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McFarland, J.W.

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9. ABSTRACT

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Groundwater Management and Salinity Control: A Case Study in Northwest Mexico

James W. McFarland

Policy issues associated with the management of a coastal groundwater aquifer and soil salinity are examined for an irrigation area in northwest Mexico. The primary policy issues are the intertemporal rate of use of the groundwater stock, the allocation of water between irrigation and leaching, and the selection of crops. A management model, cast in a dynamic programming format, indicates that the aquifer should be mined at a rapid rate near the beginning of the planning horizon, gradually decline through time, and converge to safe yield after twenty-nine years. Further, a larger percentage of total water use should be allocated to leaching to maintain soil salinity at lower levels.

Key words: groundwater, soil salinity, management, dynamic programming.

The effect of increased levels of soil salinity on the growth of different crops has received considerable attention in the literature (e.g., Bernstein and Richards). Factors which contribute to the buildup in soil salinity have likewise been recognized, and management policies, which relate primarily to the quality of the irrigation water, irrigation practices, and drainage conditions, have been suggested. Most of the work by economists has been in terms of intraseasonal problems associated with the specification and estimation of production relationships, the evaluation of different levels of water quality and the optimal timing and quantity of irrigation water (see Moore, Snyder, and Sun; Yaron; Young, Franklin, and Nobe).

Long-run problems associated with the effect of the accumulation of salts in soils on irrigated agricultural lands have received less attention. Yaron and Olian examine the implications of varying water quality on salt accumulations and leaching water policy in a dynamic model for a perennial crop. More recently, Cummings and McFarland have developed a discrete time control model for the conjunctive management of a groundwater aquifer and soil salinity.

The purpose of this paper, which is in the same vein as these latter studies, is to address selected policy issues encountered in a coastal irrigation area. The next section contains a discussion of the study area and current problems and questions which are of interest. Then a management model which focuses on this set of problems is presented, followed by the empirical results and policy implications.

The Study Area

The Sahuaral irrigation district, located approximately 200 miles south of the Arizona-Mexico border, has been utilized for irrigated agriculture for nearly two decades. Irrigation water in the Sahuaral comes entirely from groundwater sources.

There are several interrelated problems facing the Sahuaral that this study specifically addresses. The first of these relates to the intertemporal rate of use of the groundwater stock, a common property resource.[1] Esti-

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James W. McFarland is an assistant professor of resource economics at the University of Rhode Island.

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[1] Considerable attention has been given to the optimal manage-

mated storage of water in the aquifer is some 2 billion cubic meters; in recent years, this stock has been mined at a relatively rapid rate. During the past four production periods, 1970–73, the average annual withdrawal was 138 million cubic meters of water with natural recharge estimated at 20 million cubic meters per year. This average annual mining of 118 million cubic meters resulted in the water table falling an average of 1.8 meters per year (Secretaria de Recursos Hidraulicos).

In addition to problems associated with falling water tables which result from high withdrawal rates in excess of recharge, the Sahuaral is experiencing difficulties due to saltwater intrusion.[2] As the groundwater stock is mined and the water level in the aquifer falls, saltwater moves in from the seaward side of the aquifer with saltwater replacing freshwater. The salt content of the water where intrusion occurs is generally too high to be used effectively in agricultural production. In the area where intrusion has occurred, pumps are no longer operated due to the high salinity concentration of the water. In the 1970–73 period, the number of pumps in the region declined from sixty-nine to sixty-four.

Based on data from the Mexican Ministry of Water Resources (Secretaria de Recursos Hidraulicos), the average salinity concentration of the aquifer where intrusion has not occurred is approximately 2 millimhos per centimeter. Using water of this quality for irrigated agricultural production requires special management practices. As water with a high salt concentration is utilized, salts build up in the soil resulting in saline soils. It is possible within limits to control the level of soil salinity. These control measures relate primarily to the application of additional quantities of water to carry the salts out of the root zone (leaching) and to maintain adequate drainage conditions.

Since crops have different tolerances for soil salinity, a decision closely related to the control of soil salinity concerns the selection of the cropping pattern. Determining the cropping pattern which results in the greatest benefits to the region entails an examination of the returns and costs involved with each crop and the relative salt tolerance of each crop.

The principal crops in the Sahuaral in 1972–73 by percentage of total hectares cultivated were: wheat—45%, cotton—29%, sesame—18%, and other (including sorghum and soybeans)—8% (Secretaria de Recursos Hidraulicos). A plan developed by the Secretaria de Recursos Hidraulicos for 1973–74 specifies the introduction of another crop, garbanzo beans, which is grown throughout northwest Mexico. Both cotton and wheat are relatively salt tolerant. Garbanzo beans are more salt sensitive, as are some of the other field crops presently grown in the region.

Given the above discussion of some current problems facing the region, the interrelated issues of concern in this study are as follows. What is the optimal rate of exploitation of the scarce groundwater resource for use in irrigation when consideration is given to present and future benefits and costs, including the impact of saltwater intrusion? Given relatively scarce water supplies and associated high scarcity values for water, to what extent should this scarce resource be used for leaching purposes in order to control soil salinity over time? What are optimal cropping patterns? What is the implication of introducing garbanzo beans on cropping patterns and water use policies?

The Management Model

To give operational form to the problems described above, consider a finite planning horizon of T years ($t = 1, \ldots, T$) where any year t is a production year dichotomized into dormant and growing seasons. The production year is defined so that the dormant season is prior to the growing season.

The groundwater stock at the beginning of year t is denoted by X_t, measured in cubic meters. Water use consists of w_t, water applied for production during the growing seasons, and y_t, leaching water applied during dormant periods.

The groundwater stock changes from year t to $t + 1$ as described by the transition equation

$$(1)\ X_{t+1} = X_t + r_t - (w_t + y_t), X_1 \geq 0.$$

The groundwater stock at the beginning of period $t + 1$ equals the stock at the beginning of t, X_t, plus recharge, r_t,[3] less total water use

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ment of a groundwater resource over time, including common property aspects of the problem (see, e.g., Burt).

[2] Several previous studies have investigated the effects of saltwater intrusion. Busch, Matlock, and Fogel discuss the problem in the Costa de Hermosillo. Cummings (1971) presents an analysis of the optimal intertemporal rate of exploitation of groundwater stocks with the intrusion of saltwater. Cummings (1974) also gives empirical results from a multistage linear programming model applied in the Costa de Hermosillo.

[3] Sufficient data are not available to estimate a relationship

during t, $w_t + y_t$.[4] The initial groundwater stock is assumed to be known.

A rather simplified approach is taken in the specification of soil salinity in the model. A single state variable, S_t, is used to reflect average soil salinity in a representative hectare under production at the beginning of year t; S represents the level of soil salinity in the top 120 centimeters of the soil profile and is measured in millimhos per centimeter (mmho./cm.). (See Richards for a discussion and definitions relating to saline soils.)

The transition equation for soil salinity follows from a model developed by Bresler for predicting the salt distribution in the soil profile. Bresler's model is based on the law of conservation of mass which states that the amount of salt added to the soil layer minus the amount leached is equal to the net increment (positive or negative) of salt in the soil profile (assuming that the amount of salt absorbed by the crop is negligible):

$$
\begin{aligned}
(2)\ S_{t+1} = {} & [[V_v - 0.5(y_t/A_t - E)]/[V_v + 0.5(y_t/A_t - E)]]S_t \\
& + c(y_t/A_t)/(V_v + 0.5(y_t/A_t - E)) \\
& + cw_t/(V_w A_t), \\
& \quad \text{for } y_t/A_t - E \leq 2V_v,\ S_1 \geq 0; \\
= {} & c(y_t/A_t)/(y_t/A_t - E) + cw_t/(V_w A_t), \\
& \quad \text{for } y_t/A_t - E > 2V_v.
\end{aligned}
$$

The expression for soil salinity is derived from Bresler's work (p. 228), as was done in the Yaron and Olian paper (see their equations 3, 4, 5, and 6, p. 469).

In equation (2), c is the salt concentration (mmho./cm.) of the water.[5] The moisture content (in meters) of the soil after leaching and irrigation are given by V_v and V_w, respectively, at the time of extraction of salt analyses; E is the soil moisture deficiency up to field capacity when leaching water is applied (in meters), and A_t is the acreage under cultivation measured in square meters.

The level of soil salinity at the beginning of $t + 1$ equals the level at the beginning of t, adjusted by a fraction which indicates the effect of leaching water, plus the salt additions due to leaching and irrigation. Additions of salt attributable to w_t are independent of the level of y_t, given that y_t is applied during the dormant season prior to the growing season during which w_t is applied. In cases where the depth of leaching water does not exceed the soil moisture deficiency, $y_t/A_t \leq E$, no leaching occurs and $y_t/A_t - E$ is set equal to zero. When sufficient leaching water is applied, $y_t/A_t - E > 2V_v$, the concentration of salts in the soil essentially equals the concentration of the leaching water, plus salt additions resulting from w; this is the second expression for S_{t+1}.

To obtain equation (2) from Bresler's paper, a single soil layer is used and his equations are applied twice, making the following assumptions. Water applied for production, w_t, is used only for irrigation. It does not leach salts and w_t is the sum of the intraperiod applications of irrigation water. It is assumed that V_w is constant throughout the growing season. Rainfall is sparse in the region, and it is assumed that it does not have a leaching effect. Leaching water, y_t, is assumed to be applied in single applications prior to the growing seasons.[6]

One problem which arises due to this specification of the transition equation for soil salinity is with respect to acreage. Acreage would be expected to depend on the controls and state variables in the model, in which case an additional state variable for acreage would be required, a requirement which would substantially increase computational complexities (see Burt and Stauber). In this application an

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between water use and return flows to the aquifer; however, the estimates of recharge used in the study include an allowance for return flows.

[4] More realistically it might be expected that specific yield of the aquifer would change as the aquifer is dewatered and water table levels fall. It was not possible to obtain adequate data to estimate such a relationship. Thus, based upon Secretaria de Recursos Hidraulicos suggestions, it was assumed that specific yield is a constant 15%.

[5] Generally it is desirable to have water quality, c, dependent upon return flows, making it a variable in the analysis as suggested by Cummings and McFarland. The author was unable to obtain data that would be required to estimate this relation. Limited data that do exist suggest that return flows to the aquifer (the water table for which is some 70 meters below the surface) may be quite small. Therefore, the author opts for a fixed value of c described above.

[6] The author was unable to obtain sufficient data to evaluate alternative technologies for leaching and irrigation. The assumed timing of leaching corresponds closely with current practices in the region. There are also some experimental data which indicate that periodical heavy leaching reduces soil salinity more efficiently than numerous applications with relatively small quantities of leaching water (Yaron, p. 72).

In specifying the salinity equation in this way, it is implicitly assumed that there is adequate drainage. When this is not the case, more numerous applications of leaching water may be more efficient. The results reported here might then overestimate the efficiency of leaching water and underestimate leaching water requirements. This would appear to be a fruitful area for future research.

iterative technique was used to generate values of A_t for use in equation (2).[7]

A dynamic programming format is used in stating the management model and as a solution algorithm. There are 12 discrete values permitted for salinity ($S^j, j = 1, 2, \ldots, 12$); 201 discrete values are permitted for groundwater storage ($X^i, i = 1, 2, \ldots, 201$); w and y are permitted 14 and 5 discrete values, respectively, ($w^k, k = 1, 2, \ldots, 14; y^m, m = 1, 2, \ldots, 5$).[8] To simplify the exposition, superscripts are used on state and control variables only when they are necessary for purposes of clarity. The general recursive relationship is

$$(3) \quad v_n(S, X) = \max \{b(w, y, S, X) - C(y, X) + \beta v_{n-1}[F(w, y, S), X + r - w - y]\};$$

$v_n(S, X)$ may be interpreted as the maximization, with regard to water use at stage n, of immediate net benefits plus the discounted value of net benefits in the remaining ($n - 1$) stages, given that an optimal policy is followed in the remaining ($n - 1$) stages. The transition for S from stage n to $n - 1$ is represented by F and is given explicitly by equation (2). Current net benefits corresponding to water use rates w and y given soil salinity and groundwater stocks S and X is given by $b(w, y, S, X) - C(y, X)$. The discount factor is $\beta = 1/(1 + i)$, where i is the discount rate. The number of decision stages remaining in the planning horizon is given by n.

Net benefits, except for dormant period pumping costs, were generated using parametric linear programming. Net farm income was used as a measure of benefits from water use.

The objective function in the linear programming model involved the maximization of net returns from seven annual crops.[9] Yield curves for each crop were estimated as functions of the level of soil salinity. These yield curves, along with prices and production costs, were used to obtain net return per hectare for each crop. Production activities and costs, of course, vary among crops; however, costs such as land preparation, seed, cultivation, fertilizer, insecticides, pumping costs (for w), and harvesting are included. Relative prices and costs were assumed constant throughout the planning horizon. Constraints in the model included restrictions on pumping capacity, land, and total water usage.

The impact of saltwater intrusion is reflected in the model through pumping restrictions imposed on water use. It is assumed that as saltwater intrusion occurs, due to a declining groundwater stock, saltwater simply replaces freshwater in the aquifer and there is no mixing at the interface between salt- and freshwater. Pumping capacity is treated as a function of the groundwater stock.[10]

The groundwater stock enters parametrically in the generation of benefits in two ways. Pumping costs are a function of the stock.[11] As the groundwater stock declines, pumping costs increase. Pumping capacities are a function of the groundwater stock (to reflect the impact of saltwater intrusion); as the stock declines, pumping capacity is reduced.

By parametrically varying the total quantity of irrigation water, the groundwater stock, and the level of soil salinity at the beginning of the growing season, the linear programming solutions yield values of net farm income associated with values of these variables. A cropping pattern is implicit to each point on the benefit function.

Dormant period leaching water enters the benefit function only indirectly through its impact in reducing the relevant level of soil salinity and via the costs associated with this water, $C(y, X)$. The cost function on leaching water is influenced by the level of the groundwater stock in the same way as pumping costs for irrigation water are affected.

Thus, the linear programming model is run for combinations of w and y with selected

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[7] Initial values for the time path of A were chosen, and the model was run. The values of the A's corresponding to this solution were then used in the program. This iterative procedure was continued until the acreages used in the model approximated the acreages implied by water use in the optimal solution.

[8] The values for X range from 0 to 2 billion in increments of 10 million; the values for S range from 2 to 24 in increments of 2; the values for w range from 0 to 130 million in increments of 10 million; and the values of y range from 0 to 40 million in increments of 10 million.

[9] The crops included in the analysis are cotton, wheat, sesame, safflower, soybeans, sorghum, and garbanzo beans. It would have been desirable to include other salt-tolerant crops, such as barley. Data relevant for such crops as they might be produced in the study area do not exist.

[10] Sufficient data for the study area does not exist to estimate the relationship between the rate of intrusion and the groundwater stock. It was necessary, therefore, to use an assumed rate of intrusion as the stock declined. The same rate as that used by Cummings (1974) for the nearby Costa de Hermosillo was assumed in this study. Using this rate and the distribution of pumps in the region, a relationship between the groundwater stock and pumping capacity was estimated.

[11] Admittedly, pumping costs in the model are represented in a somewhat simplified fashion in that they represent an average cost, with the groundwater stock used as a surrogate for depths. Of course, this treatment abstracts from a number of issues related to optimal investment strategies, a topic which lies beyond the scope of this paper. A conceptual framework for this more general problem is given in Cummings and McFarland.

combinations of X and S. Using these solutions with interpolations, a matrix of values for the benefit function is generated.[12] Values from this matrix are utilized in the dynamic programming analogue for the values of $b(w, y, S, X)$.

The decision variables in the dynamic programming model are restricted to satisfy the following conditions at each stage:

$$w + y \leq X + r, \tag{4}$$

$$y \leq DPC(X), \tag{5}$$

and

$$0 \leq w, y. \tag{6}$$

Equation (4) constrains total water use at each stage, $w + y$, so that it does not exceed the groundwater stock plus recharge, $X + r$. Dormant period leaching water applications, y, are restricted through an upper bound on dormant season pumping capacity, $DPC(X)$, by equation (5). Pumping capacity restrictions for w are imposed within the linear programming model. Both controls are restricted to be nonnegative numbers, equation (6).

Solution of the dynamic programming formulation yields optimal use rates for irrigation water and leaching water throughout the T-year decision-making horizon. The levels of the groundwater stock and soil salinity are also determined through time. Given the determination of the values of the controls for given states, cropping patterns are implied by the benefit function, and they can be obtained from the linear programming results.

Insights into the decision regarding water use policies can be gained by examining the marginal net benefits associated with irrigation water and dormant leaching water, MBW and MBY respectively, and the marginal user costs of this water in terms of the impact on the groundwater stock and soil salinity, UCW and UCY respectively. The user cost associated with w is the present value of the sum of marginal returns which are foregone in all future periods as a result of using an additional unit of w at present. This cost reflects both the effect of incrementally reducing the groundwater stock and increasing the level of soil salinity. Similarly, with regard to y, the user cost measures the marginal impact that an additional unit of y has on the groundwater stock and soil salinity. Irrigation water use in each period is pushed to the point where MBW = UCW.[13]

Over time, the marginal net benefits for w shift downward as the groundwater stock declines and pumping costs rise. Also, the user costs associated with w shift upward as the groundwater stock becomes more scarce and the impacts of seawater intrusion become more costly.

The analogous conditions for y would be to increase the use of y up to the point where the marginal net benefits for y are equated with the marginal user costs for y plus the marginal value of pumping capacity.

Empirical Results and Policy Ramifications

The management model was solved using a discount rate of 10%,[14] a value for water quality of 2.0 mmho./cm.[15] and a constant value for recharge of 20 million cubic meters. The model was solved for a fifty-year planning horizon. Using initial states $X = 2$ billion cubic meters and $S = 8$ mmho./cm.,[16] table 1 shows the time paths for the groundwater stock, total water use, irrigation water, and leaching water. For stage 50 (year 1), the optimal solution calls for total water use of 150 million cubic meters with $w_1 = 110$ million cubic meters and $y_1 = 40$ million cubic meters.[17]

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[12] Given the large number of combinations which are required for a complete enumeration of all possible runs, for purposes of practicality, eleven values of X, equally spaced between 0 and 2 billion, were used. The intermittent values of b were then approximated using linear interpolation. After initial runs, it was determined that for values of S (adjusted for leaching) above 12 mmho./cm., the benefit function is zero. Although several of the crops considered have positive yields beyond 12 mmho./cm., none of these crops were profitable when the level of soil salinity exceeded 12 mmho./cm. The variable y does not directly enter the linear programming model. This yields 11 (for X) × 6 (for S, adjusted for leaching) × 14 (for w) computer runs.

[13] For an examination of decision rules with regard to the general problem concerning optimal rates of use of resources, see Burt and Cummings. Decision rules for a model that encompasses the one presented here are discussed in Cummings and McFarland.

[14] This choice of the discount rate was made based upon the fact that this is the rate that is commonly used in the Secretaria de Recursos Hidraulicos planning process. The discount rate controversy, although interesting, is beyond the scope of this paper. A sensitivity analysis of discount rates did not materially alter the conclusions presented.

[15] Given, as suggested above, that recharge estimates include return flows, the use of a constant for natural recharge overestimates natural recharge in later years given that water use declines in time.

[16] These initial values for states approximate current conditions.

[17] In year 1 (stage 50), the approximate marginal net benefits for a value of w of 110 million cubic meters is 0.136 pesos. The marginal user cost corresponding to this value of w is approximately 0.134 pesos. Irrigation water w is applied at 110 million cubic meters since MBW is approximately equal to UCW at this

Table 1. Time Paths for Groundwater Stock, Total Water Use, Irrigation Water and Leaching Water

Year	X $(10^6 m^3)$	$w+y$ $(10^6 m^3)$	w $(10^6 m^3)$	y $(10^6 m^3)$
1	2000	150	110	40
2	1870	150	110	40
3	1740	140	100	40
4	1620	140	100	40
5	1500	140	100	40
6	1380	140	100	40
7	1260	120	90	30
8	1160	120	90	30
9	1060	110	80	30
10	970	110	80	30
11	880	110	80	30
12	790	100	70	30
13	710	80	60	20
14	650	80	60	20
15	590	80	60	20
16	530	80	60	20
17	470	70	50	20
18	420	70	50	20
19	370	70	50	20
20	320	70	50	20
21	270	40	30	10
22	250	40	30	10
23	230	40	30	10
24	210	40	30	10
25	190	40	30	10
26	170	40	30	10
27	150	30	20	10
28	140	30	20	10
29	130	20	10	10
30	130	20	10	10

As shown in table 1, the groundwater stock is mined at a rapid rate near the beginning of the planning horizon, gradually declines in time, and converges to recharge after twenty-eight years. Dormant leaching water applications y are maintained at approximately a constant percentage (33% to 43%) of irrigation water w until total water use begins to converge to steady state conditions, after which leaching water increases slightly as a percentage of irrigation.[18] The optimal policies for irrigation water and leaching water are such that soil salinity at the beginning of the growing season is maintained below 6 mmho./cm. over the entire decision horizon.

Digressing for a moment, an examination of the linear programming results suggests that for levels of soil salinity of 2 mmho./cm., the primary crops would be garbanzo beans, sesame, and cotton. Linear programming results, where higher salt concentrations are imposed, result in similar cropping patterns; however, there is a shift to a lower percentage of land used for garbanzo beans, which is a relatively salt sensitive crop. When soil salinity reaches 8 mmho./cm., the cropping pattern changes to cotton and wheat. At higher levels of salinity, cotton is the predominant crop. Beyond 12 mmho./cm., none of the crops are profitable.

Combining the results from the management model with the linear programming solutions suggests substantial changes from current crop patterns. Specially, the crop pattern indicated by this analysis for year 1 (stage 50) is: garbanzo beans—58%, sesame—31%, and cotton—11%. These results support proposals by the Mexican government (Secretaria de Recursos Hidraulicos) for the introduction of the garbanzo bean and a reduction in the large acreages which are allocated to wheat. This change in the cropping pattern is indicated since the level of soil salinity at the beginning of all growing seasons is maintained below 6 mmho./cm. throughout the planning horizon, in contrast to current practices where larger salinity levels are being maintained. The results of this study also suggest that a higher proportion of total water use should be allocated for leaching purposes than is the case under current practices. Currently about 15% of water use is for leaching.

Focusing now on groundwater storage, as the groundwater stock is being mined to the point where use is at safe yield in year 29, a number of changes of consequence take place. First, saltwater intrusion is increased by 8 kilometers. Second, the number of pumps falls from 64 to 15, and monthly pumping capacity declines to 4.4 million cubic meters.[19] These changes reduce the feasible irrigable area to 2500 hectares.

If current operating conditions continue, a situation similar to that described above would be expected sooner. The Mexican government is extremely concerned with such a possibility, not only in the Sahuaral district but in the nearby Costa de Hermosillo irrigation district. The government's response to these conditions of growing water scarcity has

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point; beyond 110 million cubic meters (with the discrete approximation), UCW > MBW. In year 28, the marginal net benefits for a value of w of 20 million cubic meters is 0.618 pesos with an associated user cost of 0.615 pesos. Again the decision is made at the margin with water use for irrigation pushed to the point where MBW approximately equals UCW.

[18] This results from the discrete nature with which the controls are specified; thus, beyond this point, the solution algorithm overestimates leaching water applications.

[19] This value for pumping capacity is derived from the relationship between pumping capacity and the groundwater stock.

been the proposal of a major interbasin water transfer, details of which are reported by Cummings (1974).

Conclusions

The results suggested in this work imply a pattern of water use in the Sahuaral irrigation district which may postpone to some extent the immediate need for alternative water sources, particularly such costly water sources as the proposed interbasin water transfer. This is particularly relevant given the possibility of developing alternative water supply systems to alleviate the problem suggested by Cummings (1974).

Several aspects of the problem studied here remain for further analysis and refinement. A wide range of investment decisions have not been considered. Structures which might increase irrigation and leaching efficiency (artificial drains) or investments to slow the rate of saltwater intrusion (injection wells, relocation of pumps) have not been evaluated. In addition, alternative technologies for irrigation and leaching, varying land types and quality, different and more salt-tolerant varieties of crops, stochastic elements of the system, and varying water quality are not reflected in the results.

To incorporate the multitude of factors associated with this problem into a framework for analysis is a formidable task. The dynamic programming framework is readily adaptable to nonlinear multistage decision problems, both deterministic and stochastic. A major drawback of this approach, however, arises due to the well-known problem of "dimensionality" (see Bellman; Burt and Stauber). If this approach is to be used to gain insights into an extended version of the problem taking into account many of the above-mentioned factors, it would appear that a partial analysis for subsets of the system combined with sensitivity analysis might be informative. An alternative approach, such as that suggested by Yaron (see also Young, Franklin, and Nobe), combines simulation techniques with optimization models. A major concern, however, regardless of the method employed, is the availability of sufficient data to use in the assessment of alternative management policies in a particular irrigation area.

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References

Bellman, R. *Dynamic Programming*. Princeton: Princeton University Press, 1957.

Bernstein, L. *Salt Tolerance of Plants*. USDA Agr. Inform. Bull. 283, 1964.

Bresler, E. "A Model for Tracing Salt Distribution in the Soil Profile and Estimating the Efficient Combination of Water Quality and Quantity under Varying Field Conditions." *Soil Sci.* 104 (1967):227–33.

Burt, O. "Economic Control of Groundwater Reserves." *J. Farm Econ.* 48 (1966):632–47.

Burt, O., and R. G. Cummings. "Production and Investment in Natural Resource Industries." *Amer. Econ. Rev.* 60 (1970):576–90.

Burt, O., and M. S. Stauber. "Economics Analysis of Irrigation in Subhumid Climates." *Amer. J. Agr. Econ.* 53 (1971):33–46.

Busch, C., W. Matlock, and M. Fogel. "Utilization of Water Resources in a Coastal Groundwater Basin." *J. Soil Water Conserv.* 21 (1966):163–69.

Cummings, R. G. "Optimal Exploitation of Groundwater Reserves with Saltwater Intrusion." *Water Resour. Res.* 7 (1971):1415–23.

———. *Interbasin Water Transfers: A Case Study in Mexico*. Baltimore: Johns Hopkins Press, 1974.

Cummings, R. G., and J. W. McFarland. "Groundwater Management and Salinity Control." *Water Resour. Res.* 10 (1974):909–15.

Moore, C. V., J. H. Snyder, and P. Sun. "Effects of Colorado River Quality and Supply on Irrigated Agriculture." *Water Resour. Res.* 10 (1974):193–226.

Richards, L. A., ed. *Diagnosis and Improvement of Saline and Alkali Soils*. USDA Agr. Handb. 60, Feb. 1954.

Secretaria de Recursos Hidraulicos. "Informacion del Distrito de Riego No. 51." Mimeographed. Hermosillo, Sonora, Mexico: Secretaria de Recursos Hidraulicos, 1974.

Yaron, D. "Economic Analysis of Optimal Use of Saline Water in Irrigation and the Evaluation of Water Quality." *Salinity in Water Resources*, ed. J. Flack and C. Howe, pp. 60–85. Boulder: Merriman Publishing Co., 1974.

Yaron, D., and A. Olian. "Application of Dynamic Programming in Markov Chains to the Evaluation of Water Quality in Irrigation." *Amer. J. Agr. Econ.* 55 (1973):467–71.

Young, R. A., W. T. Franklin, and K. C. Nobe. "Evaluating Agricultural Effects of Salinity Abatement Projects in the Colorado River Basin: Agronomic and Economic Considerations." *Salinity in Water Resources*, ed. J. Flack and C. Howe, pp. 86–107. Boulder: Merriman Publishing Co., 1974.

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