are required in each time period in order to maintain water table depth in the presence of increased leaching.

As discussed above, the impact of intruding groundwater flows can be examined by varying the value of rho in the model. Maintaining the simple quadratic criterion, the value of rho was reduced from 4.0 to 2.0 and the model was re-evaluated. Optimal instrument paths pertaining to initial salinity levels of 7 and 9 mhos appear in Table 4 and Table 5, respectively. In each case, the levels of groundwater relief pumping are approximately doubled while the leaching values are only slightly altered. Implications of these increased groundwater relief pumping levels for regional policy planning are discussed in Section V.

2. Tracking three states, subject to instrument costs

The quadratic criterion examined above is simplistic in its omission of instrument costs. A truly economic criterion should include these in order that the marginal benefit of reducing deviations from a desired target level may be equated with the marginal cost of doing so. An improved criterion would therefore be the tracking of desired state variable levels over time, subject to instrument costs. In this study, instrument costs included the costs of using soil amendments, applying leaching water, and pumping groundwater from the soil. Costs associated with obtaining information on the state variables were not considered.

The following criterion was specified:

$$(20) \quad \min_{x} L = e'Qe + x'Rx$$

$$\text{subject to: } e = y^{*} - C(x)x$$

where: R = a penalty matrix on the controls (18×18)

Initial examination was performed using an identity matrix in the place of R in the above formulation. This implies that the instrument costs are the same. In order to stress the importance of tracking crop yield within this framework, a weight of 10 was placed on deviations from this state variable, while soil salinity and depth to groundwater retained weights of unity. This formulation describes a situation in which maintenance of crop yield is of primary importance and allows for some intertemporal movement in salinity levels and water table depths.

Results of this analysis pertaining to an initial salinity level of 7.0 mhos and a rho value of 4.0 appear in Table 6. Comparison of optimal instrument values with those presented in Table 2 yields several important points. Primarily, the amount of groundwater relief pumping performed in each time period is significantly reduced. The use of soil amendments becomes more prominent and allows for a smaller amount of leaching water to be applied in each year. Soil salinity is allowed to increase over time, but remains below the 8.0 mhos level. These results indicate that it may be economically rational to allow soil salinity to increase above the 7.0 level when instruments are not costless.

The present specification was re-examined with a rho value of 2.0 (Table 7). As expected, the rates of groundwater relief pumping were higher and leaching applications declined. Furthermore, the use of soil amendments was no longer optimal. Soil salilnity was allowed to increase above the 8.0 mhos level. These results indicate that intruding groundwater flows may have an even greater impact on growers in the presence of instrument costs.

3. Tracking yield, subject to instrument costs

Inclusion of instrument costs in the criterion function has added richness to the model specification. However, additional usefulness may yet be gained by introducing even greater flexibility into the objective function. In particular, pre-selection of the desired levels of soil salinity and depth to groundwater imposes a restriction on the model. In actuality, this framework may be useful in determining the truly optimal intertemporal paths for these state variables.

A more appropriate model criterion might therefore be the tracking of desired <u>yield levels only</u> over time, subject to instrument costs. This would allow for selection of the optimal paths for soil salinity and depth to groundwater. The following criterion was specified and examined:

(21) $$\min_{x} L = e1'Q1e1 + x'Rx$$

subject to: $e1 = y1^{*} - C1(x)x$

where: $y1^{*}$ = vector of desired levels of yield after accounting for uncontrollable exogenous effects (6 x 1)

$C1(x)$ = that portion of the nonlinear model pertaining to yield (6 x 18)

$Q1$ = penalty matrix on yield values (6 x 6)

Initial examination was performed using weights to describe the relative costliness of deviations from yield and the instruments. The R matrix in this case is a diagonal matrix of instrument costs. In particular, a weight of 100 was placed on yield deviations, while costs of 3, 5, and 1 were placed on leaching, soil amendments, and groundwater relief pumping, respectively. Given the quadratic framework, these weights were chosen to reflect the relative costs of the three instruments. In pertinent areas of the San Joaquin Valley, leaching water is less expensive than soil amendments on a per acre basis and the variable cost of groundwater relief pumping is minimal.

Results of this analysis for an initial salinity level of 7 mhos appear in Table 8. Given these cost coefficients, salinity is allowed to increase over time, while depth to the water table is maintained at the five foot level. This indicates that it is more economical to allow for some yield reduction due to salinity than to drive the salt level downward.

Results pertaining to an initial salinity level of 9 mhos appear in Table 9. In this scenario, soil salinity is maintained around the 9.0 level and depth to the water table is kept at five feet. Leaching is applied in order to maintain the initial salt level, but it is not used in quantities sufficient to reduce soil salinity over time.

An additional set of analyses pertains to the groundwater disposal externality discussed above. As social agencies have become more concerned with the dumping of subsurface drainage water into adjacent streams and rivers, several policy alternatives have arisen. In some areas, growers have been prohibited from discharging these waters into natural water courses. In other areas, effluent taxes have been discussed as a means of requiring lower elevation growers to internalize the effects of their disposal activities. In either case, the cost of groundwater relief pumping rises substantially as disposal is no longer a virtually free good.

In order to examine the impact of such an instrument price increase on a grower's optimal strategy, the penalty coefficient on groundwater relief pumping was increased to a value of 15. Results pertaining to initial soil salinity levels of 7 and 9 mhos appear in Table 10 and Table 11. Comparison of these results with those in Table 8 and Table 9 reveals an interesting result. In the case of lower initial salinity (Table 10), the significant increase in the price of groundwater relief pumping motivates more efficient use of this instrument without any corresponding reduction in depth to the water table. Leaching remains economically sub-optimal and hence the yield scenario is similar to that in the free disposal situation.

In the case of higher initial salinity (Table 11), groundwater relief pumping is significantly reduced and leaching becomes economically sub-optimal. This result differs from that in the free disposal situation and hence salinity levels rise steadily over time. The resulting set of yield values is lower than those in the unconstrained case.

B. Regional Considerations

1. The Standard Externality Model

Literature pertaining to the economic aspects of externality theory is well developed. Pigou provided an early description of external effects as they pertained to divergence between "private" and "social" costs. He suggested that a system of taxes and subsidies may be used to eliminate this divergence and motivate private agents to produce socially optimal output levels. Coase examined the nature of bargaining undertaken to achieve an optimal solution in the presence of externalities. He concluded that initial assignment of property rights was irrelevant to achievement of a Pareto optimal outcome. However, this result depends upon the insignificant magnitude of relevant transaction costs. Externality theory was further developed in the late 1960's and 1970's. Mishan provides a survey of postwar efforts and Baumol and Oates present more recent and rigorous conclusions.

In general, an externality exists when the private economy lacks sufficient incentives to create a market in some good and a loss of Pareto efficiency occurs (Heller and Starrett). The task for policy-makers, then, is that of providing agents with the motivation to internalize these external effects. This can be accomplished through the use of taxes, subsidies, effluent standards, and other policy instruments.

With respect to pollution externalities, the common setting is one in which one set of economic agents is affecting the utility of another group through its production or consumption activities. The planner's objective is to maximize social welfare by considering both environmental quality and output goals (Hochman and Zilberman). It has been shown that taxes are the most efficient means of achieving a given level of environmental quality, but that effluent standards result in a higher level of output and lower product price (Baumol and Oates). This is one explanation for the relative abundance of standards versus taxation policies (Buchanan and Tullock).

Empirical examination of pollution externalities has been facilitated by use of the putty-clay technology approach developed by Johansen and Salter. This technique allows for description of a distribution of input-output coefficients for an industry, given that capital inputs are fixed in the short-run. From this distribution, an aggregate short-run supply function can be derived. This function provides the analytical tool for investigating the response of an industry to potential pollution-control policies. Implementation of this technique has provided useful information regarding the tradeoffs between taxation and effluent standards (Moffitt, Zilberman, and Just).

In order to evaluate the welfare effects of environmental policy, a model of the potential response of economic agents to various alternatives is required. As noted above, the putty-clay model of technology has been useful in this regard. This approach allows for description of firms in terms of short-run input-output parameters. These may also include parameters which describe the amount of pollution generated per unit of output and the amount of inputs required to abate a unit of pollution.

The principle feature of the putty-clay model is the existence of two production functions for the firm: 1) ex ante and 2) ex post. In the *ex ante* case, the firm can choose its technique of production; that is, its capital stock. Once this has been done, the firm faces an *ex post* production function in which the input-output ratios are fixed. That is, for a given level of capital which is fixed in the short-run, the firm may alter only its variable inputs. In the putty-clay model, the rate at which output changes in response to variable inputs is fixed in the short-run.

The short-run input-output ratios of firms in an industry can be measured by use of econometric methods. An industry or group of firms can then be described by its distribution of input-output ratios. For example, let l denote the short-run labor-output ratio of a firm. Then there exists a feasible set in any period of $(0,\bar{l}]$,* where $\bar{l}$ is the largest input-output ratio in the industry. One can then define a capacity density function g(l), such that $g(\hat{l})\Delta l$ indicates approximately the output capacity of firms in which l is between $\hat{l}$ and $\hat{l} + \Delta l$, where Δl is small. More rigorously, the aggregate output capacity can be obtained by integrating g(l) over a segment of l values.

Profit maximization on the part of firms in an industry ensures that firms operate when quasi-rents are positive. Therefore, firms in which p - wl is greater than zero, where p and w are the prices of output and labor, will operate in the short-run. For a given set of output and labor prices, then, the output of the industry is the output capacity of all firms with non-negative quasi-rent. For example, given initial prices of p_1 and w_1, industry output is the area under g(l) up to this price ratio (Figure 1). If output price is increased, the area under g(l) will also increase. This generates the aggregate supply response function. Similarly, if the wage rate is increased while output price is held constant, aggregate output will fall.

As noted above, the putty-clay method is easily extended to include pollution-output ratios and pollution abatement coefficients. Therefore, notation and concepts pertaining to putty-clay models are used throughout the developments in this paper.

* Note that this is the letter l, and not the number 1.

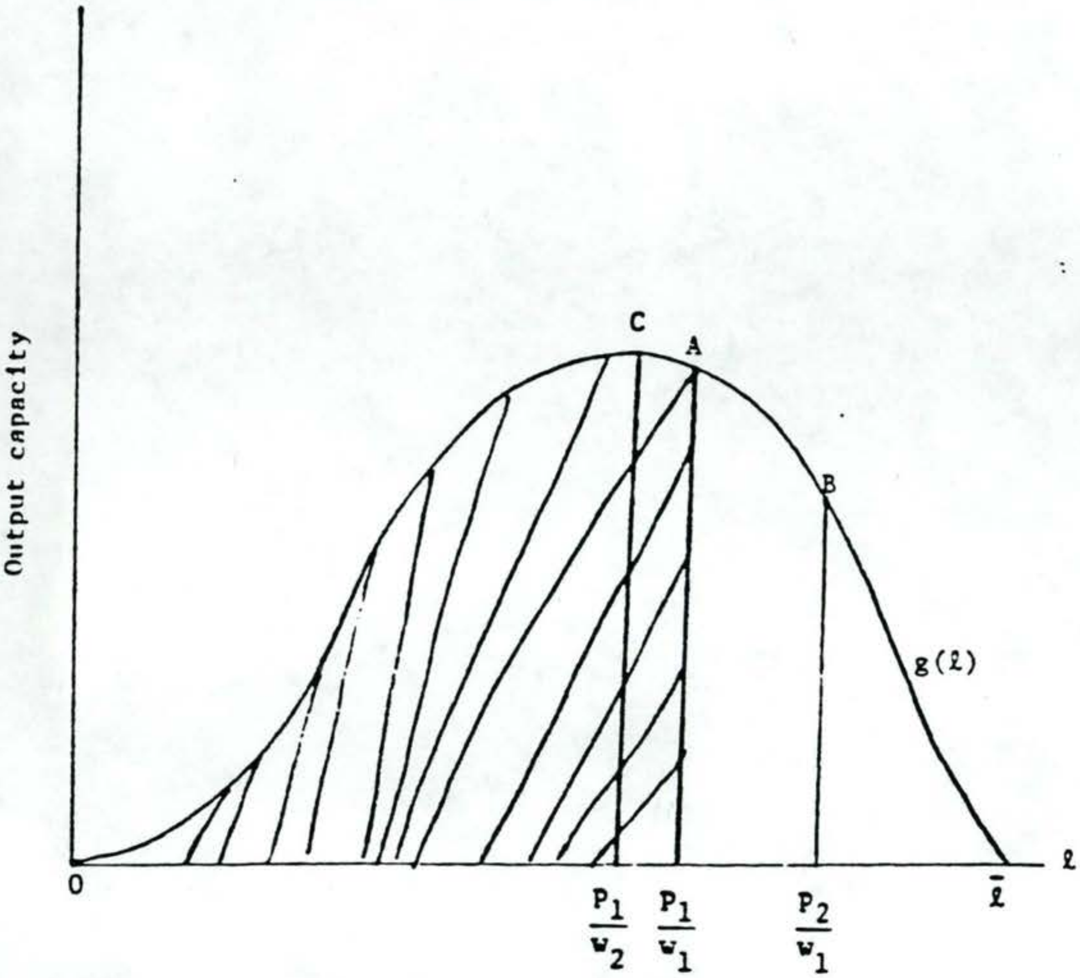


FIGURE 1. The Determination of Output in a Johansen Model

2. The Pivotal Externality Model

The literature and examples noted above pertain to the standard case of two groups of agents: a set of pollution generators and a set of agents (or society) being affected. An additional case of interest is that in which three groups of economic agents are involved in a special way. In particular, one group of agents generates the pollution as a result of production or consumption activities. A second set of agents is affected by the pollution and would be willing to compensate the generators in order to avoid these effects. However, insufficient incentives exist for market formation (eg. high transaction costs) and an externality results. Meanwhile, the second set of agents, in carrying out its production or consumption activities, transforms the nature of the externality while subsequently affecting a third set of economic agents. The second group is effectively "passing along" some of the original external effects, but does not account for this action in its own utility function. The third set of agents is affected by these external effects and is willing to pay in order to avoid them, but a market still does not arise. Hence the externality persists, although its characteristics have been altered by the second set of agents.

The important feature of this type of externality is the way in which its characteristics are altered by the second group of agents. In particular, the transaction costs of potential market formation are transformed from a very high level to a relatively low one. This suggests that market formation and/or policy action will be more likely to occur among the second and third sets of agents and may not include the first group.

This type of externality, in which a set of economic agents significantly transforms the transactions costs of market formation and/or policy action is defined as a pivotal externality. Within this framework, the first group of agents is viewed as the generators of the externality and the second group contains the pivoters. The action which renders an agent pivotal is that consumption or production activity which significantly transforms the transaction costs.

A pivotal externality is defined herein as an absence of market formation (in a Heller and Starrett sense) in which an intermediate set of agents significantly transforms the transaction costs of market formation and/or policy actions. The example of groundwater intrusion and disposal problems existing in the San Joaquin Valley can be described within this framework.

As noted above, intruding groundwater flows affect the ability of growers to leach salts from the soil. The lower elevation growers adjust their methods of production in order to cope with these external effects. One important practice is the pumping of groundwater out of the soil profile. This lowers the water table and allows for leaching and plant growth to occur. As this groundwater is pumped from the ground it must also be disposed. Whereas the water often contains concentrated levels of salts and other deleterious elements, it is not directly suitable for reuse as irrigation water. Many lower elevation growers are located proximal to rivers, however, and the cost of pumping this excess water into a stream is relatively low. A river, then, is often chosen by the grower as the disposal option. Formal disposal rights, however, have not been granted to many farmers in the area.

Over time, as the magnitude of these problems has increased, public agencies have become concerned about the groundwater being disposed into the rivers. As noted above, concern exists regarding salts and pesticides in the drainage water. Society has proceeded to claim a property right to clean water in the river and has not permitted lower elevation growers to dispose of drainage water. At this point, transaction costs of identifying the agents responsible for the pollution and measuring the effluent of each are relatively low. The lower elevation growers who are dumping water into the river (often at point sources) become the public agency's focal point in eliminating the externality.

The key feature of the groundwater intrusion and disposal problem which renders it a pivotal externality is the switching of transaction costs from very high to very low as a result of production activities on the part of lower elevation growers. These agents become the pivoters in this problem and the higher elevation growers are the generators (Figure 2). From a policy perspective, efficiency gains may be realized by considering not just the lower elevation growers, but also those at higher elevations, as they represent the source of increased groundwater flows.

The pivotal externality model described above can be formulated using the putty-clay technology framework. In this setting, there exists two sets of firms, generators and pivoters (I and J). Each of these sets will possess a different capacity density function, as technology and capital stocks will differ among the agents in each. In addition to the labor-output and pollution-output coefficients already described, a parameter denoting the amount of labor required to abate a unit of pollution is added to the putty-clay model. This parameter, l_2, will also vary among firms in the two sets of agents. The model is depicted in Figure 3, where g and p superscripts denote generators and pivoters, respectively, and Z represents pollution.

The important linkages between the generators and pivoters can be decribed in terms of the model parameters. For example, γ_i^p is functionally related to Z^g. That is, the amount of water which must be pumped out and disposed is a function of the amount of pollution entering the lower elevation area. Furthermore, l_{1i}^p is related to Z^g in a

Figure 2.

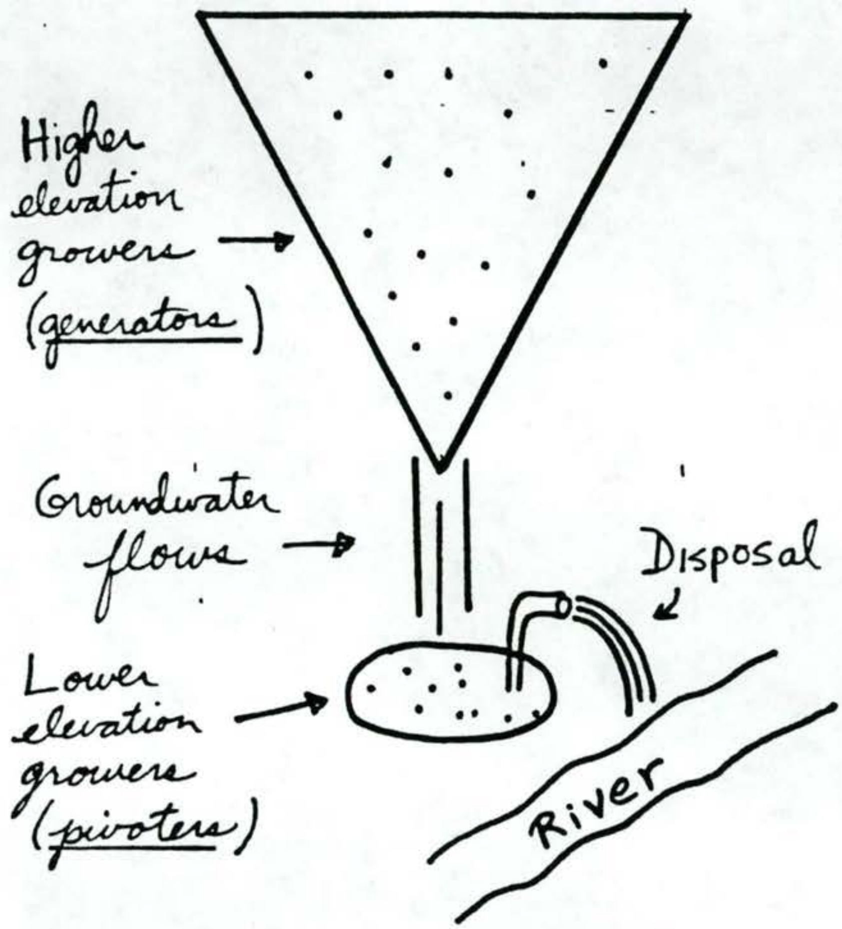
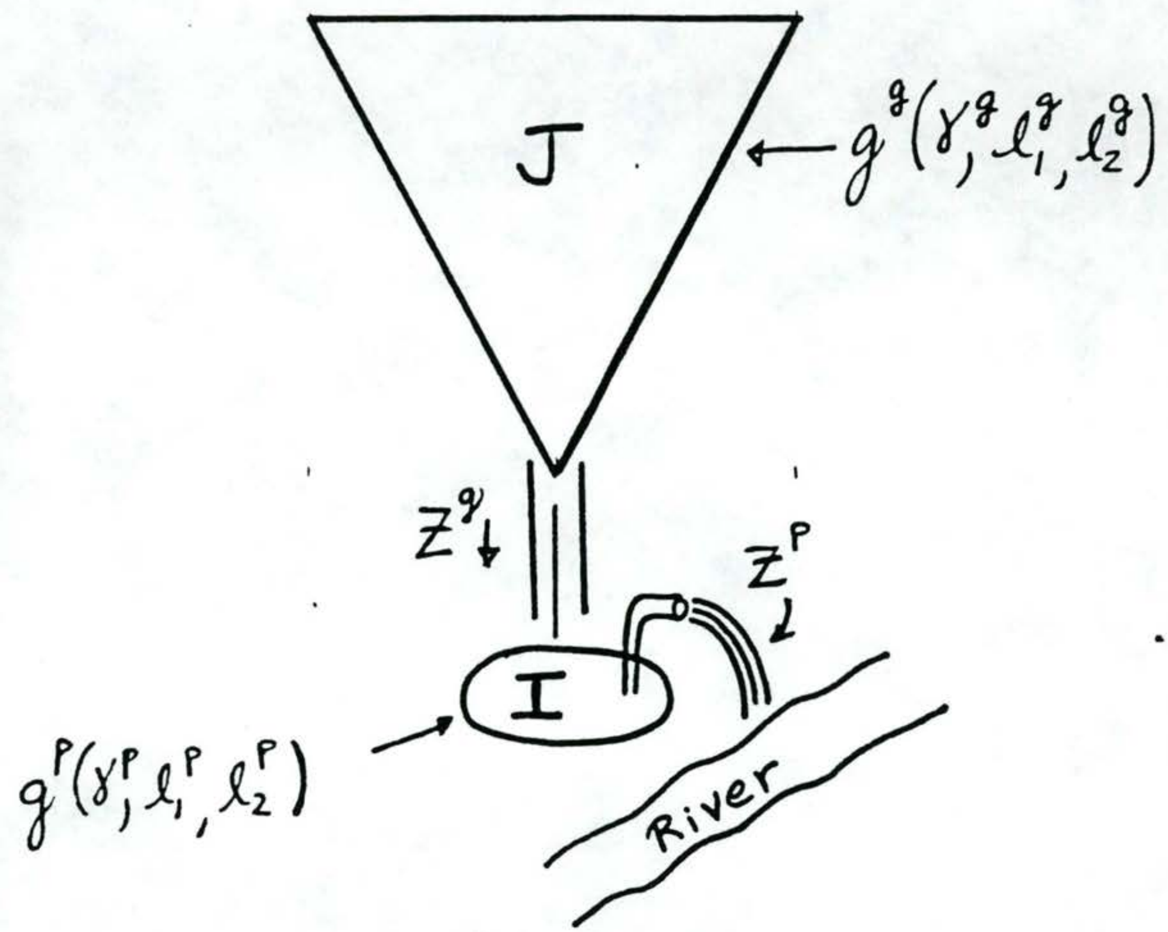

Higher elevation growers (generators)
Groundwater flows
Disposal
Lower elevation growers (pivoters)
River

Figure 3.

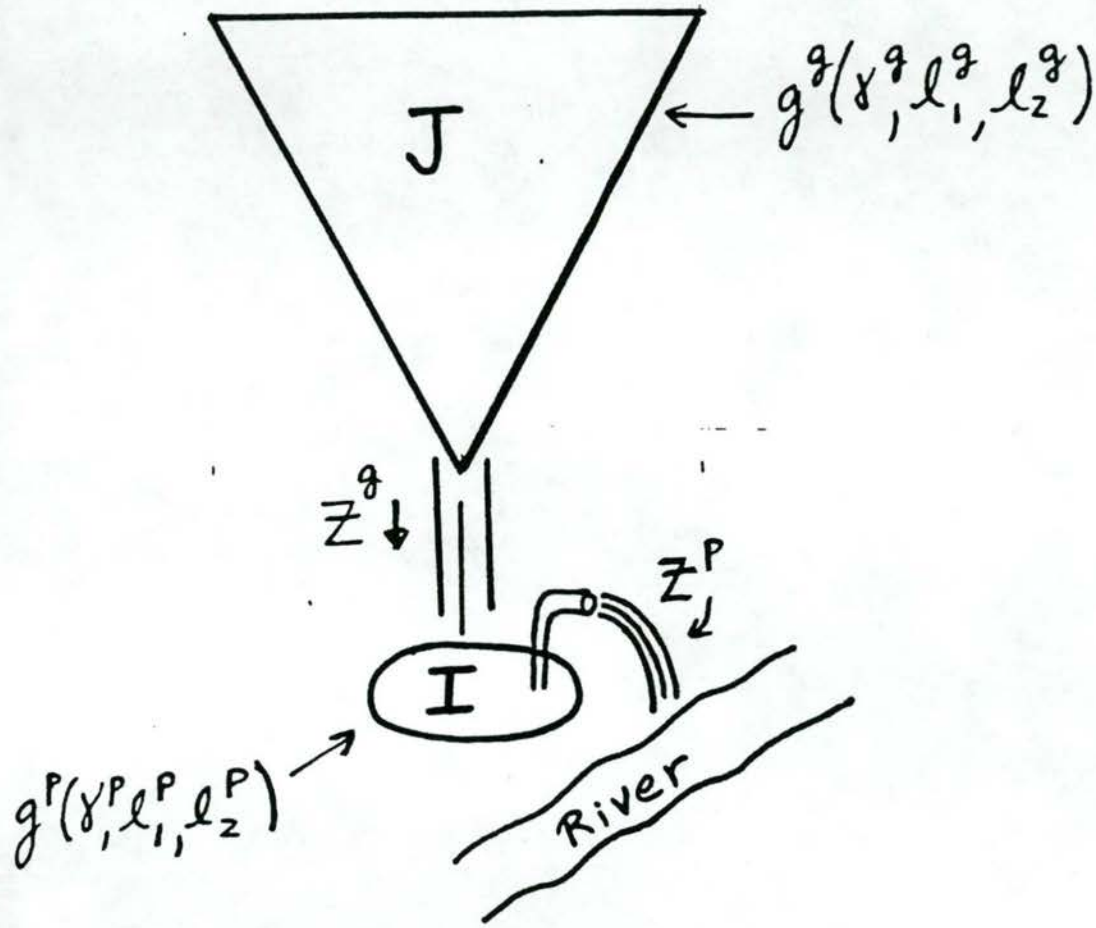


similar fashion. The variable costs of production in the lower elevation region are in part dependent upon the amount of groundwater flows. As these increase, the efficiency of labor used in production decreases.

An additional point which merits consideration during policy evaluation is that γ_j^g is <u>endogenous</u> on the part of the generators, while γ_i^p is largely <u>exogenous</u> to the pivoters. The generators have control over γ_j^g by selecting different irrigation technologies and/or varying the amount of water applied. These factors affect the rate at which excess water will enter the aquifer. Pivoters, however, accept γ_i^p as given and cannot alter its value. Hence there exists an extra "degree of freedom" with respect to the generators versus the pivoters in this regard. In areas of low water prices, it may even be possible to reduce γ_j^g significantly with minimal impact on net returns. Recalling that Z^g is just the sum of pollution amounts produced by each firm, the importance of this consideration becomes evident.

A further note of interest pertains to the labor efficiency coefficients. It is likely that both l_1 and l_2 are lower in magnitude for most of the generators than for most of the pivoters. This would reflect greater efficiency in both production and pollution abatement at the higher elevations. The complete model, including linkages and notes, is presented in Figure 4.

Figure 4.



Linkage:

$\gamma_i^p = h_1(Z^g) \; \forall_{i \in I}$

$l_{1i}^p = h_2(Z^g) \; \forall_{i \in I}$

Notes:

a) γ^g endogenous to generators
γ^p exogenous to pivoters

b) $l_1^g < l_1^p$ for most $i \in I, j \in J$.

c) $l_2^g < l_2^p$ for most $i \in I, j \in J$.

3. Analysis

Given the pivotal externality model outlined above, implications pertaining to the public planner's objective function can be derived. In particular, parameter linkages described above should be included in order to achieve an efficient solution to the problem. Consideration of these linkages exploits the pivotal aspect of the externality and allows for efficiency gains which may arise from the relationship between pivotal and generating agents.

In the groundwater intrusion example, concerns regarding the efficiency of policy alternatives arise. For example, a policy focusing on the pivoters alone may result in many of these agents terminating production. The question, then, is to what extent pivoters will be forced from operating while maintaining productivity of the generators. By examining the full pivotal nature of the problem, it may be possible to determine whether or not the socially optimal solution involves allowing the pivotal region to become a natural valley sump in this example.

An initial revision of the standard social objective function is presented in Figure 5. In this model, consideration of pivotal characteristics is reflected in the objective function and constraints. In particular, the social planner is now choosing the generators' total output and pollution level, X^J and Z^g, in addition to X^I. The levels of output for which pollution is abated are also

Figure 5. Social Objective Function

$$\max_{X^I, X^J, Z^g, X_A^I, X_A^J} \int_0^{X^I+X^J} D^{-1}(\varepsilon)\,d\varepsilon - w\left[l_1^p X^I + l_1^g X^J\right] - w\left[l_2^p \gamma^p X_A^I + l_2^g \gamma^g X_A^J\right] - b^p \gamma^p X_A^I - b^g \gamma^g X_A^J \tag{20}$$

s.t. $X_A^I + X_u^I \equiv X^I$, $X_A^J + X_u^J \equiv X^J$

$\gamma^p X^I - \gamma^p X_A^I \leq \bar{Z}^p$, $\gamma^g X^J - \gamma^g X_A^J \leq Z^g$

$X^J \leq \bar{X}^J$, $X^I \leq \bar{X}^I$

$\gamma^p = h_1(Z^g)$, $l_1^p = h_2(Z^g)$

where: $D^{-1}(\cdot)$ is an inverse demand function

X_A^I is output for which pollution is abated

X_u^I is output for which pollution is unabated

$\gamma^p X_A^I$ is an amount of pollution abated

b^p, b^g are transaction costs per unit of pollution abated.

Figure 5, continued. A Lagrangian

$$\max_{\substack{X^I, X^J, z^g \\ X_A^I, X_A^J}} \quad \mathcal{L} = \int_0^{X^I + X^J} D^{-1}(\varepsilon)\, d\varepsilon - w\left[h_2(z^g) X^I + l_1^g X^J\right]$$

$$- w\left[l_2^p h_1(z^g)(X^I - X_u^I) + l_2^g \gamma^g (X^J - X_u^J)\right] \qquad (21)$$

$$- b^p \gamma^p X_A^I - b^g \gamma^g X_A^J$$

$$+ \lambda^p \left[\bar{z}^p - h_1(z^g) X^I + h_1(z^g) X_A^I\right]$$

$$+ \lambda^g \left[z^g - \gamma^g X^J + \gamma^g X_A^J\right]$$

$$+ \mu^p \left[\bar{X}^I - X^I\right] + \mu^g \left[\bar{X}^J - X^J\right]$$

$$X^I, X^J, z^g, X_A^I, X_A^J \geq 0$$

included as endogenous variables in the revised formulation. The motivation for this setup is that the social planner could choose an optimal value of Z^q and impose this constraint on the generators via some institutional arrangement. Given that γ_j^q is endogenous to the generators, they could optimize over $X_{j \in J}$ and $\gamma_{j \in J}^q$ subject to the Z^q constraint. Transaction costs of identifying pollution sources and imposing selected restrictions are included in the objective function.

The first order conditions of the pivotal model incorporate the linkages between pivoters and generators (Figure 6). Equations (24a) and (24b) imply that if there is a positive level of Z^q, the optimal tax per unit of pollution created by the generators will equal the value of negative effects this pollution has on the pivoters, at the margin. These effects include increases in the marginal costs of production, pollution abatement, and pollution tax payments. This is a result which cannot be derived without consideration of the pivotal characteristics. Equations (25) and (26) denote that for both pivoters and generators, abatement of pollution will occur up to the point where the marginal cost of abatement is just equal to the marginal benefit derived. Marginal cost in this case includes abatement and transaction components.

Figure 6. Kuhn-Tucker First-order Conditions

$$\frac{\partial \mathcal{L}}{\partial X^I} = D^{-1}(X^I) - w h_2(z^g) - w l_2^p h_1(z^g) - \lambda^p h_1(z^g) - \mu^p \leq 0 \quad (22a)$$

$$X^I \cdot \frac{\partial \mathcal{L}}{\partial X^I} = X^I \cdot [\cdot] = 0 \quad (22b)$$

$$\frac{\partial \mathcal{L}}{\partial X^J} = D^{-1}(X^J) - w l_1^g - w l_2^g \gamma^g - \lambda^g \gamma^g - \mu^g \leq 0 \quad (23a)$$

$$X^J \cdot \frac{\partial \mathcal{L}}{\partial X^J} = X^J \cdot [\cdot] = 0 \quad (23b)$$

$$\frac{\partial \mathcal{L}}{\partial z^g} = -w h_2'(z^g) X^I - w l_2^p h_1'(z^g) X_A^I - \lambda^p h_1'(z^g) X^I + \lambda^p h_1'(z^g) X_A^I + \lambda^g \leq 0 \quad (24a)$$

$$= -w \underbrace{h_2'(z^g)}_{+} X^I - \underbrace{h_1'(z^g)}_{+} \left[w l_2^p X_A^I + \lambda^p (X^I - X_A^I) \right] + \lambda^g \leq 0$$

$$z^g \cdot \frac{\partial \mathcal{L}}{\partial z^g} = z^g \cdot [\cdot] = 0 \quad (24b)$$

Figure 6, continued.

$$\frac{\partial \mathcal{L}}{\partial X_A^I} = \underbrace{-w l_2^p h_1(z^g) - b^p \gamma^p}_{MC} + \underbrace{\lambda^p h_1(z^g)}_{MB} \leq 0 \qquad (25a)$$

$$X_A^I \cdot \frac{\partial \mathcal{L}}{\partial X_A^I} = X_A^I \cdot [\cdot] = 0 \qquad (25b)$$

$$\frac{\partial \mathcal{L}}{\partial X_A^J} = \underbrace{-w l_2^g \gamma^g - b^g \gamma^g}_{MC} + \underbrace{\lambda^g \gamma^g}_{MB} \leq 0 \qquad (26a)$$

$$X_A^J \cdot \frac{\partial \mathcal{L}}{\partial X_A^J} = X_A^J \cdot [\cdot] = 0 \qquad (26b)$$

$$X^I, X^J, Z^g, X_A^I, X_A^J \geq 0$$

It should be noted that the pivotal model reduces to the standard framework when Z^g is not included as a choice variable. This implies that the effects described by derivatives of the h functions with respect to Z^g cannot be captured in a model where Z^g is not chosen. Whereas the costs of measuring Z^g were described as high for individual pivoters or groups of pivoters, a social planner may be able to monitor this variable less expensively. Access to hydrologic models and water district data would facilitate this endeavor.

V. Summary and Extensions

A. Farm-level Model

The farm-level problem of managing soil salinity in the presence of diminshing depth to the underlying water table has been examined. An optimal control model incorporating dynamic physical relationships and instruments available to the growers was constructed. The model describes the intertemporal path of state variables in the absence of any controls and allows for selection of an optimal set of instruments for use in achieving a desired trajectory of yield, soil salinity, and depth to groundwater.

A quadratic tracking criterion was used to determine optimal intertemporal strategies. In the absence of instrument costs, desired levels of state variables are maintained over time through the use of leaching and groundwater relief pumping. Soil amendments are of insignificant value in this situation. As the initial level of soil salinity is increased, greater amounts of leaching and pumping are required in each time period.

The introduction of instrument costs into the objective function results in more efficient use of these controls. Additionally, soil amendments become important as they improve the efficacy of water used in leaching. Salinity levels are allowed to increase somewhat over time, reflecting the economic tradeoffs involved in their control.

As intruding groundwater flows increase, more pumping is required to achieve a given increase in depth to the water table. Therefore the impact of intruding groundwater flows was examined by varying the coefficient on the groundwater relief pumping variable. A reduction of 50% in the pumping coefficient resulted in a two-fold increase in the amount of pumping required when instrument costs were not considered. In the presence of instrument costs, the effect is less dramatic with respect to control variables, but is significant in relation to the state variables. In particular, soil salinity is allowed to increase over time and depth to groundwater decreases. This causes yields to decline over time. This result reflects the relative costs of controlling salinity in the presence of intruding groundwater flows and indicates the economic severity of the problem. To the extent that yields are allowed to decline over time, sustainability of the farming enterprise may diminish.

Another consideration examined in this study is the case of restrictions placed upon disposal of subsurface drainage water into adjacent rivers and streams. This was done by raising the value of the penalty coefficient on groundwater relief pumping. The effect of this policy action on a grower's optimal strategy was one of severely limiting the use of groundwater relief pumping. In addition, the use of leaching was discontinued as it became too costly to dispose of the subsurface water. Hence soil salinity was allowed to increase over time and yields subsequently declined.

Implications derived form these results may be important to regional policy considerations. As noted above, regional water quality authorities have expressed concern regarding disposal of subsurface drainage water into rivers and several policy options have been suggested. The potential impacts of these alternatives can be estimated using the optimal control framework presented herein. Both qualitative and quantitative effects can be evaluated.

As we have seen, the tracking of soil salinity and depth to groundwater state variables becomes more expensive in the presence of intruding groundwater flows. The placement of restrictions on the disposal of subsurface drainage exacerbates this situation for the low elevation growers. The economic value of resulting yield reductions can easily be determined and the cost of policy actions can therefore be estimated. Policy-makers can then evaluate alternatives in terms of their efficiency effects.

For example, policy-makers might consider an irrigation water taxation scheme on higher elevation growers in order to reduce the amount of intruding groundwater flows. This would cause the effectiveness of groundwater relief pumping to remain relatively high and therefore keep disposal levels low. The impact upon total output may be lower than that caused by placing restrictions or high prices on the amount of subsurface drainage disposed into rivers. Efficiency gains may be realized by evaluating these effects within this framework.

Further extensions of the farm-level research would include respecification of the objective function. A more general criterion involving the maximization of economic returns over time might provide useful information regarding the truly optimal paths of yield and other state variables. Results could be compared with those obtained through use of quadratic tracking criteria.

Restructuring the optimal control model to allow for crop rotations would also be of value. In the San Joaquin Valley, barley is grown primarily in rotation with cotton and/or alfalfa. It is cotton which produces desirable net returns, while barley is usually a break-even proposition. Determination of optimal rotation schemes in areas with salinity and depth to groundwater problems would be a valuable research endeavor.

B. Regional Considerations

With respect to regional policy considerations, the salinity and groundwater intrusion problem has been formulated in a pivotal externality framework. It has been demonstrated that consideration of the pivotal characteristics of these problems when examining policy alternatives may result in more efficient solutions. Where significant technological differences exist between the groups of agents, these concerns may become even more important as they pertain to survival in the industry.

The pivotal model examined above was formulated in a static framework in order to derive basic implications. Given the dynamic relationships involved in this example, however, an intertemporal model should be constructed. Such an effort could better examine the socially optimal relationship between the pivoters and generators. For example, if it is optimal to allow the pivoters to terminate production over time, the optimal path for achieving this state could be described. Conversely, it optimality involves maintaining production at the pivot, this result would arise.

A final note of interest pertains to the potential "switching" of the negative externality to a positive one, over time. If the pivotal agents could successfully achieve a salt balance situation at some point in the future, it may become possible to utilize the inflow of groundwater as a blendable source of irrigation water. This would greatly reduce or eliminate the disposal problem. A dynamic model of the groundwater intrusion problem incorporating pivotal aspects could identify and describe such a solution, if it exists. The implications with respect to social policy alternatives and pivotal agent options would be important.

Tables

Table 1. Time path of soil salinity, depth to water table, and yield in the absence of any controls, given an initial salinity level of 9.0 mhos

STATES				INSTRS			
YEAR	SEC	DWT	YIELD	YEAR	L	SA	CRP
1	9.0835	4.85	1.8496	1	0	0	0
2	9.1536	3.9077	1.6996	2	0	0	0
3	9.2126	2.9938	1.5305	3	0	0	0
4	9.2622	2.1072	1.3313	4	0	0	0
5	9.3039	1.2472	1.0768	5	0	0	0
6	9.3389	.41306	.67322	6	0	0	0

Table 2. Optimal solution to the problem of tracking yield, salinity, and depth-to-groundwater, given an initial salinity level of 7.0 mhos and a non-impacted drainage situation (rho=4)

OPTIMAL
****
RESULTS
****

STATES				INSTRS			
YEAR	SEC	DWT	YIELD	YEAR	L	SA	GRP
****	******	******	******	****	*******	*********	*******
1	7.0439	5	1.9535	1	1.0732	0	1.124
2	6.9856	5	1.955	2	1.3419	0	1.1091
3	6.9028	5	1.955	3	1.4651	0	1.0452
4	6.8589	5	1.955	4	1.4203	0	.93079
5	6.9043	5	1.955	5	1.1753	.0034795	.76223
6	7.0916	4.9785	1.9487	6	.68981	.0186	.52301

OPTLOSS

TARGLOSS	INSTLOSS	TOTALOSS
********	********	********
.06239	0	.06239

Table 3. Optimal solution to the problem of tracking yield, salinity, and depth-to-groundwater, given an initial salinity level of 9.0 mhos and a non-impacted drainage situation (rho=4)

OPTIMAL RESULTS

STATES				INSTRS			
YEAR	SEC	DWT	YIELD	YEAR	L	SA	GRP
1	7.7169	4.826	1.9035	1	2.0921	.23229	1.575
2	7.2377	4.8448	1.9242	2	1.87	.032798	1.3178
3	7.0281	4.9508	1.947	3	1.6189	0	1.1727
4	6.9732	4.8974	1.9403	4	1.345	0	.97953
5	7.0476	4.8152	1.9266	5	.98429	.012416	.77418
6	7.2648	4.7123	1.9037	6	.52369	.0034135	.50492

OPTLOSS

TARGLOSS	INSTLOSS	TOTALOSS
.86461	0	.86461

Table 4. Optimal solution to the problem of tracking yield, salinity, and depth-to-groundwater, given an initial salinity level of 7.0 mhos and a drainage situation affected by intruding groundwater flows (rho=2)

OPTIMAL
RESULTS

STATES				INSTRS			
YEAR	SEC	DWT	YIELD	YEAR	L	SA	GRP
1	7.0987	5	1.9515	1	.90888	0	2.2048
2	7.004	5	1.9549	2	1.4033	0	2.1858
3	6.8524	5	1.955	3	1.6549	0	2.0809
4	6.7602	5	1.955	4	1.6161	0	1.8876
5	6.8129	4.6938	1.9104	5	1.2426	0	1.5996
6	7.0684	4.7754	1.9201	6	.55685	0	1.1361

CPTLOSS

TARGLOSS	INSTLOSS	TOTALOSS
.29582	0	.29582

Table 5. Optimal solution to the problem of tracking yield, salinity, and depth-to-groundwater, given an initial salinity level of 9.0 mhos and a drainage situation affected by intruding groundwater flows (rho=2)

OPTIMAL
RESULTS

STATES				INSTRS			
YEAR	SEC	DWT	YIELD	YEAR	L	SA	GRP
1	7.6882	4.8387	1.9065	1	2.7041	0	3.4348
2	7.0202	4.9711	1.9502	2	2.4222	0	3.2621
3	6.7017	5	1.955	3	2.1369	0	2.9224
4	6.619	5	1.955	4	1.7359	0	2.4818
5	6.7307	5	1.955	5	1.1739	0	1.9489
6	7.0075	5	1.9547	6	.54385	0	1.1968

OPTLOSS

TARGLOSS	INSTLOSS	TOTALOSS
.82693	0	.82693

Table 6. Optimal solution to the problem of tracking yield, salinity, and depth-to-groundwater subject to instrument costs, given an initial salinity level of 7.0 mhos and a non-impacted drainage situation (rho=4)

OPTIMAL RESULTS

STATES				INSTRS			
YEAR	SEC	DWT	YIELD	YEAR	L	SA	GRP
1	7.274	5	1.9452	1	.33965	.13173	.64552
2	7.376	5	1.9415	2	.52282	.29042	.64956
3	7.4152	5	1.94	3	.58043	.35548	.63731
4	7.4792	5	1.9377	4	.55177	.30324	.60533
5	7.6376	5	1.9317	5	.39478	.16604	.54487
6	7.8946	5	1.9217	6	.12729	.030202	.41569

OPTLOSS

TARGLOSS	INSTLOSS	TOTALOSS
2.0725	3.6315	5.7039

Table 7. Optimal solution to the problem of tracking yield, salinity, and depth-to-groundwater subject to instrument costs, given an initial salinity level of 7.0 mhos and a drainage situation affected by intruding groundwater flows (rho=2)

OPTIMAL
RESULTS

STATES				INSTRS			
YEAR	SEC	DWT	YIELD	YEAR	L	SA	GRP
1	7.3111	4.9943	1.9431	1	.27269	0	.7773
2	7.5318	4.9763	1.9323	2	.36408	0	.8739
3	7.6818	4.7938	1.9002	3	.43805	0	.87458
4	7.8297	4.7683	1.8907	4	.36777	0	.87126
5	8.0074	4.887	1.901	5	.22539	0	.78281
6	8.1258	3.9719	1.7547	6	.28955	0	.3399

OPTLOSS

TARGLOSS	INSTLOSS	TOTALOSS
5.9789	4.2889	10.268

Table 8. Optimal solution to the problem of tracking yield subject to instrument costs, given an initial salinity level of 7.0 mhos and a non-impacted drainage situation (rho=4)

OPTIMAL
RESULTS

STATES				INSTRS			
YEAR	SEC	DWT	YIELD	YEAR	L	SA	GRP
1	7.3876	5	1.9411	1	.043629	0	.45302
2	7.7089	5	1.9289	2	.051759	0	.46295
3	7.977	5	1.9184	3	.052885	0	.46332
4	8.2041	5	1.9092	4	.045987	0	.44885
5	8.4007	5	1.9011	5	.030761	0	.40865
6	8.5755	5	1.8937	6	.009144	0	.3135

OPTLOSS

TARGLOSS	INSTLOSS	TOTALOSS
4.4517	1.1325	5.5842

Table 9. Optimal solution to the problem of tracking yield subject to instrument costs, given an initial salinity level of 9.0 mhos and a non-impacted drainage situation (rho=4)

OPTIMAL
RESULTS

STATES				INSTRS			
YEAR	SEC	DWT	YIELD	YEAR	L	SA	GRP
1	8.9277	5	1.8782	1	.29123	.042651	.55409
2	8.8973	5	1.8796	2	.24114	.032156	.56243
3	8.8998	5	1.8795	3	.19003	.023154	.5596
4	8.9296	5	1.8782	4	.13723	.014605	.53932
5	8.9824	5	1.8758	5	.083226	.0042046	.48875
6	9.0534	5	1.8726	6	.029764	.0072444	.3733

OPTLOSS

TARGLOSS	INSTLOSS	TOTALOSS
9.0354	2.2411	11.276

Table 10. Optimal solution to the problem of tracking yield subject to instrument costs including a high price on subsurface drainage disposal, given an initial salinity level of 7.0 mhos and a non-impacted drainage situation (rho=4)

OPTIMAL RESULTS

STATES				INSTRS			
YEAR	SEC	DWT	YIELD	YEAR	L	SA	GRP
1	7.4022	5	1.9405	1	0	0	.25342
2	7.7403	5	1.9277	2	0	0	.25897
3	8.0245	5	1.9165	3	0	0	.25918
4	8.2634	5	1.9068	4	4.5064E-6	0	.25108
5	8.4642	5	1.8984	5	1.3799E-5	0	.22859
6	8.6331	4.9958	1.8906	6	2.1708E-5	0	.17535

OPTLOSS

TARGLOSS	INSTLOSS	TOTALOSS
4.6717	5.1676	9.8393

Table 11. Optimal solution to the problem of tracking yield subject to instrument costs including a high price on subsurface drainage disposal, given an initial salinity level of 9.0 mhos and a non-impacted drainage situation (rho=4)

OPTIMAL

RESULTS

STATES				INSTRS			
YEAR	SEC	DWT	YIELD	YEAR	L	SA	GRP
1	9.0789	5	1.8714	1	.0096692	.0091072	.26389
2	9.1265	5	1.8693	2	.045401	2.3397E-5	.26787
3	9.1799	5	1.8668	3	.018681	5.443E-5	.26656
4	9.2347	5	1.8643	4	0	0	.25696
5	9.2808	5	1.8622	5	0	0	.23298
6	9.3195	4.9932	1.8594	6	0	0	.1782

OPTLOSS

TARGLOSS	INSTLOSS	TOTALOSS
10.854	5.4756	16.329

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