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WATER RESOURCE DEVELOPMENT IN THE SALINAS VALLEY: ECONOMICS AND HYDROLOGY IN A CLOSED CONTROL MODEL†

During the past several decades, many of the world's arid and semi-arid irrigated areas have begun to take more seriously the management of groundwater resources. In part, this concern has arisen because water tables have been falling, in some areas precipitiously. In addition, the increasing cost of the energy required for pumping has multiplied the impact of declining water levels and produced an added incentive for efficient utilization.

The efficient allocation of water resources has both spatial and temporal dimensions. Spatial efficiency requires that water be allocated among areas in such a way that the net return from an additional unit of water is the same in all regions; temporal efficiency demands that the productivity of water in present and future uses be equated at discount rates reflecting the time preferences of individuals or of society.[1] The two objectives are connected by the fact that adjustments, i.e., groundwater flows, are governed by complex physical phenomena and do not occur instantaneously.

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[1] Intertemporal efficiency necessitates the distinction between the "stock" and the "flow" of a resource. Following Ciriacy-Wantrup (1956), a stock resource is one whose "total physical quantity does not increase significantly with time...each rate of use diminishes some future rate." A flow resource, on the other hand, is one whose "different units become available for use in different intervals of time...the present flow does not diminish future flows, and it is possible to maintain use indefinitely, provided the flow continues."

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Difficulties in implementing the efficiency criteria, at least in market economies, arise because individuals or communities, making independent decisions about groundwater use, are nevertheless linked by the underlying physical characteristics of the groundwater hydrology. All parties acknowledge that they are drawing water from a common pool, but in the absence of institutions that permit collective decisions about the disposition of the water, each individual or group correctly assumes that neighbors will place private interests first. The result, under situations of scarcity, may be socially non-optimal withdrawals.

Alternative social and political institutions exist that can force convergence between public and private interests, e.g., taxes, subsidies, and quotas or the assumption of jurisdiction over the resource by a superior body. However, each type of intervention has significant transaction costs that must be included when evaluating the likelihood that a particular institutional solution is viable. Water resource development in the United States has generally avoided comprehensive management issues by removing its rationale, i.e., by developing additional water supplies.

MODELING GROUNDWATER MANAGEMENT: A CLOSED CONTROL APPROACH

The development of models to assist with groundwater management has been slow because of the inability to include, in the same model, optimization algorithms that allocate water on the basis of its economic value across space and through time, and simulations of the movement of water in the aquifer as a result of stresses imposed by pumping or recharge. Most modeling efforts to date have proceeded either by iterating between independent optimization of the economic and hydrologic models or by using simulation (as opposed to optimizing) techniques.[2]

In the present study, the use of a closed control model in the optimization procedure makes possible the integration of the two facets of the management problem.[3] Net revenues as a function of water availability are generated for each

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[2] The present approach has a number of forerunners. In a series of seminal articles on intertemporal efficiency, Oscar Burt (1964, 1966), using the concepts of dynamic programming, introduced the notion of the marginal value of stored groundwater into the literature. Martin, Burdak, and Young (1969), employing a complex hydrologic model, concentrated on the requirements of spatial efficiency. Both intertemporal and spatial considerations were incorporated in the simulation models of Bredehoft and Young (1970) and Young and Bredehoft (1972). More recently, Noel (1980) developed a method based on Control Theory that integrates the dynamic physical variations of groundwater storage in various sub-regions of a larger aquifer.

[3] For a formal statement of the control problem, see Intriligator (1971). The language of control theory is designed to describe situations in which the optimization of scarce resources involves not only competing ends, but a time interval as well. The problem is that of choosing time paths for control variables ("activities" in the static

sub-area using a conventional linear programming approach. These functions become one of the elements of the control model's objective function.

The equations of motion that relate groundwater stocks to flows are developed independently from a hydrologic model that simulates the behavior of the aquifer when stresses are imposed at various points. The information developed by the simulation model is then summarized with the aid of regression techniques to produce the constraints of the control model.

By including information on both the demand and supply for water as well as the movement of groundwater in a functional form, it is possible to obtain an optimal spatial and temporal allocation of groundwater in a single step. The resulting methodology offers increased efficiency and flexibility in dealing with the quantitative issues that arise in groundwater management.

The Salinas Valley and the Arroyo Seco Project

The Salinas Valley is an example of an area in which the debate over water resource management has intensified in recent years. The valley is one of the most intensely cropped agricultural areas in the country and produces a wide variety of vegetable and field crops. It is also a relatively arid area and, with the exception of some dryland grains in the southern part of the valley, agriculture is synonomous with irrigation. Irrigation, in turn, means groundwater. Virtually the entire 290,000 acres that make up the valley floor is watered by wells pumping from depths of 30 to 150 feet.

The groundwater aquifer is in large measure fueled by the Salinas River, one of the longest subterranean rivers in America. After the impact of large-scale pumping became apparent in the 1930s, the residents of the area organized the construction of two reservoirs on the Nacimiento and San Antonio Rivers to provide additional recharge. The two reservoirs capture roughly 100,000 acre feet annually which is released during the otherwise dry summer period.

In recent years, residents in the northeastern part of the valley have again begun to talk about water development, this time on the Arroyo Seco River. Two forces have interacted to produce the pressure for additional investment. On the demand side, a substantial increase in the area under double-cropped, high-valued vegetable crops made possible by a favorable agroclimatic niche, produced a concomitent increase in annual water requirements. Unfortunately, these are precisely the areas in which the supply of water to recharge the aquifer has been limited. The lack of recharge sufficient to keep up with withdrawals is related in part to the placement of the Salinas River: it does not run through a part of the valley that has the most favorable microclimate for vegetable

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linear programming framework) so as to maximize a function that depends upon both the control variables and the time paths of the state variables that describe the structure of the system. In closed (as opposed to open) loop control systems, the optimal control path is determined as a function of the current state of the system and time. No decisions regarding the path of the control variable are made in advance; decisions are revised in light of the current state variables.

production. In other areas, the physical structure of the aquifer is a factor. The movement of water between the areas of greatest demand and the areas with a high natural recharge is limited by relatively impermeable soils and obstructive geological formations. Current infiltration rates have therefore been insufficient to maintain an equilibrium between recharge and withdrawals.

The traditional response to this type of problem has been to develop more water supplies and the Arroyo Seco Project is the preferred approach by many Salinas Valley residents. The project would dam the Arroyo Seco River in order to prevent winter precipitation from being lost to the sea. More important, it would provide the irrigation works and conveyances to deliver surface water to areas where groundwater deficits are becoming increasingly obvious.

The debate in Salinas centers on who would gain and who would lose from the Arroyo Seco scheme. Because there are areas adjacent to the deficit areas that have high natural percolation rates (albeit with limited permeability), another possiblity for improving the overall social welfare of the valley's agricultural economy would be to manage the existing groundwater supplies more efficiently. Decreasing pumping in areas where groundwater is more abundant in order to create an increased flow to areas where it is scarce would generate significant increases in total net returns to the deficit areas. Theoretically, these returns, accruing in this case to the farmers on the eastern and northern side of the valley, could be used to offset the losses of farmers elsewhere who would have to decrease their pumping.

The identification of gainers and losers under alternative management and project development scenarios is a key element in the discussion about the most appropriate water resource development strategy. Because it is not an experiment that can be carried out on a pilot scale, the mathematical modeling techniques described in the previous section provide one of the few means of developing quantitative information on the project's probable distributive effects.

DATA SOURCES AND ESTIMATION OF CONTROL MODEL PARAMETERS

The valley is a portion of the Lower Basin of the Salinas River. It is 3 miles wide at the upper southeastern end, 15 miles wide at the lower northwestern end along Monterey Bay, and approximately 150 miles long (Map 1). Proximity to the Pacific Ocean is the key to the mild Mediterranean climate of winter rains and summer droughts and to location of micro-climatic regions within the valley. Farmers close to the coast experience moderate year-round temperatures, mild rainy seasons, and cool summers. Inland, winters are colder and summers hotter and a dry wind sweeps up the valley.

Average rainfall ranges from about 18 inches near the coast to about 10 inches in Soledad and King City, but it varies considerably from year to year.[4]

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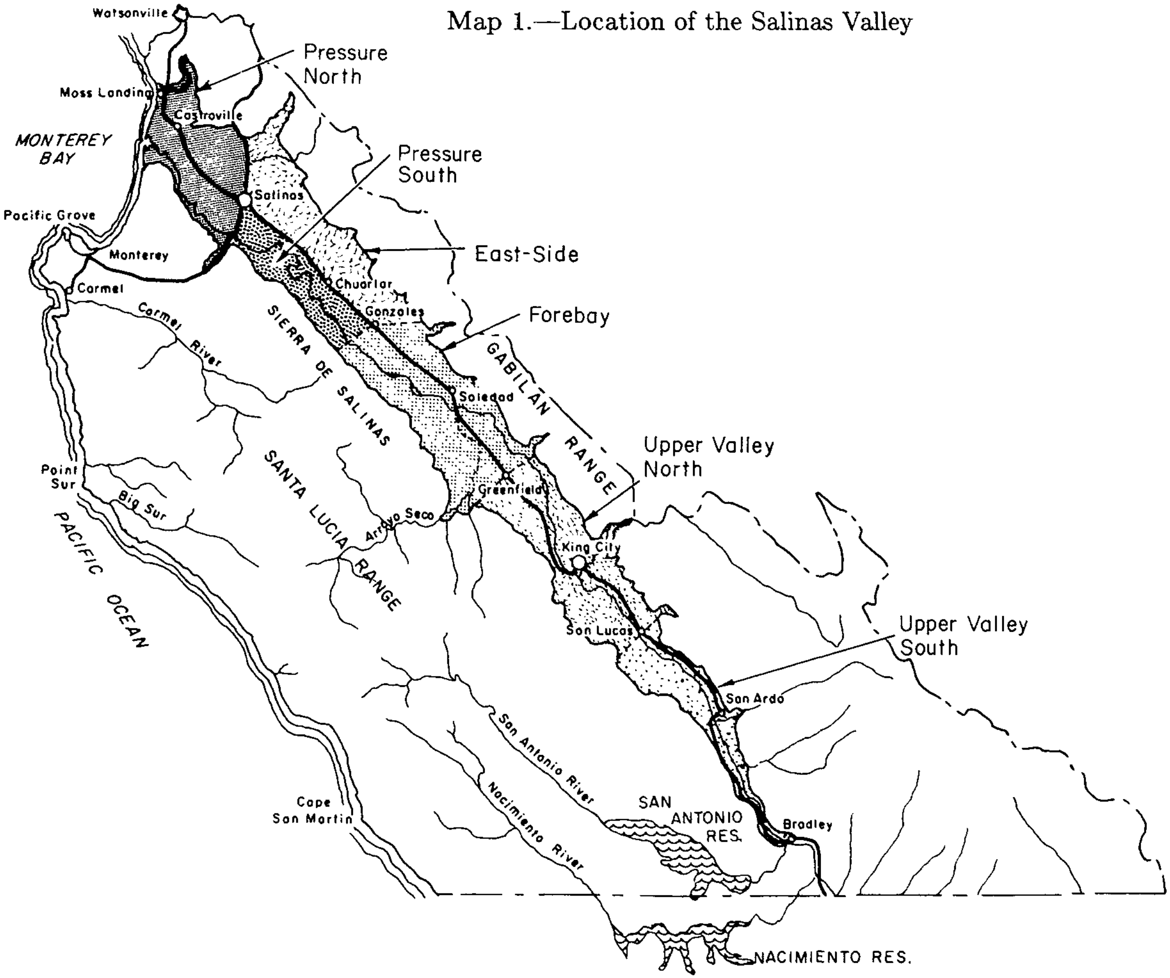
[4] For the 30-year period ending in 1960, the annual precipitation at Salinas and at King City ranged from a low of 5.74 and 3.14 inches, respectively, to a high of 28.10 and 23.81 inches.

Map 1.—Location of the Salinas Valley



The generally semi-arid conditions make irrigation a valley-wide cultivation requirement except for dryland grains such as barley. The climate allows year-round production of a great variety of vegetable crops, especially in the northern part of the valley. The somewhat more severe climate in the southern end gives a comparative advantage to hardier crops such as sugar beets, small grains, and dry beans.

Although it covers only about 15 percent of the county's area, the valley's production makes up the major part of the agricultural output of Monterey County. Monterey County, in turn, produces 95 percent of the country's artichokes, 55 percent of its broccoli, 35 percent of its cauliflower, 30 percent of its lettuce, and 20 percent of its celery.

In terms of value, lettuce is by far the leading crop. Broccoli, which occupies roughly two-thirds as much land as lettuce, accounts for only about one-third of its value. Nevertheless, broccoli and cauliflower have shown an impressive growth in acreage, doubling over the last decade. The share of tomatoes and celery is also increasing, although at a slower rate. Along with many other areas in California, vineyards have also become important in recent years. Ten years ago, few grapes were grown in the valley. Now they are the fourth largest source of revenue in the county and their acreage is the third largest among the irrigated crops. Sugar beets, dry beans, carrots, and potatoes lost ground in the past 10 years. The increasing acreage in irrigated and double-cropped vegetables is the major factor in explaining the overdraft of the underlying groundwater in the northern part of the valley.

The Four Areas

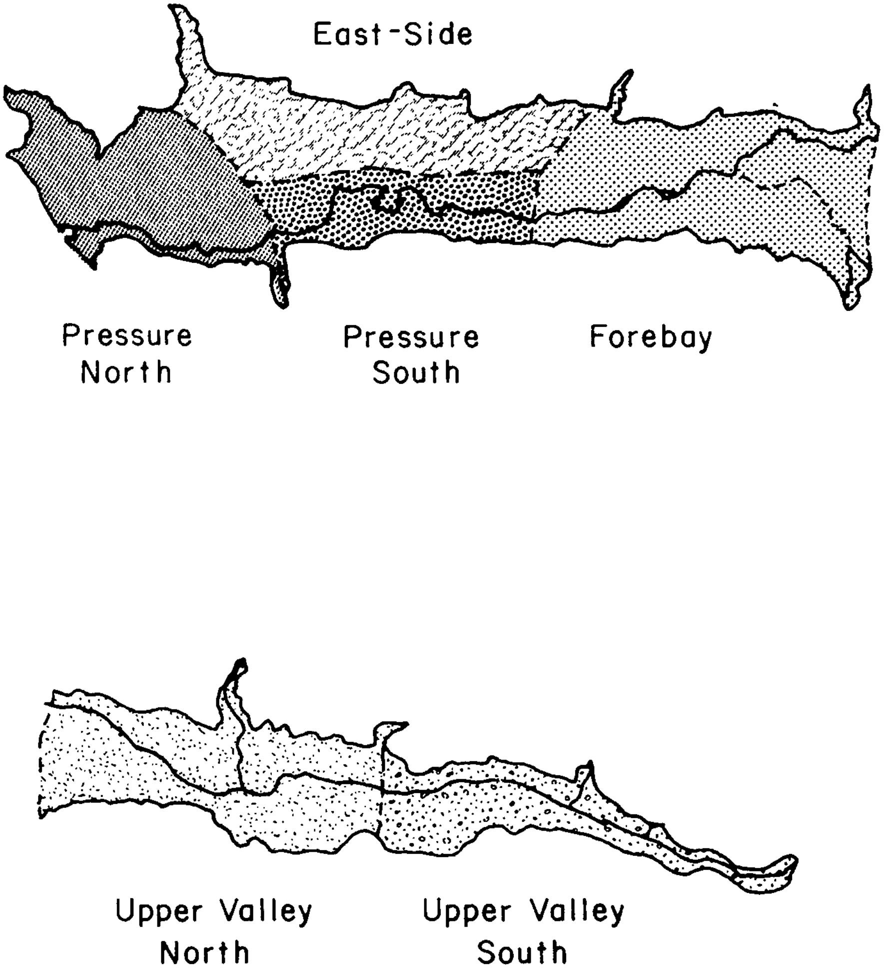
The California Department Water Resources identifies four major hydrologically interconnected units on the valley floor: Upper Valley, Forebay, Pressure, and East-Side (Map 2). Each of the first three is divided at mid-point into northern and southern sub-units to obtain the seven sub-areas used in our analysis. Brief descriptions of the most important characteristics of the areas recognized by the department are given below:

Upper Valley: The Upper Valley extends from about Greenfield to Bradley and has a gross area of 85,000 acres. Its unconfined aquifer is recharged by natural runoff from the Salinas River, local streams, agricultural return flows, and precipitation.

Forebay: The Forebay extends to the north of the Upper Valley unit to about Gonzales and contains approximately 77,000 acres. It includes the Arroyo Seco Cone, a highly permeable alluvial sub-area south of Soledad and west of the Salinas River. Infiltration from the Arroyo Seco River, on the order of 70,000 acre-feet annually, recharges the unconfined Forebay aquifers. The Forebay area is also recharged by seepage from natural and regulated flows of the Salinas River, agricultural return flows, and precipitation.

Pressure: The Pressure unit extends over 81,100 acres north from the Forebay to Monterey Bay covering the western and central portions of the valley. Its alluvium is characterized by two quasi-continuous clay layers that divide

Map 2.—Monitored Groundwater Basins



the upper part of the groundwater basin into two aquifers and prevent replenishment by deep percolation. The Pressure area is now primarily recharged by inflow from the Forebay and from sea water intrusion. The East-Side appears once to have been one of the natural sources of recharge to the Pressure area, but overdrafting of that area has reversed the direction of groundwater flow. The magnitude and direction of groundwater transfers between East-Side and Pressure sub-units are among the most critical groundwater movements in the computation of optimal allocation.

East-Side: The East-Side comprises 43,000 acres lying along the eastern fringe of the valley's alluvial fill. It is a semi-confined basin recharged primarily from local streams draining the west slope of the Gabilan Mountain Range. It also receives recharge by groundwater inflow from the Forebay and Pressure areas, and by irrigation return flows. However, the groundwater flow from the Forebay is limited due to a reduction in transmissivity at the lower edge of that area.

Utilizing yearly changes in groundwater levels, the Monterey Water District computed changes in water storage for the period 1961–76 and estimated the annual overdraft by sub-basin (Chart 1).

The foregoing overview of the characteristics of the hydrology of the Salinas Valley reveals two crucial factors that are major determinants of the subsequent modeling results (Chart 2):

1. There has been a substantial increase in the demand for water in the East-Side and Pressure areas because their proximity to the ocean permits the double cropping of water intensive vegetable crops.
2. These are the very areas whose recharge is limited by the spatial configuration of the Salinas Valley, i.e., the placement of the river, and by the structure of the aquifer that joins them to areas in which percolation is more abundant.

The Agricultural Model

A linear programming model was developed for each sub-area to simulate agricultural production and to provide the net revenue function required for the control model. The function, which excludes pumping costs, is generated by relating revenue to the amount of groundwater pumped. Each solution provides a profit-maximizing response when the sub-area is treated as a single decision unit. It simulates the short-run impact of decisions by firms in each sub-area, and is generated by the parametric variation of the water availability constraints.

The programming model is formulated as follows:

$$Max\ R = \sum_i \sum_k (GR_k^i - PC_k^i) \cdot z_k^i$$

Subject to:

$$\sum_i \sum_k a_{jk}^i \cdot z_k^i \le b_j \qquad j = 1 \ldots s$$

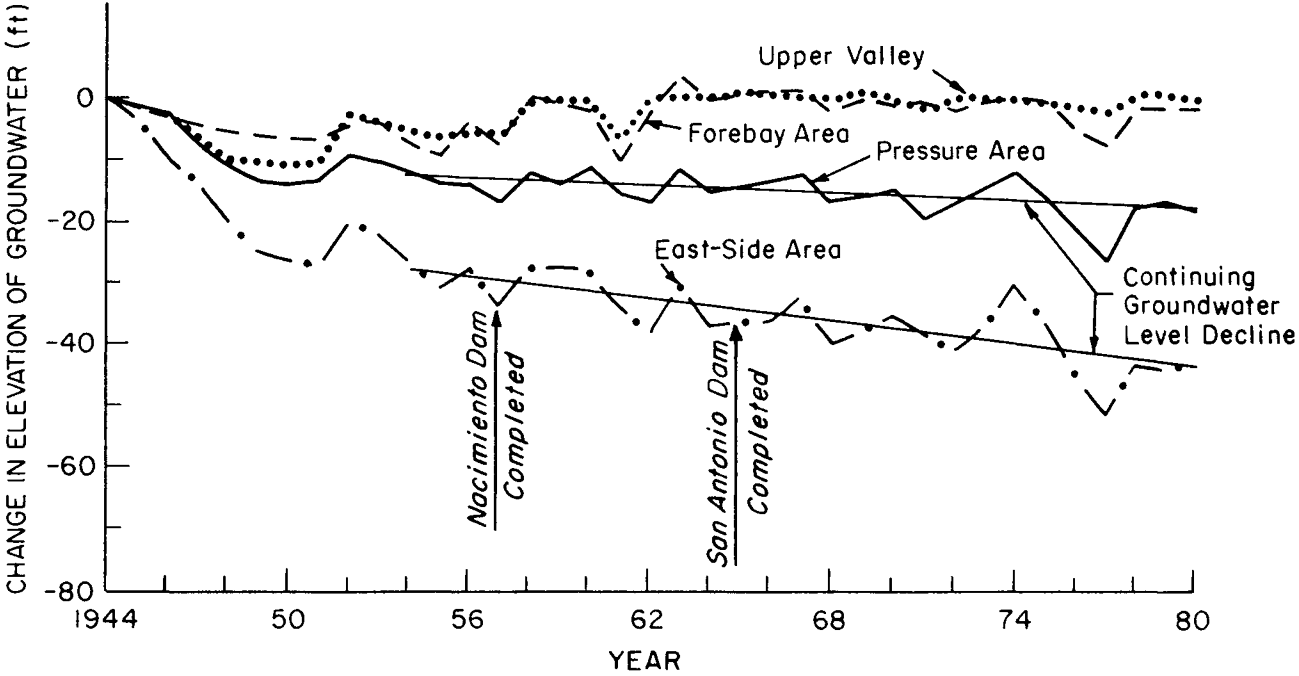
$$z_k^i \ge 0$$

Where

$i = 1, 2, 3 =$ type of soil

$k = 1, \ldots, 17 =$ type of crop

Chart 1.–Changes in Groundwater Levels



Activities

In the above notation:

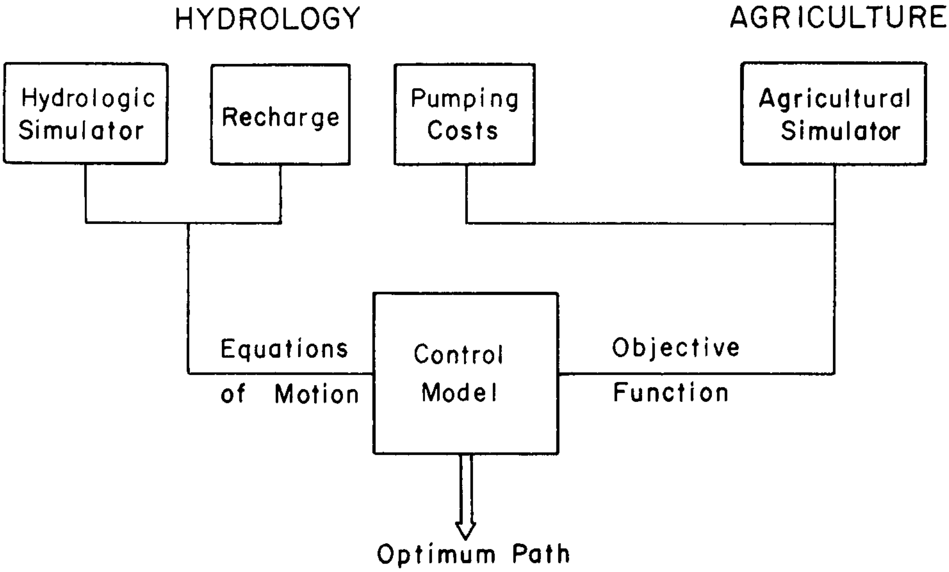
z_k^i = acreage of the k^{th} crop grown on the i^{th} soil type

GR_k^i = gross revenue (\$/acre) obtained from(tons/acre) times [sales price (\$/ton) – harvest cost (\$/ton)]

PC_k^i = production costs, excluding pumping costs (\$/acre)

b_j = a vector of resource constraints

Chart 2.—Flow Chart of the Model



The 17 activities are composed of 14 crops of which lettuce, cauliflower, and broccoli are double cropped and artichokes are a semi-perennial. Note the following tabulation listing crops grown in the Salinas Valley by district:

All districts
Lettuce
Beans
Sugar beets
Barley
Broccoli

Pressure
Celery
Artichokes

East-Side
Potatoes

Forebay
Carrots
Tomatoes

Upper Valley
Tomatoes
Alfalfa

CROP DISTRIBUTION BY SUB-AREAS

Crop specific yields depend upon the type of soil and the location within the valley. Estimates made in the model come largely from publications of the Agricultural Extension Service.

Constraints

The constraints of the model are as follows:

Water availability: The irrigation water constraint is the pivot of the parametric variation that generates the net revenue function. The irrigation coefficients are given in acre-feet of water that must be pumped in order to meet consumptive use requirements after natural precipitation has been accounted for. They were estimated for each crop from publications of the Monterey County Water Control and Flood Control District (MCWC and FCD), the USDA Soil Conservation Service, and the University of California Extension Service. The estimates have been corrected to reflect potential evapotranspiration and soil properties of specific locations. For double-cropping, water use coefficients of crops that occupy the land during the fall and winter were taken to be 10 percent less than the estimates for summer crops due to the higher evapotranspiration during the summer months.

Irrigation practices are relatively homogeneous within the study area and therefore only one irrigation technology has been included. During the pumping season, irrigation by sprinklers is generally used in the early stages of growth to insure a better distribution of water. Furrow irrigation is then used in order to avoid the accumulation of dirt on the aerial parts of the vegetables.

Land and soil availability: Constraints consist of land available by different soil quality types, the maximum share of double-cropped acreage in the cropping pattern, the suitability of soils for specific crops, and rotation constraints. Three categories of soil are differentiated according to their Storie Index: high quality => 80; medium quality = 60–80; low quality =< 60. Double-cropping is limited by the agro-climatic characteristics of each sub-area, principally defined by the length of the frost-free growing season. It is estimated that the cropping intensity could reach as much as 135 percent in the Pressure area, 130 percent in East-Side, 115 percent in Forebay and 110 percent in Upper Valley. A typical example of the impact of soil conditions are the relatively poor yields obtained from celery and artichokes when grown on land with inadequate drainage and high salt concentrations.

Crop distribution constraint: In order to insure a steady flow of products to processing plants and fresh markets, the production of double cropped vegetables is not concentrated in a single season. A constraint is therefore required to insure that a minimum percentage of the supply be produced in each period. There is some arbitrariness in this constraint because the planting and harvesting seasons are quite extended. However, contracts with processors create incentives to avoid market gluts and scarcities.

Risk and uncertainty: Banking institutions in the valley allocate credit to farmers using guidelines that link lending to the cropping pattern and the share of financing that the farmer supplies himself. Because the risk associated with volatile prices and fluctuating yields is higher for vegetable crops than for field crops, a measure of a grower's solvency is obtained from rules based on a minimum percentage of land grown in field crops and a minimum percentage of the cultural costs borne by the grower. Risk-sharing by bankers, processors, and shippers decreases the individual farmer's risk by spreading it over a large number of contracts. In exchange, farmers accept limitations on cropping choices.

Selecting a cropping plan in the high-risk vegetable industry characterized by various specific marketing arrangements, is analogous to selecting an investment portfolio. An individual farmer chooses the crops to be grown in order to maximize the expected value of his revenue while minimizing its variance. The approach used to integrate risk in the sub-area linear programming model was to choose a cropping pattern that minimized the total absolute deviations (MOTAD) of the individual crop revenues from their means for a given income level. This technique approximates quadratic risk programming without having to assume a normal distribution of crop revenues or to use a quadratic objective function (Hazell, 1971, pp. 53–62).

Revenue Functions and Model Verification

To obtain the maximum net revenue in a sub-area R_i as a function of the quantity of irrigation water applied, the corresponding linear programming model was optimized over a range of values for the water constraint. The continuous function needed for the control model's objective function was obtained by regressing net revenues on the amount of water used to produce the revenue. The resulting functions $R_i(x_i)$ are shown in Table 1.

The estimated revenue functions, net of irrigation costs, are independent of time. Therefore, they can be used, without modification, for the entire simulation period as long as production costs and gross revenue per acre are assumed to remain constant. These assumptions seem realistic; during the past 10 years, virtually none of the time series on production costs and revenues per acre showed a significant trend.[5]

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[5] The exceptions were the gross revenue of broccoli and tomatoes, which showed a

Table 1.—Revenue Functions of Irrigation Water*

Area	Function	R^2
Upper Valley South	$R_1 = -1.222 + 1.6915\ x_1 - .09131\ {x_1}^2$	.989
Upper Valley North	$R_2 = -.189 + 1.4029\ x_2 - .05697\ {x_2}^2$	.993
Forebay South	$R_3 = -1.6 + 1.7848\ x_3 - .08107\ {x_3}^2$	.994
Forebay North	$R_4 = -1.763 + 1.7634\ x_4 - .086\ {x_4}^2$	.996
East-Side	$R_5 = 5.604 + 1.908\ x_5 - .0723\ {x_5}^2$	.984
Pressure South	$R_6 = -3.348 + 2.7629\ x_6 - 0.1227\ {x_6}^2$	.992
Pressure North	$R_7 = .228 + 3.4231\ x_7 - .1714\ {x_7}^2$	.985

Source: Pierre H. Lemoine, 1984, "Water Resource Management in the Salinas Valley: Integration of Economics and Hydrology in a Closed Control Model," Ph.D. Dissertation, Stanford University.

*R = revenue, in millions of 1972 dollars; x = water use, in ten-thousands of acre-feet of water.

Under the assumption that net revenues are time-independent, the annual net revenue of the i^{th} sub-area, obtained by pumping $x_i(t)$ at time t, is equal to $R_i[x_i(t)]$, and can be directly integrated into the objective function of the control model.

Because the results of the agricultural sector model are an input into the ultimate multi-period optimization model, it is important to check the model's predictions against the current situation. The most obvious method of validation is to compare the cropping patterns predicted by the linear program against those implemented by private decision makers. The year 1981 was selected for

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positive and a negative trend respectively for the 1972–81 period. However, it would be unrealistic to project the broccoli and tomato trends both because they have shown increasing stability in the past 5 years and because the assumption that the trends would continue suggests a questionable long-term result, namely, that the comparative advantages of growing broccoli and tomatoes with respect to the other crops would be, after 20 years, drastically different from the initial conditions.

this exercise because it was the last year for which aggregate Monterey County cropping data were available.

None of the crop acreages predicted by the model differs more than 5 percent from the actual county totals. This close correlation is significant because the only cropping pattern constraints built into the agricultural model are the upper-bound on the acreage of artichokes in the Pressure North sub-area and the diversification of double-cropped vegetables for processing purposes. The former constraint is justified on the grounds that it reflects production limitations instituted by an artichokes marketing order. The latter is a function of contracts between farmers and the various processing firms.

The latest cropping pattern data by major sub-aquifers (Pressure, East-Side, Forebay, and Upper Valley) refer to crops grown in 1976. The largest deviation in the model for any crop in any sub-area is less than 8 percent when the model is run at 1976 prices. Each sub-area agricultural model accurately estimates the acreages of sugar beets, carrots, tomatoes, and cauliflower. However, the model slightly overestimates the acreages of lettuce and broccoli, while underestimating the area in small dry beans.

The foregoing results prompt the conclusion that the data and specifications used in the agricultural model are sufficiently accurate to develop the net revenue functions needed for subsequent global optimization exercises.

The Hydrologic Modules

The hydologic system of the Salinas Basin is depicted in Chart 3. The sub-areas are hydrologically interdependent because they belong to the same aquifer, i.e., groundwater transfers between sub-areas are significant, and 5 of the 7 areas are recharged by percolation from the same river. Modules have been developed for aquifer recharge, equations of motion, and pumping cost functions.

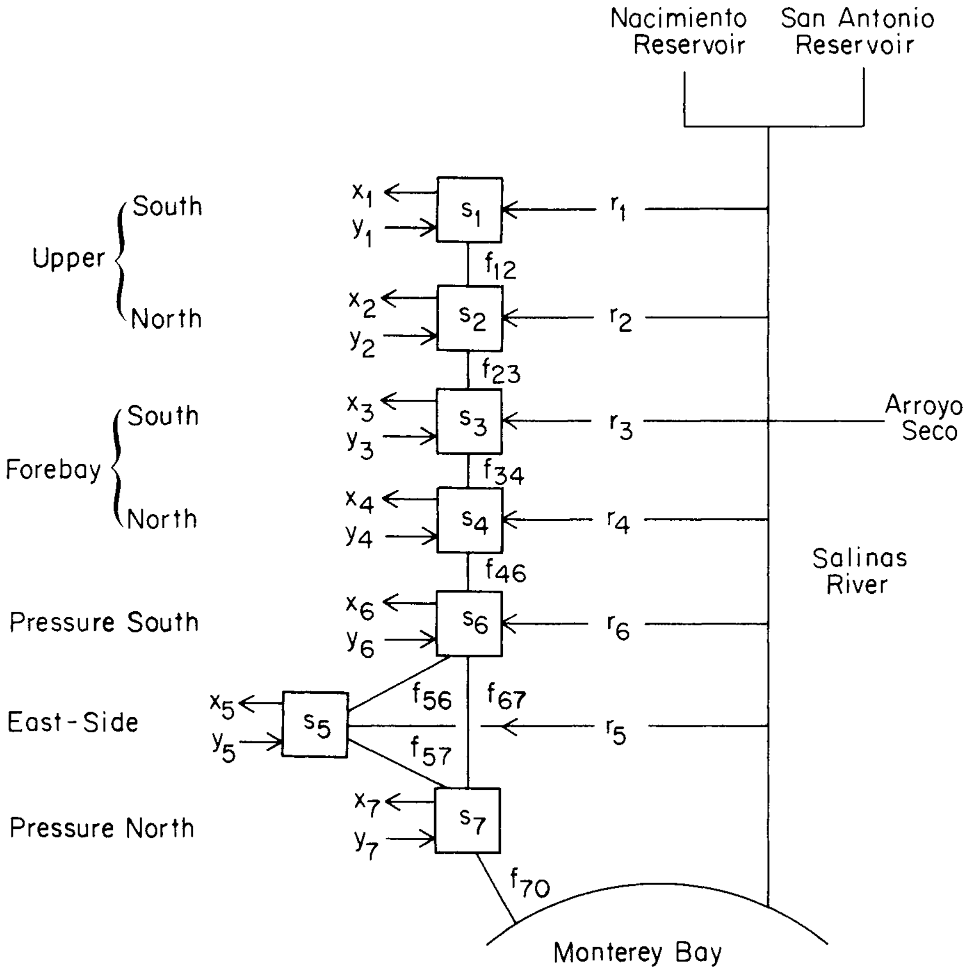
Aquifer recharge: Recharge is a positive (negative) flow to (from) the groundwater stock. Its components are either independent of the stock levels (e.g., precipitation, small streams and urban pumping) or they are a function of the depth to groundwater (e.g., percolation from the main channels).

The stochastic variation of annual precipitation is neglected in this study, and therefore the recharge from direct precipitation and from small streams percolation are both assumed constant and evenly distributed over one year.

Urban pumping is assumed to be evenly distributed over one year. The deterministic estimation of the demand in each sub-area is adapted from the global projections of municipal and industrial pumping by the Army Corps of Engineers. The distribution of population and the aggregate growth rate of the valley are assumed to remain unchanged over the study period.

The most important source of groundwater recharge in the Salinas Basin is the deep percolation from the channel of the Salinas River. The river is hydraulically connected to the aquifer. Exchanges of water occur between the two systems, except near the sea where the riverbed consists of, or is underlain, with fine-grained materials that limit percolation.

Chart 3.—Hydrologic System of the Salinas Valley



s Stock of groundwater
x Agricultural pumpings
y Natural and constant net recharge
r Recharge by percolation from the Salinas River
$i = 1, 2, 3, 4, 6$ Natural recharge
$i = 5$ Irrigation return of surface water
f Groundwater transfer

Because the flow in the Salinas River channel varies considerably and its marginal impact on the quantity of water percolating is limited, the discharge in a sub-area i from the channel is assumed proportional to the depth of the groundwater, i.e., $r_i = (c_i)(s_i)$, where (c_i) is a function of the average flow, the reach length, the vertical permeability of the channel bed, and the ability of the groundwater to move laterally in the immediate vicinity of the river.

The Arroyo Seco Project is incorporated into the model by assuming that the release pattern of the water that is captured in the winter will follow the same pattern as the releases from the Nacimiento and San Antonio Reservoirs. The resulting flow to the lower reaches of the Salinas River would, under the project, be sufficient to accommodate the proposed surface water diversions to the East Side and Pressure North sub-areas.

Equations of motion: The state of the system $s(t)$, measured by the average depth to groundwater, is a aggregate function of the initial state, the successive stresses on the system, and the physical characteristics of the aquifer as measured by its transmissivity, effective porosity, and saturated thickness. The stresses consist of pumping (including percolation of the non-consumed water) $x(t)$, the recharge independent of groundwater levels $y(t)$ and the discharge from the Salinas and Arroyo Seco Rivers, $r[s(t)]$.

The purpose of the equations of motion is to express the annual changes of groundwater level in each sub-area as a function of the groundwater level and stresses in the sub-area and its adjacent sub-areas. These relationships are captured in a "response" or "technological" function which can be generated by a hydrological simulation model (Venetis, 1968, pp. 53–62; Maddock, 1972, pp. 139–52). When used with the principle of superposition (Bear, 1972) and linear hydraulic conditions, the response function relates the drawdowns in the aquifer to the pumping in the present and previous periods.

Differentiating "active" from "passive" effects in the response matrix (Lemoine et al., 1984) opens the way for a critical simplification of the response matrix that eliminates the need to keep track of all previous time periods in the equations of motion.

The active effect of a stress occurs during the period that the stress is actually being applied. Pumping at any well, for example, affects the water level and thereby creates flows specific to that particular type of stress. (This specificity is illustrated by the fact that the cone of groundwater depression at a well is deeper for higher pumping rates.)

The passive effect represents the lagged impact of the active changes in storage. It is simply the flow of groundwater from areas of high water level to areas of low water level. Because this passive transfer of water in any period depends only on the state of the aquifer at the beginning of the period, no matter how the groundwater stocks have been reached, the passive effect can be described adequately as a Markov chain. It is therefore not necessary to include the complete history of discharge and recharge stresses in the equations of motion as long as the aquifer water levels are known at the start of each time period.

To estimate the equations of motion, a mathematical simulator of the aquifer system was prepared by Eric Reichard, Earth Science Department, Stanford University, using the finite difference code of Trescott (1975). The dependent variable, depth to groundwater in time $t+1$, was obtained using the simulation model's estimates for various parameters in time t. The resulting equations (Table 2) incorporate the hydrologic interactions between sub-areas by including terms that reflect the groundwater transfers between two adjacent sub-areas. The equations are key constraints in the control model because they capture the intertemporal and spatial aspects of water movement. The active effect coefficients are associated with groundwater pumping x, natural (constant) recharge y, and recharge by percolation from the Salinas River r. The passive effect coefficients provide information on subterranean transfers associated with the stock of groundwater, i.e., the level of groundwater s.

Seawater intrusion, which corresponds to recharge of the aquifer by saline water, is included in the hydrologic simulation by assuming a constant head at the Monterey Bay boundary of the aquifer. The constant head assumption is justified by the unlimited quantity of seawater available. After a stress, e.g., pumping in the northern region, the simulator automatically generates an inflow from the ocean to the aquifer in order to keep the same water pressure at this boundary. The area of the land forced out of production because of groundwater salinity is thus related to the amount of saline water coming in, and to the average depth to groundwater in the Pressure North sub-area.

Pumping cost functions: The pumping cost functions are part of the control model's objective function and are related to both stock and flow variables. The cost of pumping a unit of water is proportional to the lift, unless there is considerable fluctuation in the aquifer storage. Indeed, the coefficient of proportionality, D, which is determined by the theoretical energy requirements per foot of lift, the total efficiency of water use by plants and energy costs, is expected to remain constant if the actual lift is in the range for which the pump was designed.

If the parameter m is the volume of groundwater stored per foot of aquifer, the withdrawal of one unit of water increases the lift by $1/m$ and the cost of pumping the next unit by D/m. Therefore, assuming that the recharges and natural groundwater transfers during the pumping season are negligible, the marginal costs of pumping x_i units in sub-area i, given the initial lift s_i, is expressed as:

$$MC_i(x_i \mid s_i) = d_i(s_i + x_i/m_i).$$

The assumption is supported by two arguments: (1) the pumping distribution is uniform within the sub-area, whereas the discharges from the Salinas River are localized in the short term but affect the sub-areas uniformly only late in the pumping season, and (2) the recharge by irrigation return reaches the aquifer uniformly after the pumping season because of the infiltration delay.

By integrating the marginal costs, the formulation of total pumping costs becomes:

Table 2.—Equations of Motion*

Area	Equations
Upper Valley South	$s_1(t+1) = .9971\ s_1 + .0017\ s_2 + .127\ x_1 + .001\ x_2 - .232\ r_1 - .001\ r_2 - .233\ y_1$
Upper Valley North	$s_2(t+1) = .955\ s_2 + .0104\ s_3 + .002\ x_1 + .457\ x_2 + .002\ x_3 - .769\ r_2 - .001\ y_1 - .771\ y_2 - .001\ y_3$
Forebay South	$s_3(t+1) = .0262\ x_2 + .871\ s_3 + .0912\ s_4 + .016\ x_2 + .864\ x_3 + .075\ x_4 - .011\ r_2 - 1.475\ r_3 - .069\ r_4 - .013\ y_2 - 1.49\ y_3 - .065\ y_4$
Forebay North	$s_4(t+1) = .0375\ s_3 + .9251\ s_4 + .0086\ s_6 + .089\ x_3 + .396\ x_4 + .03\ x_6 - .094\ r_3 - .62\ r_4 - .032\ r_6 - .088\ y_3 - .623\ y_4 - .03\ y_6$
East-Side	$s_5(t+1) = .0183\ s_4 + .8154\ s_5 + .0306\ s_6 + .0157\ s_7 + .003\ x_4 + .88\ x_5 + .158\ x_6 + .174\ x_7 - .412\ r_6 - .001\ y_4 - 1.792\ y_5 - .325\ y_6 - .302\ y_7$
Pressure South	$s_6(t+1) = .1211\ s_4 + .0627\ s_5 + .7103\ s_6 - .1176\ s_7 + .017\ x_4 + .347\ x_5 + .324\ x_6 + .268\ x_7 - .019\ r_4 - 1.055\ r_6 - .014\ y_4 - .342\ y_5 - 1.127\ y_6 - .538\ y_7$

Table 2.–Equations of Motion*
(Continued)

Area	Equations
Pressure North	
	$s_7(t+1) = .1202\ s_5 + .0906\ s_6 + .3321\ s_7 + .734\ x_5 + .255\ x_6 + .166\ x_7 - .685\ r_6 - 1.023\ y_5 - .63\ y_6 - 1.727\ y_7$

Source: Pierre H. Lemoine, 1984. "Water Resource Management in the Salinas Valley: Integration of Economics and Hydrology in a Closed Control Model." Ph.D Dissertation, Stanford University.

*s = depth to groundwater (tens of feet); x = groundwater pumping (ten-thousands of acre-feet); y = recharge independent of lift (ten-thousands of acre-feet); and r = discharge from channels (ten-thousands of acre-feet).

$$TC_i(x_i \mid s_i) = D_i[K_i + s_i x_i + (x_i)^2/2m_i].$$

The constant term K_i captures fixed costs and can be ignored in the maximization of the objective function.

The storage and energy coefficients are presented in Table 3, where the coefficient m_i is obtained by multiplying the storage coefficient i that describes the feet of water per foot depth of aquifer, with the area A_i of the sub-unit i. The unit pumping cost per foot of lift ($/acre-foot/foot of lift) is calculated from average well capacity, number of operating hours and energy and replacement costs (Moore and Snyder, 1965). The resulting functions for pumping costs are summarized in Table 4.

Summary

Two characteristics are important in determining the context of groundwater management policies. First, there has been a substantial increase in the acreage under water intensive, double-cropped vegetables in the eastern and northern parts of the valley. The concentration of crops like artichokes, broccoli, cauliflower, and lettuce is made possible because of the climate mitigation brought about by the proximity to the Pacific Ocean. Second, these same areas benefit least from the direct percolation of the Salinas River and they suffer from impediments in the aquifer structure that hinder the inflow of groundwater from adjacent areas. The result is that in recent years, the Pressure and East-Side areas have experienced considerable groundwater overdraft.

To provide revenue functions for the optimal control model's objective function, a linear programming model was developed for each of the seven hydrologic sub-areas in the valley. Activities in the model consist of growing the crops that

Table 3.—Storage and Energy Cost Coefficients*

Area	γ_i	A_i	m_i	D_i
Upper Valley South	.150	28,500	4,275	.241
Upper Valley North	.036	35,600	1,282	.234
Forebay South	.018	32,200	580	.164
Forebay North	.050	30,600	1,530	.171
East-Side	.010	37,200	372	.205
Pressure South	.017	33,100	560	.245
Pressure North	.007	31,700	220	.248

Source: T. J. Durbin, 1978, *Two-Dimensional and Three-Dimensional Digital Flow Models for the Salinas Groundwater Basin, California,* U.S. Geological Survey, Water Resource Investigations, 78-113; C. V. Moore and J. H. Snyder, 1965, "Pump Irrigation Cost Increases in the Salinas Valley," *California Agriculture,* Vol. 19.

*γ = storage coefficient (feet of water per foot of aquifer); A = area of aquifer; $m = \gamma \, . \, A$ = storage coefficient (acre-feet of water per foot of aquifer); D = acre-feet of water per foot of lift (1980 costs in 1972 dollars).

are the ingredients of the valley's farming system. Land is constrained by soil type and the extended season required by processing plants is simulated by appropriate crop constraints. Risk is introduced into the agricultural model by specifying that the model minimize the absolute total deviations from the mean crop revenues over the planning period.

For intertemporal and spatial optimization purposes, knowledge about the level of water at the beginning of each period is sufficient, when information about within-period stresses is added, to determine the level of water at the end of the period. The whole history of groundwater movement between areas is not needed for the optimization of one period to the next.

OPTIMIZATION: CONTROL MODEL SPECIFICATION AND EMPIRICAL RESULTS

The functions estimated in the previous section (revenue, pumping costs, and equations of motion) can now be combined in a global optimization algorithm that maximizes both the control and state variables (Intriligator, 1971).

The deterministic, discrete time control model, sometimes called a "multistage optimization model" can be formalized as follows:

$$Max \; F = \sum_{t=1}^{\infty} G_t[s(t), \; x(t), \; t] = \sum_{t=1}^{\infty} b^t G[s(t), \; x(t)]$$

Subject to:

(a) dynamics (equations of motion): $s(t+1) - s(t) = f[s(t), \; x(t)t]$;

(b) state and control constraints: $h_t[s(t), \; x(t), \; t] < 0$;

Table 4.—Pumping Costs Functions

Area	Functions
Upper Valley South	$C_1 = .0241\ s_1 \cdot x_1 + .00282\ x_1{}^2$
Upper Valley North	$C_2 = .0234\ s_2 \cdot x_2 + .00913\ x_2{}^2$
Forebay South	$C_3 = .0164(s_3 + 1) \cdot x_3 + .01459\ x_3{}^2$
Forebay North	$C_4 = .0171\ s_4 \cdot x_4 + .00559\ x_4{}^2$
East-Side	$C_5 = .0205\ s_5 \cdot x_5 + .02758\ x_5{}^2$
Pressure South	$C_6 = .0245\ s_6 \cdot x_6 + .02187\ x_6{}^2$
Pressure North	$C_7 = .0248\ s_7 \cdot x_7 + .05640\ x_7{}^2$

Source: Pierre H. Lemoine, 1984, "Water Resource Management in the Salinas Valley: Integration of Economics and Hydrology in a Closed Control Model," Ph.D. Dissertation, Stanford University.

(c) initial conditions: $s(0) = s_o$; and
(d) terminal conditions: $s(T+1) = s(T)$.

After $t = T$, stationarity is assumed and $f[s(T),\ x(T),\ T] = 0$. The time period of the optimization is infinite, but for $t \geq T$, $G[s(t),\ x(t)] = G[s(T),\ x(T)]$. Because $b < 1$,

$$F = \sum_{t=1}^{T} b^t\ G[s(t),\ x(t)] + \frac{b^T}{1-b}\ G[s(T),\ x(T)].$$

In this notation, $s(t)$ and $x(t)$ represent the vector of state variables (stocks) and the vector of control variables (flows), the objective function $G[s(t),\ x(t)]$

is a social welfare function, the constraint $f[s(t), x(t), t]$ is the vector of equations of motion that relate state and control variables, the coefficient b is the appropriate discount factor and is equal to $(1 + r)^1$, where r is the discount rate.

The version of the control model used in the computation makes use of the so-called Maximization Principle (Pontryagin et al., 1962; Holmes, 1968) in which the Kuhn-Tucker conditions of non-linear programming are applied to difference equation models.

Private vs. Social Optimization

Using the information generated by the agricultural and hydrologic modules, two types of decision rules were simulated in the optimization exercise. The first, which will be referred to as the private optimization model, assumed that present practices will continue over the model's time horizon, i.e., that individual pumping will remain uncontrolled. The externalities of the "common pool" problem were not accounted for in farmers' actions.[6] Total net returns were the result of successive, independent, annual optimization of each sub-area. For each sub-area i, the short-run optimum x_i^* was determined as a single function of $s_i(t)$. Then the groundwater stock in sub-area i at the beginning of the next period $s_i(t + 1)$ was deterministically computed from the stocks $s_j(t)$ and pumping x_j^* for all sub-areas $(j = 1, \dots 7)$. This procedure was repeated for all t.[7] To obtain the 20-year series of the drawdowns in each of the seven sub-areas, 20 x 7 optimizations were needed.

The second type of decision rule under which the model was optimized is referred to as the "social" optimization or "collective action" model. It captures all common pool externalities of the intertemporal and spatial allocation of groundwater. It reflects not only the future value of the groundwater stock for each period t and each sub-area i, but explicitly, through the equations of motion, takes into account physical hydrological interactions as well.

Social optimization was implemented by optimizing the control model over 20 years. Only one run of the model was required to estimate the 20-year optimum path of the level of groundwater in all seven sub-areas.

The Private Optimization Rule and the Current Situation

Earlier comparison of the agriculture simulation with a single year's cropping pattern (1981) suggested that maximizing net revenues subject to water,

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[6] The common pool problem occurs when a number of overlying property owners are engaged in competitive pumping from a common underlying groundwater basin. The divergence between the social and private costs of pumping is caused by the lack of accountability of the private user for his impact on other users.

[7] The initial groundwater stock $s_i(t)$ for each sub-area i at time t is assumed by farmers to be given. By the private optimization rule, the farmer attributes zero value to groundwater storage and its future expected benefits.

land, and soil constraints provided an acceptable approximation of the current situation. The comparison of hydrologic trends predicted by the optimization model under the private optimization scenario inspires further confidence in optimization as a behavorial assumption:

1. The levels of groundwater in the Upper Valley and Forebay sub-areas remain constant in the prediction as they have in the past.
2. The private optimization model predicts that the level in the East-Side will drop about one foot annually or about half the average rate observed between 1950 and 1980. (In the last 10 years, however, the change in groundwater levels has been increasing more rapidly.)
3. The levels in the Pressure South and North sub-areas are forecast to decrease by .15 feet and .5 feet annually. The historical average decline for all of the Pressure areas is about .25 feet per year.

The comparison between model predictions and observed trends suggest that the hydrological dynamics associated with different pumping intensities have been adequately modeled by the recharge equations and the equations of motion estimated from the groundwater simulator. Furthermore, it appears that the combination of the functions generated by the different modules produces, not only a reasonable forecast of the absolute values of groundwater elevations in the base year (1981), but also an estimate of relative changes in the groundwater levels that is in agreement with historical trends.

Comparison of Private Optimization with Social Optimization

Comparison of the results from the optimization of the long-run control model (social optimization) with results of the private optimization model is organized around two physical variables and two economic variables, each measured annually: (1) depth to groundwater (stock variable); (2) irrigation pumping (flow variable); (3) net revenue; and (4) the "stock value" of one foot of aquifer.

Depth to groundwater: In the private optimization model, water levels are forecast to remain constant or drop in all sub-areas over time. In the simulation of collective management, an initial rise in the water tables is forecast in each of the sub-areas, followed by groundwater mining which occurs more or less rapidly among the sub-areas. The result is an inverted U-shaped curve of groundwater withdrawals (Chart 4).

In the southern half of the valley, the difference between private and social optimization is relatively modest. The maximum difference is 2.5 feet for Upper Valley South, 6 feet for Upper Valley North, 4 feet for Forebay South and 3 feet for Forebay North. In the last three areas, the groundwater adjusts rather rapidly after its initial rise, starting to decrease again after three or four years. Because of its relatively large recharge, the water table in Upper Valley South does not drop until the year 12.

The water level in East-Side is forecast to drop at the rate of one foot per year under private optimization. Under collective management, the groundwater would be used optimally if it was permitted to rise by some 70 feet during

Chart 4A.—Depth to Groundwater:
Base Model for Upper Valley and Forebay Areas

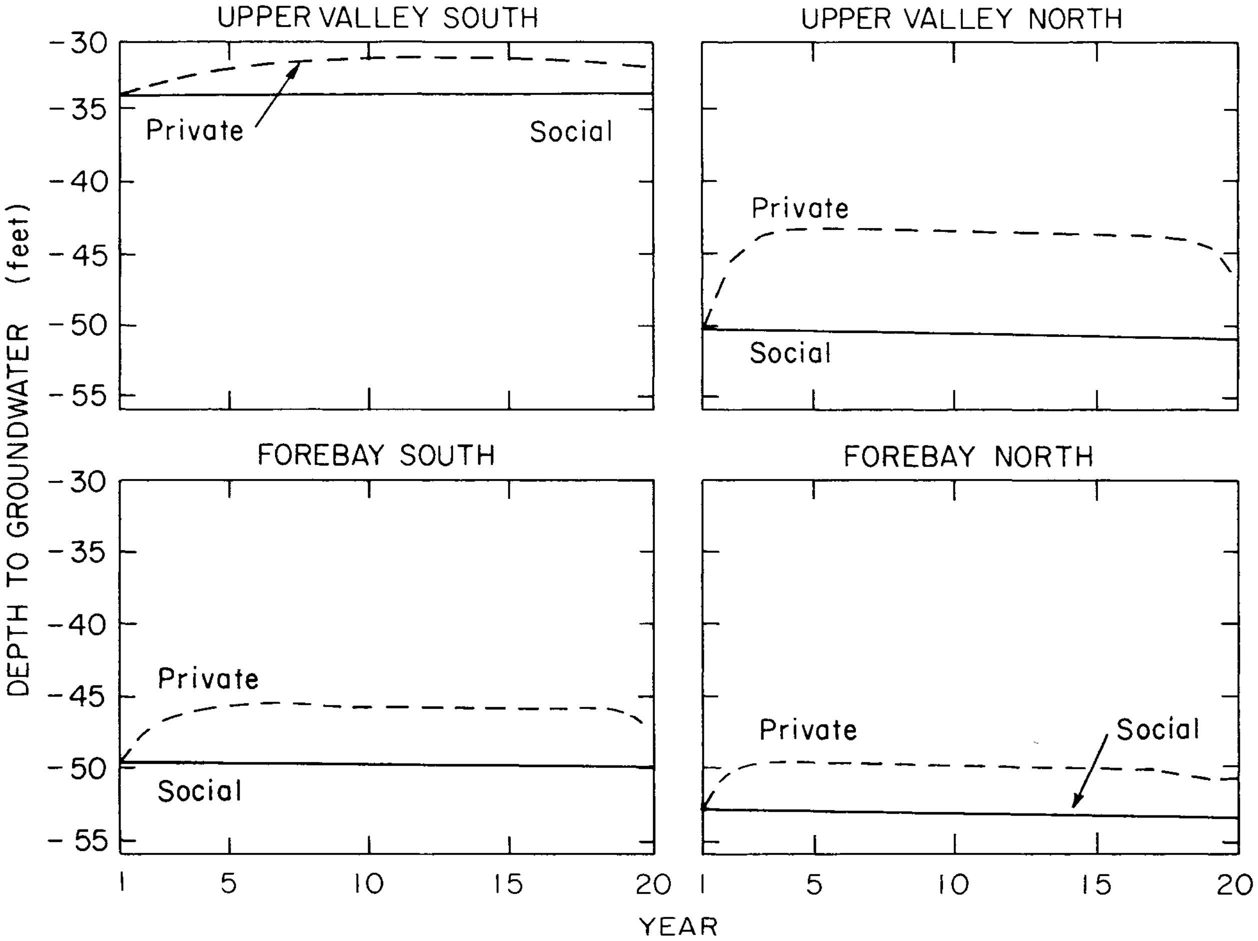
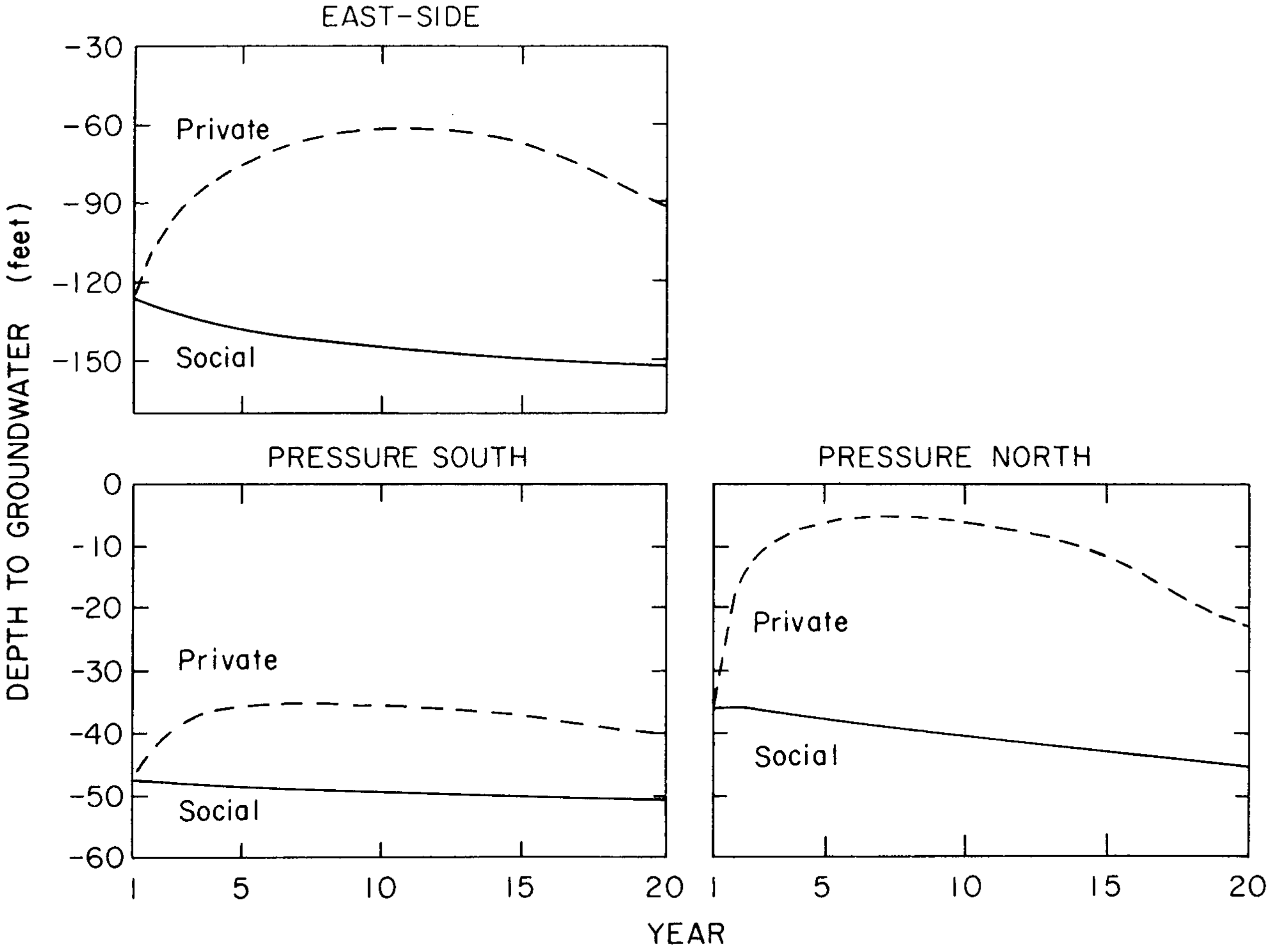


Chart 4B.—Depth to Groundwater:
Base Model for East-Side and Pressure Areas



the first 10 years. Optimal pumping in the latter part of the study period would cause the level to decline by 30 feet from its peak. The large rise and fall in groundwater levels in the East-Side has several determinants:

1. The initial lift is large (125 feet) and pumping costs therefore represent a relatively large share of production costs. Even in the presence of high value crops such as strawberries, the optimal solution over the long run requires that these costs be reduced by permitting the water level to rise.

2. The aquifer is semi-confined, i.e., the storage coefficient is small and thus even modest recharges and withdrawals induce a large change in the water level.

3. The Salinas River does not flow through East-Side. Unlike other sub-areas, pumping that lowers the water level does not induce additional river recharge.

The most obvious effect of the significant decrease in East-Side pumping and the concomittant increase in groundwater stocks is the reversal of the subterranean flow between East-Side and Pressure North (Chart 5). In the private optimization solution, water flows from the Pressure North to East-Side in response to the high agricultural productivity, low storage coefficient, and limited recharge. If a collective management scheme were adopted, optimality conditions would require a short-run rise (rather than a fall) in the East-Side water table that would lead to groundwater movements toward Pressure North.

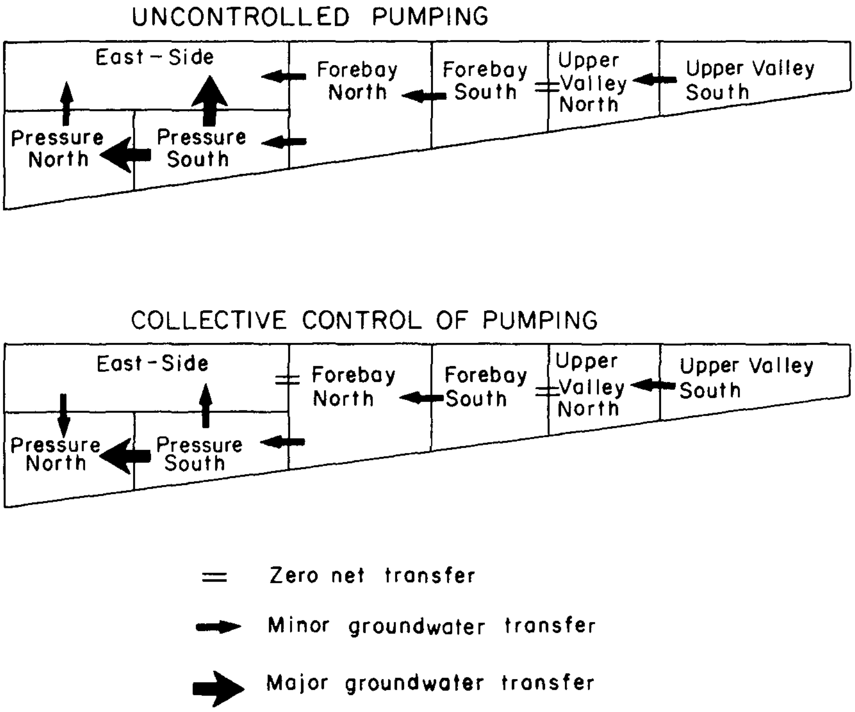
The inflow from Pressure South under social optimization is reduced from the magnitudes predicted under private optimization because of the simultaneous solution of the intertemporal and spatial allocation problem. The equations of motion generated by the hydrologic model insure that the amount of water pumped in time t in sub-area i is dependent not only on the water being pumped in that sub-area but on the optimal pumping for all other relevant areas as well.

As Chart 4 indicates, the depth to groundwater in Pressure North also varies considerably over the time period. It rises initially by 30 feet and then falls three to four times faster than the constant rate of fall predicted under private optimization. Explanations (2) and (3) for variations of the water table in East-Side apply to the Pressure North sub-area also.

Irrigation pumping: For all areas except Pressure North, average annual pumping is 3 to 9 percent less in the social optimization solution than in the private solution. This is the major reason why the predicted water levels are always higher under social optimization.

Except for East-Side and Pressure North, the amount of water pumped in every sub-area remains relatively constant through time for both private and social optimization (Table 5). In East-Side, the rates of pumping increase over time even though future benefits are lowered as a result of applying a discount rate. As noted previously, the main reason for the groundwater behavior in East-Side is the substantial decrease in pumping costs associated with the rise in water levels. However, the dynamics of the optimal adjustment path are complicated. First, a substantial rise is dictated because the current lift (approximately 125 feet) is sufficient to have a relatively large impact on production

Chart 5.—Groundwater Transfers



costs. In the long run it would therefore be desirable to limit pumping now in order to lower pumping costs later. However, there is also a strong demand for irrigation water that derives from the high-value, multiple-crop farming system that is used in the East-Side sub-area. Both forces are at work simultaneously. The cost component is dominant in the initial periods, but in later periods the productivity component produces a downward trend in the water level.

Lower pumping costs in East-Side are the reason for limiting withdrawal of water in Upper Valley also. However, pumping limits are imposed by the model on the Forebay area for another reason, namely, to increase the amount of groundwater transferred downstream as the level in the Forebay area rises. Forebay South has a large potential recharge from the Salinas and the Arroyo Seco Rivers. It also has a low storage coefficient compared to the adjacent Forebay North and the Upper Valley. The two combine to make the area an

Chart 6.—Groundwater Withdrawals Over Time

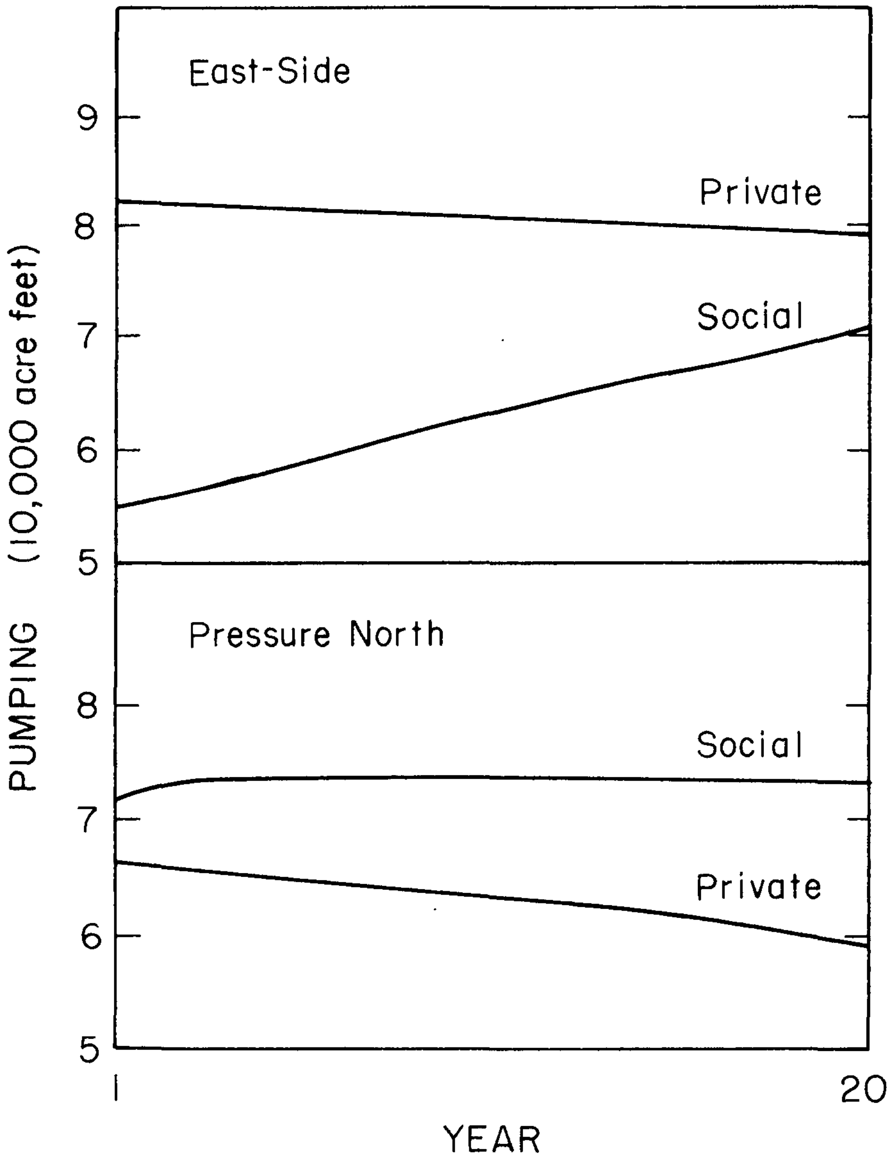


Table 5.—Average Annual Pumping:
Base Model
(Ten-thousands of Acre-Feet)

Area	Private	Social	Difference (percent)	Private irrigation (feet)
Upper Valley	8.55	8.21	−4	3.0
Upper Valley North	9.71	8.83	−9	2.7
Forebay South	8.89	8.29	−7	2.8
Forebay North	9.13	8.72	−4	3.0
Pressure South	9.13	8.88	−3	2.9

exporter of groundwater.

Net revenue: The total discounted benefits of private and social optimization for each sub-area and for the entire valley are summarized in Table 6. Based on these comparisons, the net additional income from a comprehensive management scheme would be on the order of 5 million 1982 dollars annually or an increase of approximately 4.5 percent.

Table 6.—Discounted Revenues Over 20 Years:
Base Model
(Millions of 1972 Dollars)

Area	Private	Social	Difference (percent)
Upper Valley South	45.1	45.3	+.4
Upper Valley North	48.2	48.8	+1.2
Forebay South	47.4	46.1	−2.7
Forebay North	46.8	47.0	+.4
East-Side	97.1	99.1	+2.1
Pressure South	69.6	71.6	+2.9
Pressure North	86.5	102.5	+18.5
Total	44.0	460.3	+4.5

All areas except Forebay South are better off when collective controls are implemented although discounted net revenues in Pressure North would increase much more, nearly 20 percent, than in the other areas.

The reasons are implicit in Chart 5. Pressure North is clearly the beneficiary of substantial increases in water availability. From being an exporter of groundwater to the East-Side under private optimization, it becomes an importer from the same area. The resulting increase in water availability largely explains the change in total net revenues (Table 6).

Stock value and shadow prices of groundwater stocks and flows: The stock value of groundwater water is reflected in the control model's costate multiplier.[8] The value of the multiplier integrates the shadow price of both one acre foot of pumping (a flow variable) and one foot of lift (a stock variable). Hence it provides a single measure of the opportunity cost of pumping water now rather than saving it for future use. The multiplier reflects three parameters: (1) the future savings in pumping costs associated with smaller lifts; (2) the future losses of benefits due to smaller recharge; and (3) the future benefits associated with the exploitation of the quantity of water contained in one foot of aquifer.

An important parameter in the third component of the stock value is the storage coefficient, i.e., the number of acre-feet of groundwater stored per foot of aquifer for the sub-area considered. The higher the storage coefficient, the larger the quantity of groundwater available for irrigation per foot of aquifer and, of course, the greater the stock value of the water. Upper Valley South (Table 7) provides a dramatic illustration of the impact of the storage coefficient on the stock value. Upper Valley is not a particularly productive agricultural area as evidenced by its low marginal productivity of water. However, because the storage coefficient is so large, the amount of water that is stored in a foot of aquifer is substantial, hence the stock value is large.

Table 7.—Shadow Prices and Stock Value:
Base Model

Area	Shadow price 1 acre-foot[a]	Shadow price 1 foot[b]	Stock value[c]	Storage coefficient[d]
Upper Valley South	.073	.199	.574	4,275
Upper Valley North	.133	.208	.286	1,282
Forebay South	.092	.136	.083	580
Forebay North	.080	.149	.184	1,530
East-Side	.569	.126	.585	372
Pressure South	.108	.218	.150	629
Pressure North	.095	.180	.276	32

[a] Shadow price of 1 acre-foot of water in hundreds of 1972 dollars.
[b] Shadow price of 1 foot of lift in hundred-thousands of 1972 dollars.
[c] Stock value of 1 foot of aquifer in hundred-thousands of 1972 dollars.
[d] Storage coefficient in acre-feet of water per foot of aquifer.

A different mechanism produces the large stock value in the East-Side. There the low storage coefficient indicates that the drawdown would be rapid

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[8] The costate multiplier is defined as "the present value of future profit foregone by a decision to produce a unit of output today" (Scott, 1967). It can be interpreted as the dynamic analog of the Lagrangian multiplier associated with static optimization problems.

if pumping were to occur, i.e., a foot of aquifer does not contain much water. However, as the marginal product of water indicates, the pumped water is extremely productive in irrigating the area's multiple season, high valued crops. The stock value of water is, consequently, the highest of any sub-area.

The undiscounted stock values of groundwater are positive and constant in each sub-area over the first 15 years of the simulation period. After that, they decrease to reach the same final value for each sub-area. The exception is Forebay South, where values in each time period must increase to reach the long term equilibrium stock value.

The final value reflects steady-state equilibrium in the sub-aquifers of each area in which: (1) the inflow (recharge + transfer from adjacent sub-areas) to groundwater stock is equal to the outflow (pumping + transfer to adjacent sub-areas); and (2) the marginal productivity of pumping is equal to zero. This is the short-term optimum characterized by the absence of groundwater saving for future use.

For Forebay South and Pressure South, the short-term marginal costs of one foot of lift are greater than their respective stock values for one foot of aquifer. This is because the rise in the level of water in one foot of aquifer does not correspond to a decrease of lift by one foot. A large share of an additional foot of water in these two sub-areas is rapidly transferred to Pressure North and East-Side, so rapidly that the revenue functions in Forebay South and Pressure South cannot capture a saving, over time, in pumping costs over time corresponding to a one-foot decrease in lift.

Implementation of Comprehensive Management Schemes

Interviews with knowledgeable farmers and agricultural engineers in the valley suggest that the optimization model is consistent with their judgments about groundwater exploitation. For example, it is generally believed that:

1. Upper Valley has no particular problem because of its large groundwater storage, and its high recharge.
2. Forebay South has the highest potential for water recharge, but the relatively small storage of water per foot of aquifer and below-average agricultural productivity restrain its full exploitation.
3. Pressure South is the main source of aquifer recharge for the East-Side and Pressure North via groundwater transfers.
4. East-Side and Pressure North sub-areas would benefit most from such management interventions as artificial recharge and pumping restrictions. They are not only the most productive sub-areas, they also benefit least from the percolation recharge of the Salinas River.[9]

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[9] The purpose of the new dam proposed on the Arroyo Seco is, in part, to increase the recharge in Pressure South; it is also designed, however, to divert surface water directly toward East-Side and Pressure North to improve water levels, and to short-

If a comprehensive management scheme is to be implemented, the initiative will have to come from farmers in Pressure North. With an 18 percent return from collective action, they would be the major beneficiaries of reduced pumping rates in the East-Side and Pressure South. It is groundwater transfers from these two areas to Pressure North that would produce positive returns to any overall scheme that treated water as a regional resource.[10]

Comprehensive management of the existing water resources would require a substantial investment in institutional processes. The overriding need, of course, is for a mechanism that would pay farmers located in the middle and upper parts of the valley to reduce pumping in order to permit groundwater to flow to the coastal region. If this is not done by fiat of some higher administrative body like the Federal or State government, it would require several steps. First, there would have to be negotiations within various sub-areas to determine what prices regional groups would be willing to pay and accept. For example, the farmers in the Pressure North would have to figure out among themselves what the additional water was worth to them. Second, the groups would have to negotiate with each other in order to reach an agreement about the magnitude of the transfer payments that would be required. The former may be as difficult to achieve as the latter because the sub-areas used in the study were not based on administrative delineations, but on hydrological characteristics. Although their dimensions are roughly known, the region comprising Pressure North and East-Side could have been carved up in several different ways. Farmers with land on the borderline might end up either paying or receiving depending upon which side of a somewhat arbitrary administrative boundary they found themselves on.

The ability to tax and redistribute implies the existence of an institutional framework with appropriate legal powers. Currently, no institution to facilitate the negotiations exists and, although the farmers of Pressure North may be highly motivated by the important additional revenues they might capture, social inertia and the practical difficulties of implementation are such that mobilization of groups of farmers who would benefit is likely to prove difficult. Most pumpers in the district are unlikely to be fully aware of the potential gains in revenues associated with collective control of individual pumping. In general, farmers are more likely to be concerned about costs of setting up and maintaining the necessary institutional arrangements—lengthy negotiations, continuous participation, restriction of individual freedom, and metering costs. This evaluation of transaction costs undoubtedly accounts to a considerable extent for the surface water development that is being considered by the district's managers. If implemented, it would virtually eliminate the benefits of a comprehensive

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circuit the percolation region of Forebay South. This project is analyzed in the next section.

[10] In addition to the benefits of increased agricultural production, increased groundwater transfers to Pressure North would decrease the damages of seawater intrusion as well.

management scheme by making water a less constraining resource in the areas where its scarcity value is high. The next section provides a more detailed economic and hydrologic analysis of the proposed project.

EVALUATION OF THE PROPOSED ARROYO SECO PROJECT

Previous sections described a basic framework for estimating the optimum allocation of groundwater between regions and over time. Private and social optima reflecting alternative decision rules were compared. The present section utilizes the methodology to explore a practical example in which the groundwater allocation model is used as part of a standard benefit-cost analysis. In addition to the usual comparison with the current situation, the exercise also compares the net benefits of the project with an alternative program of collective water management and provides evidence on the frequently argued point that it would be better for California to concentrate on managing its water resources more efficiently than seeking to develop additional sources of supply.

Project Analysis of the Arroyo Seco Dam

In 1981, the Board of Supervisors of the Monterey County Flood Control and Water Storage District authorized a consulting firm to examine the feasiblity of constructing a dam and reservoir on the Arroyo Seco River for flood control, water supply, hydroelectric power generation, and recreational purposes (CH2M Hill, 1982). The feasiblity study's scope of work included consideration of alternative facilities for delivery of water developed by the project to potentially water-deficient areas of Monterey County and an assessment of project benefits that would accrue to the areas served. The district's initiative was the result of the growing concern of Lower Valley farmers (as well as municipal and industrial managers) about declining water tables and increasing seawater intrusion in the Castroville area. Because the Arroyo Seco River is the only major tributary of the Salinas River still uncontrolled, its development was the obvious target for study.

The general concept of the surface water delivery project that evolved was to capture the presently unused waters of the Arroyo Seco River that are running off to the ocean, and to deliver that water to areas where current water shortages occur. (The average annual run-off of the Arroyo Seco River for the 50-year period 1929–79 was 110,400 acre-feet.) The proposed project would be implemented through the construction of a new dam and reservoir. That reservoir would be operated jointly with the Nacimiento and San Antonio Reservoirs to increase usable water yields from those reservoirs. The Salinas River would be utilized as the main conveyance system to deliver water to areas of current overdraft. Two pumping plants, along with pipelines and canals, would then deliver the water within the areas where it would be used directly for surface irrigation.

The primary new facility of the proposed surface water delivery project would be a dam on the Arroyo Seco River at the Pools or Greenfield dam site.

(Map 3). A rockfill dam of up to 400 feet in height has been envisaged for the project. Facilities at the dam would include outlet works, a spillway, and a powerhouse. Reservoir releases would be diverted from the Arroyo Seco River at an existing irrigation diversion dam just downstream of the Arroyo Seco Road bridge. The canal at the diversion structure would be extended northeast to the Salinas River. At the Salinas River, the Arroyo Seco water would join releases from the Nacimiento and San Antonio Reservoirs. The released water would then flow in the Salinas River channel to pumping plants near Spence and possibly near Blanco Road, 30 to 40 miles downstream, respectively, where it would be diverted for surface water delivery.

In operating the reservoirs, stored water would be released to maximize the amount of water percolated, while minimizing losses to the flow within the 11-mile channel reach between Chualar and Spreckels, with the target point being 6 to 9 miles downstream from Chualar. This point is essentially the southern border of the Pressure North sub-area where little or no infiltration takes place because of the heavy sub-surface clay lenses.

By assuming that distribution of the monthly releases from the Arroyo Seco Reservoir would be the same as that of the Nacimiento and San Antonio Reservoirs, the flow from the Arroyo Seco River can be added to the stream of the Salinas River. This permits the derivation of a unique equation of discharge for use in the management model.

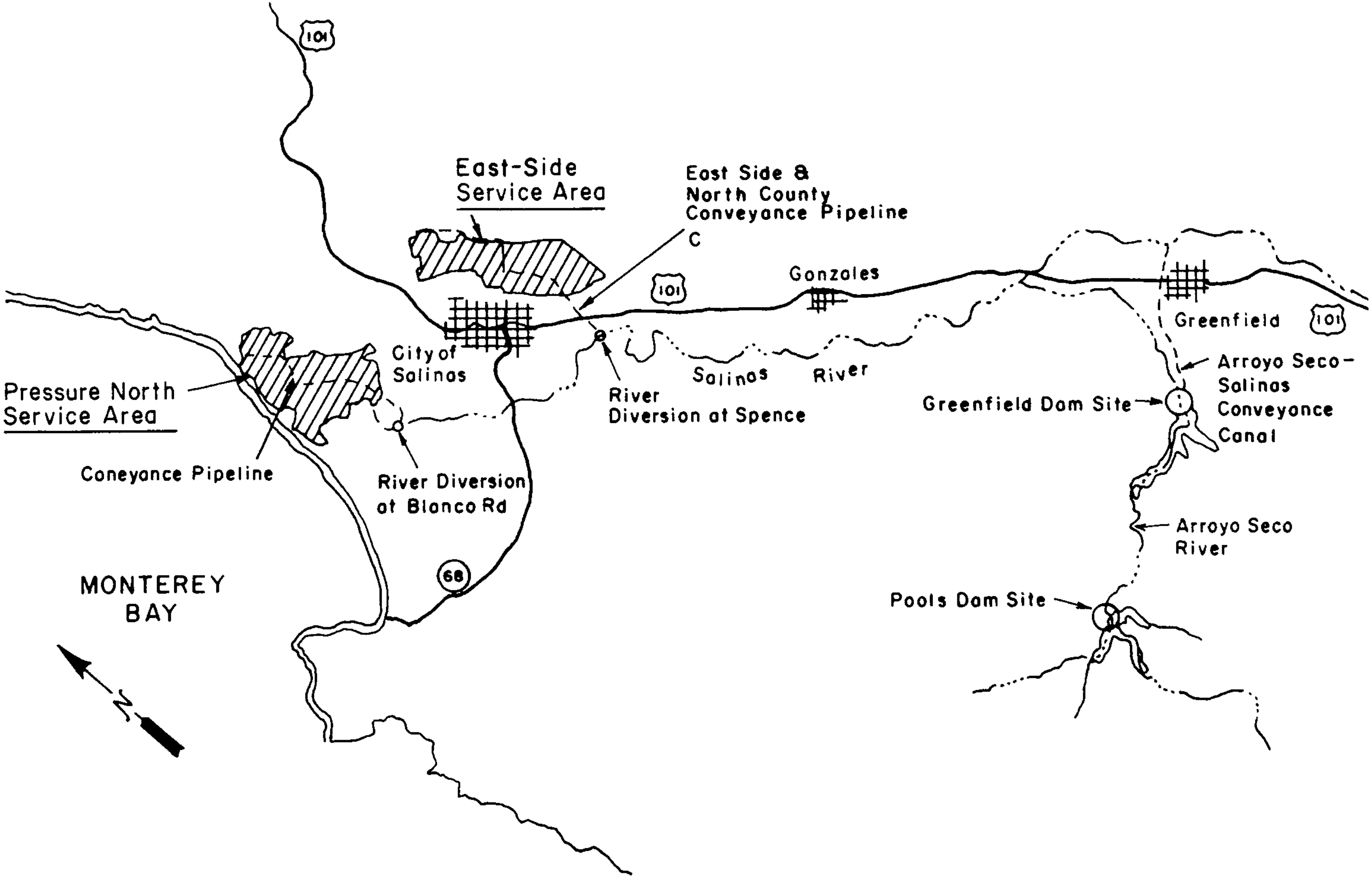
The Arroyo Seco Cone, where the major part of the deep percolation from the Arroyo Seco River channel occurs, would be partially by-passed by a pipeline beginning below the existing diversion dam on the Arroyo Seco River. This would prevent the river releases from percolating into the highly permeable aquifer at this point and would deliver the water to a reach in the river channel where recharge losses are minimal.

Costs of the project: The consulting firm estimated that the total construction costs of the reservoir on the Arroyo Seco River and the conveyance pipeline would be approximately $60 million in 1981 dollars. The facilities for the two diversion dams in the river and associated pumps and distribution appurtances would cost $16 million for the East-Side sub-area and $14 million for the Pressure North sub-area. When maintenance and operating costs are included, the unit cost of water deliveries would be $69 per acre-foot for East-Side and $63 per acre-foot for Pressure North.

Benefits of the project by region: Both Upper Valley South and Upper Valley North sub-areas are upstream from the Arroyo Seco River. Hence they would neither affect nor be affected by the project. According to the model results, the two Forebay sub-areas, however, would feel the impact of the diversions. The recharge by deep percolation from the Salinas River and Arroyo Seco River channels would decrease in the Forebay South sub-area, but increase in the Forebay North sub-area.

Because the discharge from the Arroyo Seco River channel would be reduced by the by-passing pipeline, the optimal water levels in Forebay South would be 3–4 feet lower than those previously predicted in both private and

Map 3.—Surface Water Delivery



social optimization without the dam. The effects are, however, not large. The annual irrigation pumping and the annual undiscounted revenue decrease by less than 2 percent. Over the 20-year period, the construction of the dam would induce a discounted loss for Forebay South of $400,000 in an uncontrolled environment and $300,000 if groundwater resources were managed collectively (Table 8).

Table 8.—Discounted Revenue Over 20 Years:
Arroyo Seco Project
(Millions of 1972 Dollars)

Area	Base	Project	Difference (percent)
Upper Valley South			
Private	45.1	45.1	0
Social	45.3	45.3	0
Upper Valley North			
Private	48.2	48.2	0
Social	48.8	48.8	0
Forebay South			
Private	47.4	47.0	−.8
Social	46.1	45.8	−.6
Forebay North			
Private	46.8	47.4	+1.3
Social	47.0	47.5	+1.1
East-Side			
Private	97.1	110.8	+14.1
Social	99.1	109.2	+10.2
Pressure South			
Private	69.6	70.7	+1.6
Social	71.6	71.0	−.8
Pressure North			
Private	86.5	109.7	+26.8
Social	102.5	109.7	+7.0
Total			
Private	440.6	478.7	+8.6
Social	460.3	477.2	+3.7

In Forebay North, the dam allows an increase in the regulated stream during the dry season (April–November) and in the discharge by deep percolation. The model results suggest that the optimal paths of the depth to groundwater (Charts 4.A and 4.B) are 5–6 feet higher for both private and social optimizations with the Arroyo Seco River regulation than without. After the water levels are readjusted, the trend remains the same as described in the "without dam" case. The increase in annual pumping and undiscounted revenue due to the Arroyo Seco Dam represents less than 1.5 percent for both private and social optimization. Over the 20-year period, the construction of the dam would induce additional discounted net benefits for Forebay North of $600,000 under private optimization and $500,000 under comprehensive management.

The differential impact on the southern sub-areas of the Arroyo Seco Dam and the associated conveyance canal is thus generated by: (1) the independence of the Upper Valley sub-basins; (2) the reduction of the deep percolation from the Arroyo Seco River to Forebay South sub-area, which in turn causes groundwater storage, annual pumping, and revenue to decrease in this sub-area; and (3) the increase in the flow of the Salinas River by the controlled releases from the proposed Arroyo Seco Reservoir during the dry season. This increase produces a larger groundwater recharge in the Forebay North sub-area, which allows groundwater storage, annual pumping, and revenue to increase in this sub-area.

The three most critical sub-areas with respect to the need for additional water supplies are, of course, East-Side, Pressure North, and Pressure South. If the consultants' proposal was implemented, an additional 25,000 acre-feet of surface water would be allocated to East-Side. Pressure North would receive 18,000 acre-feet. Both are possible during the normally dry summer months with the addition of Arroyo Seco water to the Salinas River.

The benefits in the model from surface water transfers are generated by savings of groundwater resources, savings of pumping costs, and recharge of groundwater from irrigation returns. In the East-Side, the annual diversion of 25,000 acre feet has a significant impact both on the levels of groundwater and the amount of water pumped when the model is optimized under the private management scenario. Instead of an average depth of 150 feet without the dam, the average groundwater level at the end of 10 years is closer to 50 feet. At the same time, discounted net revenue increases by 14 percent over the 20-year period.

The effect of the dam on Pressure North is even more dramatic. Comparison of the "with" and "without" scenarios shows an increase of nearly 27 percent in discounted net revenue over the 20-year period. (Because of the large amounts of surface water involved in the project, the water table rises from roughly minus 40 feet to about minus 10 feet as private pumping declines over the period.)

The comparison of individual management with collective action in the presence of the dam produces the expected results, namely, social optimization does not increase net revenues in the absence of resource scarcity. In Pressure North, for example, the influx of water from surface deliveries and groundwater flows eliminates any benefits to collective management. Net revenues obtained from the private pumping run are the same as net revenues under social optimization. In the East-Side, net revenues under social optimization are slightly less (1.5 percent) than under private optimization.[11]

In the past, Californians have preferred to solve their water problems by alleviating scarcity rather than by incurring the transaction costs required to use water more efficiently. In the Salinas Valley, there are a variety of reasons why local residents are likely to prefer development over management. First, the county administrators and farmers in the Salinas Valley (as well as municipal and industrial users) have already experienced the administrative and legal procedures required to build the dam. They understand the process of voting on the water bonds which also provides a basis for sympathetic identification between different water users. The risks of the outcome are reduced because the proposition specifically includes the non-negotiable terms of the different reimbursements. Unlike a comprehensive management scheme, water users negotiate only once. Furthermore, they know well in advance what to expect by way of costs associated with the project.

Such a development approach would appear to be adequate for the rather isolated watershed of the Salinas Valley. It is increasingly questionable, however, whether it can also solve the problem in areas where the water table is declining rapidly under the impact of withdrawals well in excess of recharges.

Financing the Arroyo Seco Project

While the construction of the Arroyo Seco Project seems to have merit on paper, there remains the practical question of how it is to be financed. The preceding analysis has made clear that not all residents of the valley will benefit equally from the project. As might be expected, the current debate centers around who will bear the costs.

The two main sources of financing considered in the preliminary financial analysis are loans and grants provided by the Small Projects Act of 1956 administered by the Bureau of Reclamation (P.L. 984), and Assessment District Bonds governed by the Improvement Bond Act of 1915, collectible on the tax rolls.

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[11] The decline in revenues under social optimization produces an interesting insight into the model's specification. For the purposes of these exercises, the allocations of surface water proposed by the consultants have been taken as exogeneous. Such a large infusion of water, however, creates a disequilibrium in East-Side and Pressure North and collides with the constraint that limits the rise of the water table to 5 feet below the surface. As a result, the social optimization model, unlike the private optimization model which takes the groundwater level in each period as given, forces the model to pump water in the initial years to the point where its marginal product is actually negative. The removal is the equivalent of vertical drainage. The entire system is brought into balance roughly half way through the planning period.

Obviously, the result is artificial since surface water inputs are controlled at pumping stations which can shut down as needed. The result points to the desirability of making surface water deliveries endogeneous to the model.

The P.L. 984 loan program is limited to a maximum project size based on construction costs, in this case, $39 million. The costs attributed to agricultural irrigation can be funded free if certain criteria are met.

Cost recovery of the dam construction is through assessment at the district level. According to the feasibility report, the assessment district covering those who would benefit from the construction of the Arroyo Seco Reservoir would include the district's Zone 2A which represents all of the land in the Salinas Valley (344,650 acres) plus another 50,000 acres in North County. In addition to the dam, 25 percent of the delivery systems to East-Side and Pressure North would also be financed by a district assessment. (The remaining 75 percent would be funded by loans under P.L. 948.)

The modeling results clearly demonstrated, however, that not all of the valley would be affected by the proposed project. For example, neither of the Upper Valley sub-areas significantly affect nor are affected by the Arroyo Seco Project. Therefore, in the interests of equity, the Upper Valley area should be excluded from the assessment district. The same might be said of the Forebay unit because farmers in Forebay South would actually be hurt by the undertaking. This is because water that formerly percolated into the aquifer from which they draw their groundwater now passes over the area in a pipe.

SUMMARY AND SUGGESTIONS

The present study is part of an on-going effort by policy analysts to develop more flexible tools for the quantitative measurement of groundwater management problems. Its contribution lies in integrating the economics of water use derived from an optimization model of the agricultural sector with the physical movement of groundwater as simulated by a three-dimensional hydrological model. Equations obtained from an independent investigation of economics and hydrology are subsequently combined in a closed control model which is solved in a single step for optimal water use among regions and over time. In so doing, the model accounts for the externalities related to the interdependency of pumpers in the various sub-areas as they seek to exploit a common aquifer.

The results of the exercise suggest that the overall benefits to collective management of resources in the Salinas Valley would be on the order of 4.5 percent over a planning horizon of 20 years. The positive result is a function of the existing differences among regions in the demand and supply side of water. Its modest magnitude is due to the fact that, although water is a binding constraint in agricultural production, its scarcity is not sufficient to induce higher returns to management.

Implementation of the methodology in the Salinas Valley suffers from several empirical limitations that could be alleviated by further research:

1. The equations of motion were estimated from a preliminary hydrologic simulator where the whole aquifer was assumed to be confined. This assumption should be relaxed in a more comprehensive analysis because it carries with it the questionable implication of linearity in the hydrologic environment.

2. The stream-aquifer interactions were simplified in the discharge equations. The percolation equation was not a function of the flow of the reach considered. Since the flow in the Salinas River depends not only on the initial controlled releases, but also on the quantities of water percolated in the upstream sub-areas, the equations of motion could be made more realistic by incorporating the nonlinear terms that would result from a more complete specification.

3. The pumping cost equations were estimated under the assumption that variations in the drawdown in a given sub-area during the irrigation season were independent of the pumping and recharge in other sub-areas. Instead, the coefficients of the partial active and passive effects could be used in order to increase the capacity of the control model to internalize the hydrologic interdependencies of the sub-aquifers.

4. The realism of the optimization could be improved in the analysis of the Arroyo Seco Project if the allocation of surface water to the various service areas was considered as an endogenous variable.

The model solutions show that socially optimal water allocation is more efficient than private water allocation. However, the institutions currently dealing with water management issues in the Salinas Valley would have to be strengthened substantially if a collective management scheme were to be implemented. At present, they have neither the political nor the legal mandate to carry out the necessary redistribution of costs and benefits that a comprehensive program would require. While model results show that there would be major differences in the distribution of benefits between sub-areas, they raise doubts as to whether the magnitude of the difference is sufficient to induce farmers to incur the considerable transaction costs that would be associated with social optimization. The model results are clearly a function of the specific economic and hydrologic parameters of the Salinas Valley and could be expected to vary in other areas depending upon the degree of regional heterogeneity and the basic hydrologic environment.

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