Mexico

GROUNDWATER MANAGEMENT AND SALINITY CONTROL: A CASE STUDY IN NORTHWEST MEXICO*

James W. McFarland

I. Introduction

The effect of increased levels of soil salinity on the growth of different crops has received considerable attention in the literature (see, e.g., [2], [14], [15], [23]). Factors which contribute to the buildup in soil salinity have likewise been recognized, and management techniques and policies, which relate primarily to the quality of the irrigation water, irrigation practices and drainage conditions, have been suggested (see, e.g., [3], [17], [23]). The work by economists has built on previous work by biological and physical scientists. Most of this work by economists has been in terms of intra-seasonal 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, e.g., [4], [19], [20], [21], [25], [26], [28]).[1]

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*James W. McFarland is assistant professor of Resource Economics at the University of Rhode Island.

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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 [27] examine the implications of varying water quality on salt accumulations and leaching water applications in a dynamic model for a single perennial crop. Yaron [25] indicates a possible approach for a long-run analysis of a multi-product farm which faces salinity problems. More recently, Cummings and McFarland [12] have developed a discrete time control model for the conjunctive management of a ground-water aquifer and soil salinity.

The thrust of this paper is in the same vein as these latter studies. It draws heavily on the framework presented in Cummings and McFarland. Both long-run problems associated with the accumulation of salts in agricultural soils and the intertemporal management of a coastal aquifer are of concern.

The purpose of this paper is to address selected policy issues encountered in a coastal irrigation area. To aid in this decision making with regard to these policy issues, an operational format for an intertemporal management model is presented. This model is then applied to the study area and the results are used to gain insights as to alternative policies regarding the control of water use and soil salinity.

Section two contains a discussion of the study area and current problems and questions which are of interest. A statement of a management model which focuses on this set of problems is presented in section three. Empirical results from application of the model with associated policy implications are given in section four.

II. The Decision Environment

The Sahuaral irrigation district, located approximately 200 miles south of the Arizona-Mexico border, has been utilized for irrigated agriculture for nearly two decades. The development of the Sahuaral district has been related to recent developments in the nearby Costa de Hermosillo irrigation district, some 30 miles to the north. 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.[2] Estimated storage of water in the aquifer is some two billion cubic meters; in recent years, this stock has been mined at a relatively rapid rate. During the period

1970-1973 some 124 million cubic meters of water were pumped per year with natural recharge estimated at 20 million cubic meters per year. The annual mining of 104 million cubic meters has resulted in the water table falling at a rate of about 1.8 meters per year [22].

An obvious policy issue of considerable priority then is that of determining the optimal intertemporal rate for the exploitation of the aquifer stock. This policy, of course, must reflect present and future benefits and costs, as well as those associated with saltwater intrusion discussed below.

In addition to problems associated with falling water tables which result from high withdrawal rates in excess of recharge (higher pumping costs), the Sahuaral is experiencing difficulties due to saltwater intrusion.[3] 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 effectively used in agricultural production. In the area where intrusion has occurred, pumps have ceased to be operated due to the high salinity concentration of the water. In the 1970-73 period, the number of pumps in the region declined from 69 to 64. In the calculation of costs associated with mining the aquifer, the effects of saltwater intrusion require consideration.

Based on data from the Mexican Ministry of Water Resources (Secretaria de Recursos Hidraulicos, SRH) the average salinity concentration of the aquifer (where intrusion has not occurred) is between 1000 and 1600 parts per million. 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. (These soil conditions are common to many arid and semiarid regions [25].) It is, however, possible 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, i.e., leaching, and the maintenance of adequate drainage conditions. The interrelationship between the management of soil salinity through leaching and the management of the water stock is, of course, obvious.

A decision closely related to the control of soil salinity concerns the selection of the cropping pattern. Crops have different tolerances to soil salinity [2, 14, 15, 23], and in instances where conditions exist which contribute to saline soils ". . . the judicious selection of crops that can produce satisfactory yields under saline conditions and the use of special management practices to minimize salinity may make the difference between success and failure [23, p. 65]." Determining the cropping pattern (patterns) 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 tolerances of each crop under varying soil salinity conditions. Of course, in making the crop selection the calculations should include the cost of salinity control policies with attention given to the scarcity value of the water resource.

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 sorgum and soybeans)--8% [22]. A plan developed by the SRH for 1973-74 specifies the introduction of another crop, garbanza beans. (The garbanza bean, which is primarily exported to Spain, is a major crop in the nearby Costa de Hermosillo.) Both cotton and wheat are relatively salt tolerant crops; whereas, garbanza 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 inextricably interrelated issues of concern in this study are these: 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 in time?

Some interesting insights into these key policy issues may be obtained from the manipulation of the decision model which is presented in the following section.

III. The Management Model

To give operational form to the decision environment described above, consider a finite planning horizon of T years (t=1, ..., T) where a 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. X_t is measured in cubic meters. Water use is divided into two components; w_t is water applied for production during the growing season and y_t is leaching water applied during dormant periods.

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

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

The groundwater stock at the beginning of period t+1 equals the stock at the beginning of t, X_t, plus recharge, r_t,[4] less total water use during t, $w_t + y_t$. The initial groundwater stock is assumed to be known. The relationship between the groundwater stock and saltwater intrusion is discussed below.

A rather simplified approach was taken in the specificiation of soil salinity in the model.[5] 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 (mmhos./cm.). (See [23] for a discussion and definition relating to saline soils.)

Using a modified version of the transition equation given by Bresler [3] and applied in the Yaron and Olian paper [27], the transition equation for S is:

$$(2)\quad S_{t+1} = [[(V_y-.5(y_t/A_t-E)]/[V_y+.5(y_t/A_t-E)]]S_t$$

$$+ c(y_t/A_t)/(V_y+.5(y_t/A_t-E)) + cw_t/(V_wA_t),$$

$$\text{for } y_t/A_t-E \le 2V_y,\ S_1 \ge 0 \text{ given.}$$

$$= c(y_t/A_t)/(y_t/A_t-E) + cw_t/(V_wA_t),$$

$$\text{for } y_t/A_t-E > 2V_y.$$

In (2), c is the salt concentration (mmhos./cm.) of the water and V_y and V_w are the moisture content (in meters) of the soil after leaching and irrigation, respectively, at the time of extraction for salt analyses. E is the soil moisture deficiency up to field capacity when leaching water is applied (in meters). A_t is the acreage in 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 the assumed timing of applications; i.e., y_t is applied during the dormant season which is prior to the growing season during which w_t is applied.

When sufficient leaching water is applied, i.e., $y_t/A_t - E > 2V_y$, then 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}. In cases where the depth of leaching water does not exceed the soil moisture deficiency, i.e., $y_t/A_t \leq E$, then no leaching occurs and $y_t/A_t - E$ is set equal to zero.

To obtain (2) from Bresler's paper [3], a single soil layer is used and his equations are applied twice with the following assumptions made. w_t is used only for irrigation and does not leach salts. (With minor changes, it is possible that a fixed quantity is leached.) w_t is the sum of the intra-period 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 is assumed to be applied in single applications prior to the growing seasons. Further it is assumed that there is uniform areal application of the irrigation water, that there is no removal of salt in the harvested crop, and that there is no precipitation of soluble constituents in the soil [23, p. 37].

One problem that 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. For this formulation to reasonably approximate average salinity conditions, acreage in production would have to decrease over time. Rather than introduce an additional state variable to account for acreage, iterative techniques are used so that A_t in the salinity equation closely approximates acreages implied by water levels in the optimal solution.

A dynamic programming [1] format is used in stating the management model and as a solution algorithm. In the following (see Table 1), there are 12 discrete values permitted for salinity (S^j, j=1, 2, ..., 12), 201 discrete values are permitted for groundwater storage (X^i, i=1, 2, ..., 201), w and y are permitted 14 and 5 discrete values, respectively, (w^k, k=1, 2, ..., 14; y^m, m=1, 2, ..., 5). 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:

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

TABLE 1

DISCRETE VALUES CHOSEN FOR STATES AND CONTROLS

X (10^6 million m^3)	S (mmhos./cm.)	w (10^6 million m^3)	y (10^6 million m^3)
0	2	0	0
10	4	10	10
20	6	20	20
.	.	.	.
.	.	.	.
.	.	.	.
2000	24	130	40

$v_n(S,X)$ 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. F represents the transition for S from stage n to n-1 and is given explicitly by equation (2). $b(w, y, S, X) - C(y, X)$ is current net benefits corresponding to water use rates w and y given soil salinity and groundwater stocks S and X. β is the discount factor; $\beta = 1/(1+i)$, where i is the discount rate. n is the number of decision stages remaining in the planning horizon.

Net benefits, except for dormant period pumping costs, were generated using parametric linear programming.[6] 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. Yield curves for each crop were estimated as functions of the level of soil salinity. These yield curves with prices and production costs were then 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, that saltwater simply replaces freshwater in the aquifer and that there is no mixing at the interface between salt and freshwater. Pumping capacity is then treated as a function of the groundwater stock.[7]

The groundwater stock enters parametrically in the generation of benefits in two ways. Pumping costs are a function of the stock.[8] 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 program is run for combinations of w and y with selected combinations of X and S, and interpolations are used which generate a matrix of the form in Table 2.[9] Values from this matrix are then utilized in the dynamic programming analyog 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:

(4) $w + y \leq X + r$

(5) $y \leq DPC(X)$

(6) $0 \leq w, y$

Condition (4) constrains total water use at each stage, w+y, so that it does not exceed the groundwater

TABLE 2

ILLUSTRATION DEMONSTRATING GENERATION OF BENEFIT FUNCTION

	s^1x^1	s^1x^2	...	$s^{12}x^{201}$
w^1y^1	$b(w^1,y^1,s^1,x^1)$	$b(w^1,y^1,s^1,x^2)$	...	$b(w^1,y^1,s^{12},x^{201})$
w^1y^2	$b(w^1,y^2,s^1,x^1)$	$b(w^1,y^2,s^1,x^2)$	...	$b(w^1,y^2,s^{12},x^{201})$
.	.	.		.
.	.	.		.
.	.	.		.
$w^{14}y^5$	$b(w^{14},y^5,s^1,x^1)$	$b(w^{14},y^5,s^1,x^2)$	...	$b(w^{14},y^5,s^{12},x^{201})$

stock plus recharge, X+r. Dormant period leaching water applications, y, are restricted through an upper bound on dormant season pumping capacity, DPC(X), hence, condition (5). Pumping capacity restrictions for w are imposed within the linear programming model. Both controls are restricted to nonnegative numbers (condition (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.

Analytical decision rules associated with an almost identical model for the optimal time paths of the controls have been established elsewhere.[10] Irrigation water at each stage of the process, w, is applied (assuming $w > 0$) in such a way as to equate the present value of marginal net benefits associated with an increment in w with the marginal user costs of this increment in use. The user costs of this water use at stage n would be the sum of the marginal benefits which would be foregone in stages n-1, n-2, ..., 1 as a result of using an additional unit of the stock at stage n plus the user costs associated with the impact of an increment in w on soil salinity in the future, marginal land salinity costs. (If stage n corresponds to year t, then the opportunity cost would include consideration of the impact on the groundwater stock and soil salinity in years t+1, ..., T.) The marginal value of the groundwater stock at stage n reflects both the influence of increased future pumping costs and reduced pumping capacity. Similar conditions hold for y.

IV. Empirical Results and Policy Ramifications

In the dynamic programming alogrithm the discrete levels of the states and controls are given above in Table 1 and recharge, assumed to be constant throughout the planning horizon,[11] is assumed to be 20 million cubic meters.

The management model was solved using a discount rate of 10% and a value for water quality of 2.0 mmhos./cm. The model is solved for a 50-stage planning horizon which approximates the point at which solutions become independent of n.[12] With initial states X = 2 billion cubic meters, S = 8 mmhos./cm.,[13] the optimal solution calls for total water use of 140 million cubic meters with w^{50} = 110 million cubic meters and y^{50} = 30 million cubic meters. With the adoption of these policies in the current year ("stage 50") the values of future state variables and the associated optimal policies may be traced through the 50-stage dynamic programming solution and these results are given in Figure 1.[14] (Table 3 shows the time paths for the groundwater stock, total water use, irrigation water, and leaching water.)

As shown in Figure 1, the groundwater stock is mined at a rapid rate near the beginning of the planning horizon, gradually declining in time, and converging to natural recharge after 28 years.

Dormant leaching water applications, y, are maintained at approximately a constant percentage (27 to 38%) of irrigation water, w, until total water use converges to steady state conditions, after which leaching water increases slightly as a percentage of irrigation.[15]

Insights into the decision with regard to these water use policies can be gained by examining the marginal net benefits associated with irrigation water and dormant leaching water (MBW, MBY) and the marginal user costs of this water in terms of the impact on the groundwater stock and soil salinity (UCW, UCY). The user cost asso-

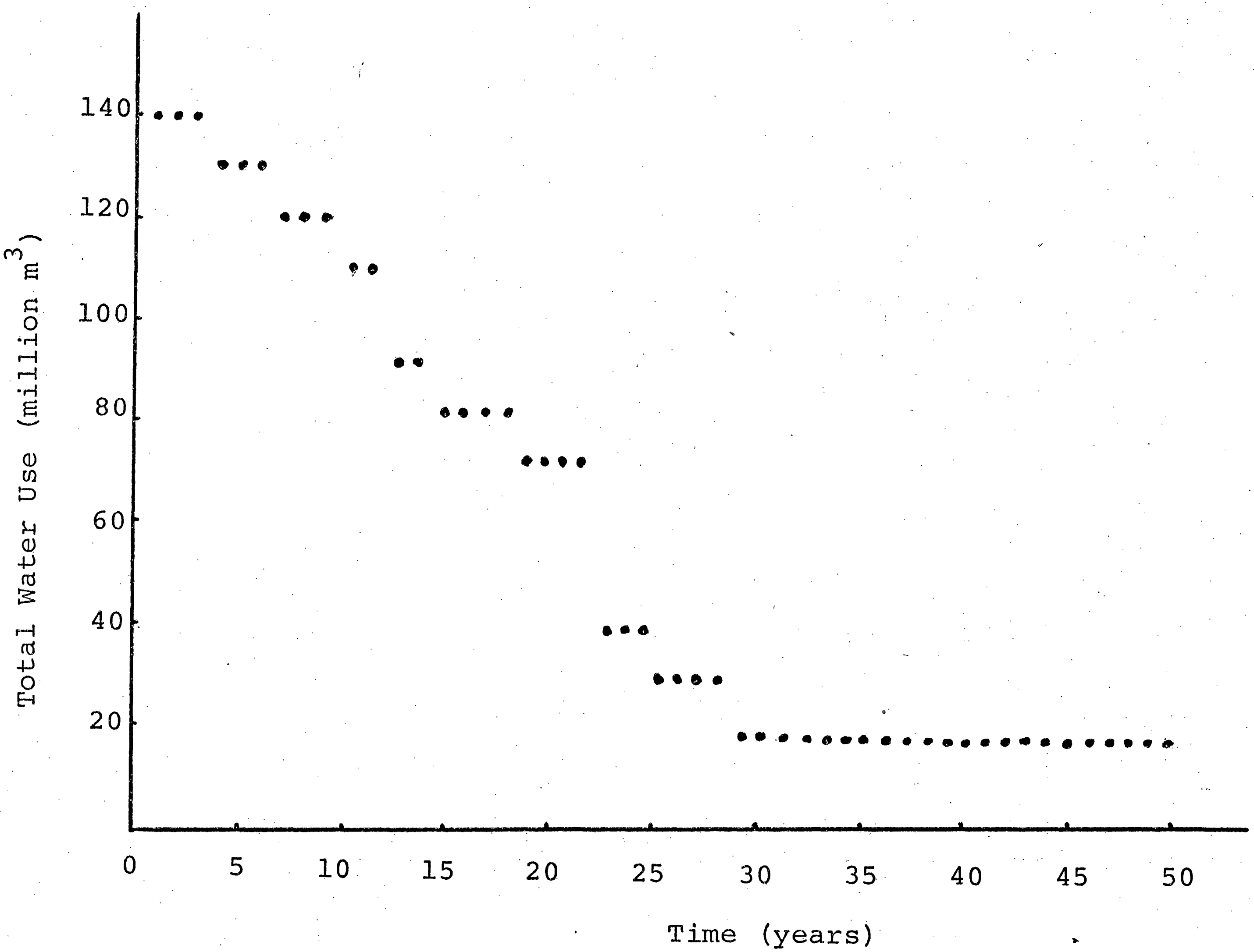

Figure 1: Time Path of Total Water Use

TABLE 3

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 ($10^6 m^3$)	YEAR	x ($10^6 m^3$)	w+y ($10^6 m^3$)	w ($10^6 m^3$)	y ($10^6 m^3$)
1	2000	140	110	30	26	160	30	20	10
2	1880	140	110	30	27	150	30	20	10
3	1760	140	110	30	28	140	30	20	10
4	1640	130	100	30	29	130	20	10	10
5	1530	130	100	30	30	130	20	10	10
6	1420	130	100	30	31	130	20	10	10
7	1310	120	90	30	32	130	20	10	10
8	1210	120	90	30	33	130	20	10	10
9	1110	120	90	30	34	130	20	10	10
10	1010	110	80	30	35	130	20	10	10
11	920	110	80	30	36	130	20	10	10
12	830	90	70	20	37	130	20	10	10
13	760	90	70	20	38	130	20	10	10
14	690	80	60	20	39	130	20	10	10
15	630	80	60	20	40	130	20	10	10
16	570	80	60	20	41	130	20	10	10
17	510	80	60	20	42	130	20	10	10
18	430	70	50	20	43	130	20	10	10
19	380	70	50	20	44	130	20	10	10
20	330	70	50	20	45	130	20	10	10
21	280	70	50	20	46	130	20	10	10
22	230	40	30	10	47	130	20	10	10
23	210	40	30	10	48	130	20	10	10
24	190	40	30	10	49	130	20	10	10
25	170	30	20	10	50	130	20	10	10

ciated 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.[16] This is illustrated in Figure 2 where w* denotes the optimum value for w.

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. These changes are illustrated above in Figure 2 by MBW_1 and UCW_1, with w** representing the optimum level of w.

In year one ("stage 50"), for example, the (approximate) marginal net benefits for a value of w of 110 million cubic meters is .457 pesos. The marginal user cost corresponding to this value of w is approximately .456 pesos. Irrigation water, w, is

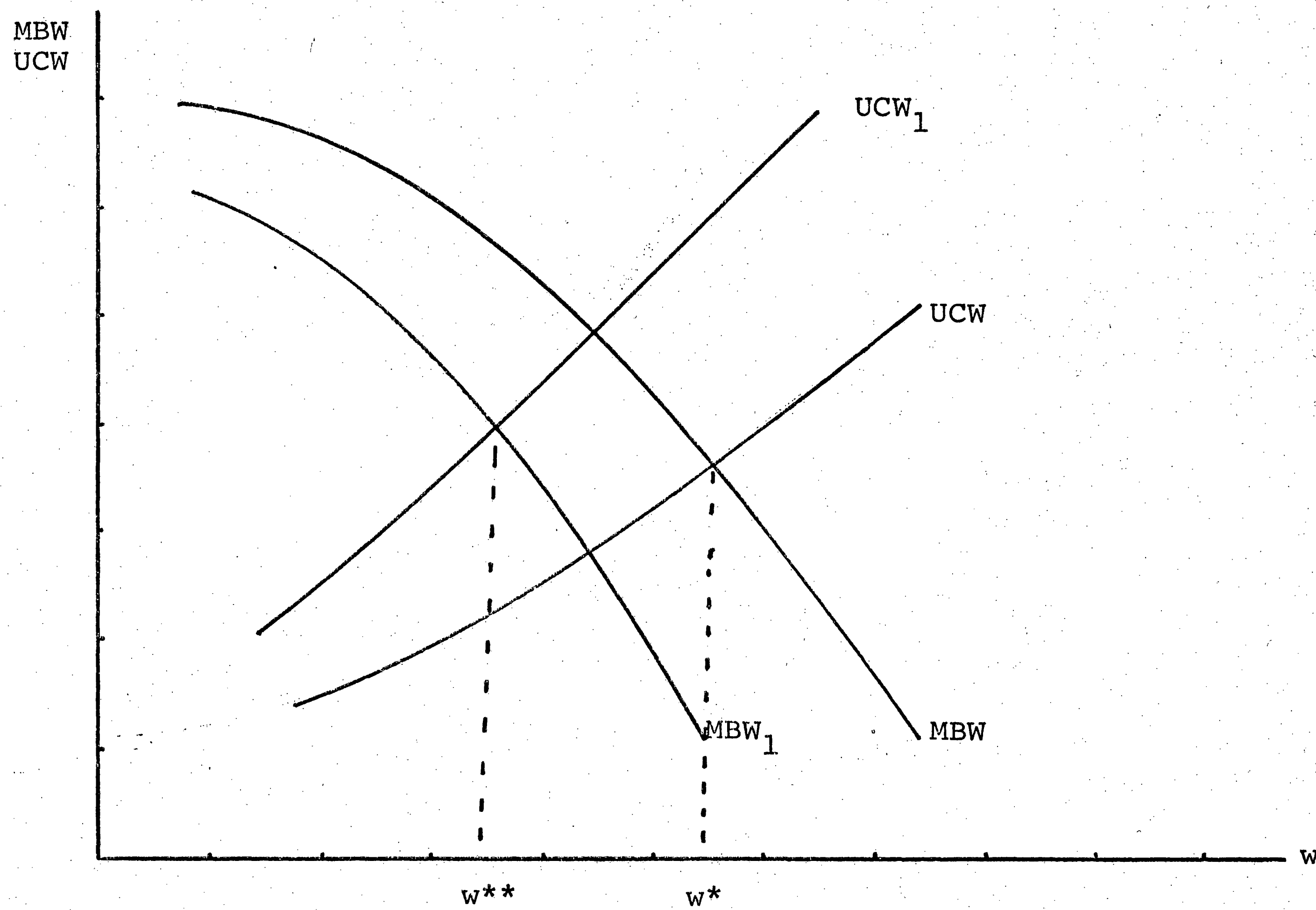

Figure 2: Illustration of Marginal Conditions Associated with Irrigation Water Usage

applied at 110 million cubic meters since MBW is approximately equal to UCW at this 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 10 million cubic meters is .618 pesos with an associated user cost of .615. Again the decision is made at the margin with water use for irrigation pushed to the point where MBW approximately equals UCW (in this discrete framework).

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.

The optimal policies for irrigation water and leaching water are such that soil salinity at the beginning of the growing season is maintained at or below 6 mmhos./cm. over the entire decision horizon.

Digressing for a moment, an examination of the linear programming results suggests that for levels of soil salinity between 2 and 6 mmhos./cm., the primary crops would be garbanza 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 garbanza beans, which is a relatively salt sensitive crop. When soil salinity reaches 8 mmhos./cm., the cropping pattern changes to cotton and wheat. At higher levels of salinity cotton is the predominant crop. Beyond 12 mmhos./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 (as discussed above). Specially, the crop pattern indicated by this analysis for year 1 (stage 50) is garbanza beans--58%, sesame--31%, and cotton--11%. These results strongly support proposals by the Mexican government (SRH) for the introduction of the garbanza 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 <u>all</u> growing seasons is maintained at or below 6 mmhos./cm. throughout the planning horizon, in contrast to current practices where larger salinity levels are being maintained.

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 are taking place. First, saltwater intrusion has increased by 8 kilometers. Second, the optimum number of pumps has fallen from 64 to 15, and monthly pumping capacity has been reduced to 44 million cubic meters. These changes have the result of reducing the feasible irrigable area to 2500 hectares.

Under current operating conditions, i.e., if the district continues to pump water at the rate of 124 million cubic meters per year, a situation similar to that described above would be expected in about 18 years. 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 been the proposal of a major interbasin water transfer, details of which are reported in [11].

Of course, the results suggested in this work imply a pattern of water use, a groundwater management policy, which may postpone to some extent the immediate need for alternative water sources, particularly such costly water sources as the proposed interbasin water transfer (see [11]). This is particularly relevant given the possibility of developing alternative water supply systems to alleviate the problem as suggested in [11].

In conclusion, the results of this work suggest a policy of groundwater management which implies gradually falling levels of total water use in contrast to the Mexican government's proposed policy of maintaining current annual levels of water use. Further, the results of this study suggest that a higher proportion (approximately 30%) of total water use should be allocated for leaching purposes than is the case under current practices (currently from 10 to 20% of water use is for leaching purposes). Finally, the results of this study strongly support current proposals by the Mexican government to increase acreage in garbanza beans with a reduction in the acreage which has historically been used for wheat. It should be pointed out, however, that success in the government's proposal to increase acreage in garbanza beans may indeed require the increase in leaching suggested in this study in order to maintain salinity at levels at which garbanza beans may be grown successfully.

Footnotes

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[1] See, also, [13], [16], [18], [24].

[2] Considerable attention has been given to the optimal management of a groundwater resource over time in-including common property aspects of the problem (see, e.g., Burt [5, 6]).

[3] Several previous studies have investigated the effects of saltwater intrusion. Busch, Matlock and Fogel [8] discuss the problem in the Costa de Hermosillo. Cum-

mings [9] presents an analysis of the optimal intertemporal rate of exploitation of groundwater stocks with the intrusion of saltwater. Cummings [11] has also given empirical results from a multi-stage linear programming model applied in the Costa de Hermosilla which includes consideration of saltwater intrusion.

[4]Sufficient data is not available to estimate a relationship between water and return flows to the aquifer; however, the estimates of recharge used in the study include an allowance for return flows.

[5]A more satisfying approach would be to allow for a possible stratification of soil layers (as in Bresler and Yaron and Olian) and a division of the study area on the basis of initial levels of soil salinity (as in Cummings and McFarland).

[6]A similar approach for the generation of benefits is utilized in Burt [5] and Cummings [10, 11].

[7]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 [11] for the nearby Costa de Hermosillo was assumed in this

study. Using this and the distribution of pumps in the region, a relationship between the groundwater stock and pumping capacity was estimated.

[8]The groundwater stock is used as a surrogate for depths.

[9]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 mmhos./cm., the benefit function goes to zero. y, of course, does not directly enter the linear programming model. The result is then the requirement for eleven (for X) times six (for S, adjusted for leaching) times fourteen (for w) computer runs.

[10]For an examination of decision rules with regard to the general problem concerning optimal rates of use of resources, see Burt and Cummings [7]. This paper considers both finite and infinite horizon problems. Decision rules for a model that encompasses the one presented here are discussed in Cummings and McFarland [12].

[11]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.

[12]According to the convergence theorem in dynamic programming (Bellman [1, pp. 12-16]), a control w^n, as a function of a state variable S^n, becomes independent of n as n approaches infinity; i.e., $w^n(S^n) = w(S)$ as $n \to \infty$. With "well-behaved" functions, such convergence occurs after a relatively short time (see, for example, [10] and [5]). Sensitivity analyses in this model suggest convergence after 50 years. To prove such convergence, of course, would require that the model be solved with an infinite planning horizon.

[13]These initial values for states approximate current conditions in the Sahuaral irrigation district.

[14]This "tracing through" process yields results analogous to those which would be obtained from a L.P., using linear approximations for all functions. This is not the traditional way of using D.P.; the D.P. format was used, first, to provide some useful computational simplifications, and second, to provide a framework for extensions involving the introduction of stochastic

elements when, or if, additional funding is obtained.

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

[16] Of course, this condition is for the continuous case. In the discrete analog the conditions would be approximate with w never being used beyond this point. Burt [6] indicates procedures for approximating user costs under a discrete specification.

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