June 1972 WRRI Report No. 004

AN INTEGRATION OF THE AGRICULTURAL DEMAND FUNCTION FOR WATER AND THE HYDROLOGIC MODEL OF THE PECOS BASIN

Technical Completion Report
Project No. B-025-NMEX

NEW MEXICO WATER RESOURCES RESEARCH INSTITUTE
Las Cruces, New Mexico 88001

TECHNICAL COMPLETION REPORT

Project No. B-025-NMEX

AN INTEGRATION OF THE AGRICULTURAL DEMAND FUNCTION FOR WATER AND THE HYDROLOGIC MODEL OF THE PECOS BASIN

Micha Gisser
University of New Mexico
Albuquerque, New Mexico 87106

and

Abraham Mercado
New Mexico Institute of Mining and Technology
Socorro, New Mexico 87801

June, 1972

The work upon which this publication is based was supported in part by funds provided through the New Mexico Water Resources Research Institute by the United States Department of Interior, Office of Water Resources Research, as authorized under the Water Resources Research Act of 1964, Public Law 88-379.

ABSTRACT

This paper provides the result of integrating the agricultural sector with the aquifer of the Pecos Basin. In particular it provides steady-state solutions to hydrologic and economic equations in which imported water is artificially recharged to the aquifer and its cost is added to the cost of pumping. The following is an outline of the paper:

A two cell model for the Pecos Basin aquifer is developed. One cell is for the confined aquifer and the other is for the shallow aquifer. The hydrological solution of the model yields two linear steady-state functions which relate the water table in the two cells to other hydrological variables, such as recharge, discharge, and irrigation. The cost of pumping water is also estimated.

The agricultural demand function for irrigation water is empirically estimated by applying the technique of parametric linear programming.

Finally, the demand function for water is linked to the water table hydrological equations. Solutions are found for a range of expected prices of imported water.

CONTENTS

TABLES and FIGURES

Introduction

Parametric linear programming models were applied in the past to estimate the agricultural demand function for imported water in the Pecos river basin. [Gisser, 1970]. The demand function for imported water is only one blade of the scissors. The hydrologic model of the basin provides the other blade. Accordingly, in this paper we provide a complete integration of the agricultural demand function for water with the hydrologic model in the Pecos river basin. This model enables us to predict the amount of imported water (replacement flows) that is needed in order to arrive at a certain steady state of the water table, given the price of imported water.

The main contribution of this paper is the model which provides a useful tool in agricultural areas where the issue of imported water might arise, or has already arisen. In order to demonstrate how the model works, we have used the same data and procedures that were previously used by Gisser [1970] in order to estimate the demand function for water. Hydrologic data was mainly taken from Hantush [1957], and Saleem and Jacob [1971]. We had only rough indication about the expected cost of imported water.

Two basic assumptions underlie this study. First, imported water will be artificially recharged into the ground. Second, farmers will pay the full price of imported water.

Note finally that all pecuniary values and prices are expressed in 1968 dollars.

Hydrologic Background

The main supply of water in the Roswell basin is from wells tapping the two main aquifers in this area: The San Andres limestone confined aquifer and the alluvium shallow and phreatic aquifer. The two aquifers are separated by a third aquifer of lower permeability, and thus of minor importance - the Artesia shallow confined aquifer.

The main source of water for the basin is precipitation on the outcrops of the San Andres limestone aquifer. The average replenishment through these outcrops was estimated to be 240,000 acre-ft./yr. [Hantush, 1957]. The shallow aquifer is replenished partly by direct percolation of rainfall (about 28,000 acre-ft./yr.), and partly by irrigation losses. The return flow coefficient for irrigation water was estimated to lie within the limits of 20% [Hantush, 1957], and 30% [Saleem and Jacob, 1971].

The main outlet of the leaky-coupled aquifer system is the Pecos river, to which the shallow aquifer is discharging either by direct seepage to the river, or through springs located on its tributaries. The present discharge to the river is rather small. It is in the order of magnitude of 20-40 thousand acre-ft./yr. However, in the early thirties the discharge to the river exceeded 130,000 acre ft./yr.

The connection between the confined and shallow aquifers is by leakage through the semi-confined Artesia aquifer. The direction of leakage is determined by the difference in the hydraulic heads between the two aquifers, where the direction of flow is from the aquifer with higher head to the aquifer with the lower one. The magnitude of leakage is proportional to the product of the differences in hydraulic heads and the leakance of the semiconfining layer. It seems that the obvious direction of leakage of the undisturbed system is from the confined aquifer to the shallow one. However, due to the intensive utilization of the confined aquifer and the high return flow to the shallow aquifer the net direction of leakage is presently from the shallow to the confined aquifer.

The evapotranspiration by salt-cedars is another important component of the natural discharge from the shallow aquifer. Salt cedars grow mainly along the Pecos river channel, and they presently cover an area of about 30,000 acres, whereas in 1937 they covered only 9,100 acres. The evaporation rate, which depends on climatic conditions, is estimated to be within 3.5 and 4.7 acre-ft./acre of salt cedars. The total evaporation between 1966 and 1968 was in the order of magnitude of 120,000 acre-ft./yr. [Saleem and Jacob, 1971].

The hydraulic characteristics of the aquifers, namely, Transmissivity, Storativity, and Leakance, were determined by Hantush [1957] and Saleem and Jacob [1971] through elaborate and intensive hydrologic studies, which are widely covered in their works.

Groundwater is withdrawn in the basin mainly from the two principal aquifers. Less than 8% of the groundwater comes from the semi-confining formation. The average pumpage between 1938 and 1968 was about 400 acre-ft./yr. About 30% of the total amount is currently pumped from the shallow aquifer and over 60% from the confined aquifer.

There are about 1,500 wells in the basin of which about 800 tap the confined aquifer, and 500 tap the shallow one. The remaining 200 wells tap the semi-confining Artesia aquifer, or any combination of the three. The representative dynamic drawdowns at the wells of the confined and shallow aquifers are 20.7 ft. and 14.9 ft. respectively.(1)

During 1967 and 1968 more than 95% of the total ground water pumped was utilized for farming, where alfalfa, cotton, and sorghum account for more than 95% of the irrigated acreage. Accordingly, for all practical purposes it will be assumed that the farm sector is the only user of water in the basin. Only 10-15 thousand acre-ft./yr. were diverted from the river for irrigation purposes.

The cost of pumping water depends on the dynamic depth to water in the wells and varies from well to well, and even from aquifer to aquifer in the basin. The average pumping costs per acre-ft. per foot of lift were estimated to be $0.0355 for the shallow aquifer wells and $0.0283 for the confined ones.

The average elevation of the land surface of the Pecos basin is 3,550 feet above sea level. The minimum safe water table is 3,340 feet above sea level. This level is approximately the level at which no flow will exist from the shallow aquifer to the Pecos river. Allowing the water table of the shallow aquifer to fall below this level will lead to a reverse flow from the Pecos River to the shallow aquifer. We have assumed that the State of New Mexico will not allow such a reverse flow.

---

(1) See Appendix A.

The Hydrologic Model

The detailed derivation of the hydrologic model is given in Appendix B. When steady-state conditions prevail, the steady-state water levels are:

Shallow aquifer

$$H_2 = \frac{R_a}{875} + 3,542 - 0.834 \cdot 10^{-3} \cdot Q_t \qquad (1)$$

Confined aquifer

$$H_1 = \frac{R_a}{875} + 3,570 - 0.912 \cdot 10^{-3} \cdot Q_t \qquad (2)$$

Where H_2 and H_1 are the steady-state water levels at the shallow and confined aquifers, respectively, Q_t is the amount of water applied for irrigation and R_a is artificial recharge. Equations (1) and (2) are constructed under the assumption that imported water is artificially recharged into the shallow aquifer. If imported water is artificially recharged to the confined aquifer, equation (2) becomes equation (2)' as follows:

$$H_1 = R_a\left(\frac{1}{875} + \frac{1}{8,500}\right) + 3,570 - 0.912 \cdot 10^{-3} \cdot Q_t \qquad (2)'$$

The reader can see for himself that the difference between equation (2) and (2)' is insignificant.

The Demand for Water

In this study we assume that imported water will be artificially recharged into the aquifer. Accordingly, we need a demand function for water in which only pumped water is used and its price to farmers varies from zero to infinity. We use a parametric linear programming model in order to empirically estimate the demand function for water.

The symbols used in the model are the following:

Z: Total profit. Profit is defined as net returns to land and management.

Π: Profit per activity, where an activity is defined to be one acre. Only the cost of the irrigation system proper is included (cost of maintaining irrigation ditches, etc.); the cost of pumping water is taken into account via the parametrization of the objective function.

X: Acreage.

P: The cost per acre-foot of pumping water.

I: Irrigation intensity, measured in acre-feet per acre.

The subscripts used in the model are the following:

i: Crop: 1-cotton, 2-alfalfa, 3-grain sorghum, 4-barley, 5-corn, and 6-vegetables.

j: Salinity: 1-.75, 2-1.50, 3-2.25, 4-3.00, 5-4.00, 6-5.00, 7-6.00, and 8-7.00 mmhos.

k: Irrigation intensity (in acre-feet)

a) Intensities, ditch method in acre-feet per acre.

Intensity Crop Acre-feet	Cotton	Alfalfa	Sorghum	Barley	Corn	Vegetables
1	1.50	6.00	2.25	1.12	2.25	2.25
2	2.25	6.75	3.00	1.50	3.00	--
3	3.00	7.50	3.25	2.25	3.50	--
4	3.75	8.25	--	--	--	--

b) To obtain intensities for irrigating by sprinklers, multiply the above table by 0.837.

1: Irrigation technique: 1-ditches and 2-sprinklers.

The model is set as follows:

maximize:

$$Z = \sum_{ijkl} (\Pi_{ijkl} - P \cdot I_{ijkl})\, X_{ijkl}$$

Subject to the following constraints:

Acreage constraint:

$$(1) \quad \sum_{ijkl} X_{ijkl} \leq 133{,}840$$

Legal constraints imposed on the use of water:

$$(2) \quad \sum_{ijkl} I_{ijkl} \cdot X_{ijkl} \leq 133{,}840 \cdot L, \; L = 0,1,2,3,4,5, \text{ and } \infty$$

Where L is the legal constraint, expressed in terms of acre-feet per acre. This constraint tells the amount of water which is allowed to be pumped per acre.

In this study we assumed that $L = \infty$, in other words this constraint was ignored.

Local Salinity Constraints:(2)

$$(3) \quad \sum_{ikl} I_{i1kl} \cdot X_{i1kl} \leq 141{,}576$$

$$(4) \quad \sum_{ikl} I_{i2kl} \cdot X_{i2kl} \leq 90{,}576$$

$$(5) \quad \sum_{ikl} I_{i3kl} \cdot X_{i3kl} \leq 90{,}576$$

$$(6) \quad \sum_{ikl} I_{i4kl} \cdot X_{i4kl} \leq 90{,}576$$

$$(7) \quad \sum_{ikl} I_{i5kl} \cdot X_{i5kl} \leq 33{,}966$$

$$(8) \quad \sum_{ikl} I_{i6kl} \cdot X_{i6kl} \leq 33{,}966$$

$$(9) \quad \sum_{ikl} I_{i7kl} \cdot X_{i7kl} \leq 62{,}271$$

$$(10) \quad \sum_{ikl} I_{i8kl} \cdot X_{i8kl} \leq 62{,}271$$

---

(2) Based on data prepared by Ralph d'Arge [1970].

Cotton constraint:

$$(11) \quad \sum_{jkl} X_{1jkl} \leq 41{,}490$$

Vegetables constraint:

$$(12) \quad \sum_{jkl} X_{6jkl} \leq 26{,}768$$

We assumed that in 1980 the cultivated acreage in the Pecos Basin will remain at the level of 133,840 acres. This figure may change if agricultural water rights will be transferred to commercial, municipal, or industrial purposes. It is unlikely, however, that water rights will be transferred under the assumption that imported water will be supplied in the future.

The vegetables constraint is based on the rough assumption that utilizing more than 20 percent of the total agricultural area will lead to a drastic decline in the price.

The cotton constraint reflects the assumption that the present arrangement will exist in 1980.

Salinity constraints give only a rough distribution of water in the Pecos basin according to salinity. Salinity constraints do not impose any restrictions on the total use of water.

Economic Data

The data used in this study is the same as the data used in a previous study by Gisser [1970]. The procedure to estimate profits for agricultural activities are the same as in Gisser [1970]. For the convenience of the reader, we repeat here the discussion on data.

> Estimates of agricultural activities in the Pecos basin showing net returns to land and management for different crops,..., irrigated at four levels of water intensities and ranging over eight degrees of water salinity were provided by the Department of Agricultural Economics, New Mexico State University. Following Daly and Egbert [1966], the changes listed below in output per acre and prices were assumed between 1968 and 1980 (Table 1):
>
> Based on the budgets compiled by Simkins [1968], we assumed that presently the price support program accounts for 23.7% of total revenue from cotton. Following Daly and Egbert [1966], the change in output per acre was estimated at 27%. A consultation with personnel at the Department of Agricultural Economics, New Mexico State University, gave rise to the following assumptions: (1) the price (real) of cotton will have declined 6% from 1969 to 1980, and (2) the cotton program will be continued in the future. Total (real) revenue per acre of cotton in the Pecos basin was estimated to increase 14%.
>
> Following Heady and Ball [1965], the assumption was made that the cost of inputs per acre in real terms in 1980 will remain at the present level; although the use of farm labor is predicted to decline substantially, this decline will roughly be offset by an increase in the use of farm capital. The reader should note that increased yields are projected with constant costs. These two

TABLE 1

A FORECAST OF PRICE (REAL) AND OUTPUT CHANGES BETWEEN 1968 AND 1980

Crop	Change in Output per Acre, %	Change in Price, %	Change in Revenue per Acre, %
Corn	34	-7	25
Barley	18	-9	7
Sorghum	16	-5	10
Alfalfa	21	0	21

trends are consistent. They are explained by technological innovations and a decline in the prices of some inputs, especially fertilizers.

Based on studies conducted at the University of Arizona [Halderman and Frost, 1968], the annual cost of initial investment in sprinklers, assuming a 15-year lifetime and 7% interest, is $15.00 per acre. The cost of additional pressure per acre-foot of water irrigated by sprinklers is $1.50. Following the studies conducted at the University of Arizona [Halderman and Frost, 1968], and a report by Lewis [1961] of the Bureau of Reclamation, the assumption was made that the amount of labor required for operating sprinklers is roughly comparable to the amount of labor required for ditch irrigation. The above sources indicated that sprinkler irrigation efficiency is 80% whereas ditch irrigation efficiency is only 67%. The coefficient that converts water pumping under ditch irrigation into water pumping under sprinklers for the same crop, taking the same amount of water, is 0.837.

Farm budgets compiled by Simkins [1968] were used to adjust the cost per acre under ditch irrigation using local water to cost per acre under sprinkler irrigation using either local or imported water, and to cost per acre under ditch irrigation using imported water.

Little information on which to base profit estimates of vegetables was available. Only one level of water intensity of 2.25 acre-feet per acre was adopted. Therefore profit per acre of vegetables using local water is $300.00, and profit per acre using imported water is $311.00. Here the assumption that profit varies with water intensity was violated because of the scarcity of data.

The Price of Imported Water

Studying various plans to import water from alternative sources to west Texas and eastern New Mexico was assigned to the Bureau of Reclamation in the Public Works Appropriation Act, 1967 (Public Law 89689), approved October 15, 1966. According to A Review of Inter-Regional and International Water Transfer Proposals [1969], importing water from the lower Mississippi is the most feasible alternative. The price of importing water from the lower Mississippi has not been determined at the time of writing. But, according to an unpublished report by Ralph N. Parsons Co. [1968] the cost per acre-foot will exceed $40.00. Since to this cost we have to add the unknown cost of artificial recharging, we have decided to test our model on a wide range of prices starting at $40.00.

The Demand Function

The results of applying parametric linear programming in order to estimate the demand function for water are given in Table 2.

TABLE 2

THE DEMAND FUNCTION FOR WATER IN THE PECOS BASIN
Parameter = Price of Water

Price Range $	Median Price $	Water Use Acre-feet/Year	Profit* Calculated for Median Price $
0.00-0.11	0.05	494,118.88	32,071,744
0.11-2.41	1.26	485,688.31	31,485,568
2.41-6.86	4.63	481,236.44	29,856,608
6.86-10.86	8.86	447,273.06	27,893,360
10.86-21.80	16.33	447,235.19	24,552,560
21.80-29.95	25.87	413,307.81	20,421,472
29.95-33.69	31.80	387,741.88	18,013,040
33.69-34.19	33.94	370,146.00	17,196,624
34.19-36.69	35.44	322,730.56	16,701,384
36.69-38.57	37.63	271,855.63	16,043,261
38.57-73.03	55.83	190,506.75	12,505,908
73.03-85.56	79.30	164,368.25	8,194,296
85.56-107.96	96.76	164,368.25	5,324,395
107.96-129.27	118.62	138,229.63	2,010,775
129.27-138.42	133.76	60,228.68	268,819
138.42-∞			

*Profit = Net returns to land and management.

A Solution Without Imported Water

Before considering the case of importing expensive water to the Pecos basin, an economist should consider the alternative, namely allowing the water table to fall to the lowest permissible level of 3,340 feet above sea level, and considering the profitability of the agricultural sector at that point.

Assuming that both quantity and distribution of pumpage would not change significantly in the future, one can predict the long run decline of the water table in both aquifers. In addition to the aquifer parameters, the following input/output values have been used:

Recharge to the confined aquifer	240,000 acre-ft./yr.
Recharge to the shallow aquifer	28,000 acre-ft./yr.
Pumpage - confined	272,000 acre-ft./yr.
Pumpage - shallow	134,000 acre-ft./yr.
Irrigation	420,000 acre-ft./yr.
Return flow	113,000 acre-ft./yr.
Evaporation from salt cedar	95,000 acre-ft./yr.

Notice that currently farmers do not use more than 420,000 acre-feet/acre because they are not allowed to pump more than 3 acre-feet/acre. The above data was divided by 12 to obtain monthly flows, and then equations (12) and (13) in Appendix B were used in order to estimate the expected water table in the future. The results are given in Table 3. As indicated in Table 3, in the year 1997 the water table will reach the lowest permissible level. At that level farmers will have to restrict themselves to using an amount of water which is consistent with a steady-state solution. Solving the steady-state equations ((14) and (15) in Appendix B) we obtain an annual level of pumping of 240,000 acre-feet/year. In other words, assuming that farmers will continue to use 420,000 acre-feet of water per year, then in 1997 they will have to be restricted to pumping 240,000 acre-feet per annum.

TABLE 3

EXPECTED WATER TABLE IN THE PECOS BASIN
(feet above sea level)

Year	H_1	H_2
1970	3366	3366
1971	3365	3365
1972	3364	3364
1973	3363	3363
1974	3362	3362
1975	3360	3361
1976	3359	3360
1977	3358	3359
1978	3357	3358
1979	3356	3357
1980	3355	3356
1981	3354	3355
1982	3353	3354
1983	3352	3353
1984	3351	3352
1985	3350	3351
1986	3349	3350
1987	3348	3349
1988	3347	3348
1989	3346	3347
1990	3345	3346
1991	3345	3346
1992	3344	3345
1993	3343	3344
1994	3342	3343
1995	3341	3342
1996	3340	3341
1997	3339	3340
1998	3338	3339

At that level the cost of pumping one acre-foot will be as follows (1968 dollars):

Shallow aquifer:

$$(3550 - 3340 + 14.9) \times 0.0355 = \$7.98$$

Confined aquifer:

$$(3550 - 3340 + 20.7) \times 0.0283 = \$6.53$$

Currently the cost of pumping an acre-foot (1972) is as follows:

Shallow aquifer:

$$(3550 - 3364 + 14.9) \times 0.0355 = \$7.10$$

Confined aquifer:

$$(3550 - 3364 + 20.7) \times 0.0283 = \$5.85$$

Thus, roughly the cost of pumping between now and 1997 will rise from $6.00 to $8.00. Adjusting profits of agricultural activities accordingly and applying linear programming with a water constraint of 420,000 acre-feet/year for the present situation and with a water constraint of 240,000 acre-feet/year for the period following 1997, the following results were obtained:

TABLE 4

COMPARING THE PRESENT WITH THE LONG-RUN SITUATION, WITHOUT WATER IMPORTATION

Year	Cost of Pumping $	Water Constraint acre-ft/year	Acreage Cultivated Acres	Returns to Land and Management $
1972	6	420,000	122,000	28,700,000
1998	8	240,000	75,428	23,100,000

Table 4 shows that without importing water in 1998, farmers will have to be restricted to using 240,000 acre-feet of water per annum. Total returns to land and management will decline by about 20 percent. Total acreage cultivated will decline by 38 percent. It can be assumed that employment will decline proportionately to cultivated land, or alternatively to water use.

Importing Water

Let the price of imported water by denoted by P_I. Recall that this price is determined exogenously. Let the price of water to farmers be denoted by P_t. This price, as well as the quantity of water used (Q_t) is given by the parametric linear programming. For example, Table 2 shows that for $P_t = \$25.87$, $Q_t = 413,307.81$ acre-feet/year. The cost of pumping per acre-foot is denoted by P_s for the shallow aquifer and P_c for the confined aquifer.

To equations (1) and (2) we now add 3 economic equations in order to obtain a system which unifies both the aquifer and the demand functions for irrigation water. The system is as follows:

$$H_2 = R_a/875 + 3542 - 0.834 \cdot 10^{-3} \cdot Q_t \qquad (1)$$

$$H_1 = R_a/875 + 3570 - 0.912 \cdot 10^{-3} \cdot Q_t \qquad (2)$$

$$P_t = 0.33 \cdot P_s + 0.67 \cdot P_c + (P_I \cdot R_a)/Q_t \qquad (3)$$

$$P_s = (3550 - H_2 + 14.9) \cdot 0.0355 \qquad (4)$$

$$P_c = (3550 - H_1 + 20.7) \cdot 0.0283 \qquad (5)$$

The following are explanations of the economic equations:

Equation 3: The total price of water P_t is made up of the cost of pumping, $0.33 \cdot P_s + 0.67 \cdot P_c$, plus a tax expressed as $(P_I \cdot R_a)/Q_t$ per acre-foot pumped. The weights of 0.33 and 0.67 will hold under the assumption that this will be the distribution of pumping between the two aquifers. The tax will be levied in order to pay for imported water. Thus, adding the cost of $(P_I \cdot R_a)/Q_t$, to the cost of pumping means that farmers will pay the full price of water. Note: $P_I \cdot R_a$ is the total cost of importing water and artificially recharging it to the aquifer.

Equations 4 and 5: 0.0355 and 0.0283 are the respective prices of lifting one foot one acre-foot of water. Recall that 14.9 and 20.7 feet are the dynamic drawdowns for the two aquifers.(3) 3550 is the surface level, and H_2 and H_1 are the water levels of the aquifers, above sea level.

System of equations 1 - 5 consists of 5 equations in 5 unknowns. The unknowns are: P_s, P_c, R_a, H_1, and H_2.

Consider the case where the price of imported water is $50/acre-foot. To find the optimal steady-state solution, we solve the system of equations 1 - 5 for each pair of P_t and Q_t as indicated by the parametric linear programming solutions (Table 2). The solutions are shown in Table 5. Notice that some of the solutions provide negative values and hence they are ignored. The optimal solution is the one for which H_1 and H_2 are feasible (lie between 3550 and 3340 feet), and for which profit is the highest. This occurs for a total price of water of $25.87, total water use of 413,307 acre-feet, artificial recharge of 167,641 acre-feet, $H_2 = 3388.89$ feet, $H_1 = 3384.65$ feet and an aggregate profit of $20,421,472. Recall

---

(3) See Appendix A.

TABLE 5

OBTAINING STEADY-STATE SOLUTIONS FOR THE CASE WHERE THE PRICE OF IMPORTED WATER = $50/ACRE-FOOT

Recharge is to Shallow Aquifer

PRICE OF REPLACE. FLOW, P_I	PRICE OF WATER TO FARMERS, P_t	TOTAL WATER USED Q_t	PUMP COST SHL. P_s	PUMP COST CON. P_c	ARTIFICIAL RECHARGE R_a	WATER TABLE SHL. H_2	WATER TABLE CON. H_1	PROFIT $
50.00	0.05	494118.88	23.79	19.43	-205706.16	2894.81	2884.27	32071744.00
50.00	1.26	485688.31	22.46	18.35	-179199.89	2932.14	2922.25	31485568.00
50.00	4.63	481236.44	20.17	16.52	-126017.13	2996.63	2987.09	29856608.00
50.00	8.86	447273.06	15.92	13.05	-45952.82	3116.46	3109.57	27893360.00
50.00	16.33	447235.19	11.97	9.90	51408.24	3227.76	3220.87	24552560.00
50.00	25.87	413307.81	6.25	5.27	167641.26	3388.89	3384.65	20421472.00
50.00	31.30	387741.88	3.21	2.78	223925.09	3474.54	3472.29	18013040.00
50.00	33.94	370146.00	2.18	1.93	236357.33	3503.42	3502.55	17196624.00
50.00	35.44	322730.56	1.42	1.22	220443.42	3524.78	3527.61	16701384.00
50.00	37.63	271855.63	0.69	0.52	201469.35	3545.52	3552.32	16043261.00
50.00	55.83	190506.75	-2.54	-2.23	221604.73	3636.38	3649.52	12505908.00
50.00	79.30	164368.25	-5.56	-4.70	277071.85	3721.57	3736.75	8194296.00
50.00	96.76	164368.25	-8.19	-6.80	341945.94	3795.71	3810.89	5324395.00
50.00	118.62	138229.63	-9.33	-7.76	350817.55	3827.65	3844.87	2010775.00
50.00	133.76	60228.68	-4.13	-3.79	165824.03	3681.28	3704.58	268819.50

again that profit is in fact net returns to land and management.

In Table 6 optimal steady-state solutions are shown for prices of imported water ranging from $40.00 per acre-foot to $80.00 per acre-foot. At this point the reader should be reminded that the price of imported water covers the cost of artificial recharge. A comparison of Table 4 and Table 6 is very instructive. Should the price of imported water lie in the range of 40-60 dollars, then in the long run, the trade off is between using 240,000 acre-feet of water with a high profit of $23 million, or alternatively using 413,000 acre-feet of water with a profit of $20.5 million. Employment can be assumed to be roughly proportional to the use of water. It seems, however, that if the price of imported water is expected to be higher than $60, the low profit of $18 million cannot justify importation of water even with the gain of a higher level of employment.

Summary and Recommendations

1. A model consisting of 5 equations has been developed. Using this model we have found optimal steady-state solutions for a variety of prices of imported water. These results are summarized in Table 6.
2. There are two alternatives that should be considered here:

   (a) Allowing pumping to continue at a rate of 420,000 acre-feet/year until 1997, and then restrict pumping to 240,000 acre-feet/year. This would lead to reducing the annual net returns to land and management from the current $28.7 million to a level of $23.1 million (in 1968 prices).

TABLE 6

OPTIMAL STEADY STATE SOLUTIONS FOR A VARIETY OF PRICES OF IMPORTED WATER

Price of Replace. Flow P_I,$	Price of Water to Farmers P_t,$	Total Water Used Acre-feet Q_t	Pump. Cost Shal. P_s,$	Pump Cost Con. P_c,$	Artificial Recharge Acre-feet R_a	Water Table Shl. Feet, ASL H_2	Water Table Con. Feet, ASL H_1	Profit (Net returns to Land and Management) $
Recharge to the Shallow Aquifer								
40	25.87	413,307.81	3.58	3.14	233,356.80	3463.99	3459.76	20,421,472
50	25.87	413,307.81	6.25	5.27	167,641.26	3388.89	3384.65	20,421,472
60	25.87	413,307.81	7.74	6.46	130,805.23	3346.79	3342.55	20,421,472
70	31.80	387,741.88	6.43	5.35	144,528.09	3383.80	3381.55	18,013,040
80	31.80	387,741.88	7.31	6.06	122,763.92	3358.92	3356.68	18,013,040
Recharge to the Confined Aquifer								
40	25.87	413,307.81	3.23	2.05	242,106.84	3473.99	3498.24	20,421,472
50	25.87	413,307.81	6.07	4.55	172,109.83	3394.00	3410.01	20,421,472
60	25.87	413,307.81	7.63	5.92	133,509.94	3349.88	3361.35	20,421,472
70	31.80	387,741.88	6.34	4.79	146,778.79	3386.37	3401.39	18,013,040
80	31.80	387,741.88	7.25	5.59	124,384.01	3360.78	3373.17	18,013,040

(b) Importing water. If the price of imported water will be between $40.00 and $60.00, annual net returns to land and management will be $20.4 million, and the annual water use will be 413,000 acre-feet. Should the price of imported water rise above that range, net returns to land and management will amount to $18 million, and water use will go down to 388,000 acre-feet per year.

3. Policy decision must wait until the range of forecasted imported water prices can be narrowed down significantly.

A comparison between alternatives (a) and (b) should be separated into two cases:

Case I: The price of imported water will lie in the range of $40-60. Farmers should be told that the average price of water will rise to $25.87/acre-foot if they choose to import water. Farmers will have to decide whether they want alternative (a) with relatively low level of employment and high profit, or alternative (b) with relatively high level of employment and lower profit.

Case II: The price of imported water will be in the neighborhood of $70.00. Farmers should be advised to accept alternative (a) and reject alternative (b).

Acknowledgements

We are indebted to J. Bear, S. Ben-David, M.L. Hanson, R. Lansford, and D. Rabinowitz. This project was financed by the Office of Water Resources Research, Department of the Interior.

REFERENCES

Daly, R.F., and Egbert, A.C., Statistical Supplement to "A Look Ahead for Food and Agriculture," 17(1), 15pp., U.S. Department of Agriculture, Agricultural Economics Research, Washington, D.C., mimeo, January 1966.

d'Arge, Ralph C., Quantitative Water Resource Basin Planning: An Analysis of the Pecos River Basin, New Mexico, Water Resources Research Institute in cooperation with the Department of Economics, The University of New Mexico, 1970.

Gisser, Micha, "Linear Programming Models for Estimating the Agricultural Demand Function for Imported Water in the Pecos River Basin," Water Resources Research, Vol. 6, No. 4, August 1970.

Halderman, A.D., and Frost, K.R., "Sprinkler Irrigation in Arizona," Bull. A-56, Cooperative Extension Service and Agricultural Experiment Station, University of Arizona, Tucson, Arizona, December 1968.

Hantush, S. Mahdi, Preliminary Quantitative Study of the Roswell Ground-Water Reservoir, New Mexico, New Mexico Institute of Mining and Technology, Socorro, 1957.

Heady, E.O., and Ball, Gordon, "Economic Growth of the Farm Firm and Projected Changes in Farming," in Proceedings of a Conference on Structural Changes in Commercial Agriculture, CAED Rep. 24, Chicago, April 1965.

Lewis, M.R., A Report Containing Information Regarding Sprinkler Irrigation, (Prepared for field personnel), mimeo, 1961.

Preliminary Results of Economic Study - West Texas Water Importation, by Ralph M. Parsons Co., mimeo.

Saleem, Z.A., and Jacob, C.E., Dynamic Programming Model and Quantitative Analysis, Roswell Basin, New Mexico, Water Resources Research Institute in cooperation with New Mexico Institute of Mining and Technology, January 1971.

Simkins, Arthur R., An Economic Analysis of Irrigation Water Requirement for Crop Production in the Roswell-Artesian Basin, New Mexico, Master's thesis, New Mexico State University, Las Cruces, 1968.

A Review of Inter-Regional and International Water Transfer Proposals, Western States Water Council, 1725 University Club Building, Salt Lake City, Utah, June 1969.

Appendix A

The average discharge rate from the confined aquifer wells is 1,080 gpm. The average discharge rate from the shallow aquifer wells is 556 gpm. The average use is within the limits of 80 to 120 days per year [Saleem and Jacob, 1971, Table 11].

The relationship between the dynamic drawdown denoted by s and the discharge rate denoted by Q is

$$s = BQ + CQ^2$$

The empirical estimates of the constants B and C were determined by Saleem and Jacob [1971] by analyzing more than 340 Step-Drawdown pumping tests. Following their analyses the logarithmic average values of $\underline{B}$ and $\underline{C}$ for the shallow aquifer were 8.37 ft/cfs and 2.98 ft/(cfs)^2 respectively. The corresponding values for the confined aquifers were determined to be 3.41 ft/cfs and 2.20 ft/(cfs)^2. Taking into account the values of 1,080 gpm and 556 gpm as the representative discharge rates from the confined and shallow aquifers, respectively, the representative dynamic drawdowns at the wells of the confined and shallow aquifers are 20.7 ft. and 14.9 ft., respectively.

Appendix B

The Hydrologic Model

(a) Mathematical Formulation - The model (Figure 1) consists of two cells, representing the average hydraulic characteristics of the two main aquifers.

The flow $Q_{12}(t)$ between the two cells obeys Darcy's Law:

$$Q_{12}(t) = A\frac{K'}{b'} (H_1(t) - H_2(t)) \qquad (1)$$

Where:

A - The leakage area between the confined and shallow aquifers.

K' - The permeability of the semi-confining layer.

b' - The thickness of the semi-confining layer.

Equation (1) can be rewritten as

$$Q_{12} = k_{12}(H_1(t) - H_{2(t)}) \qquad (2)$$

Where k_{12} may be defined as the leakance proportionality constant.

Similarly the flow from the shallow aquifer to the river and it's tributaries is determined by:

$$Q_r = k_r(H_2(t) - B) \qquad (3)$$

Where B serves as reference level of the shallow aquifer for which $Q_r = 0$.

It seems that only part of the water naturally discharging from the shallow aquifer is entering the river by direct seepage while the other part flows through springs. For the sake of simplicity, and applying some safety factor in the forecoming predictions, we assume that $Q_r = 0$ for $H_2 \leq B$.

Water conservation requires that the following holds at each cell:

$$\text{Input} - \text{Output} = \text{Change of Storage} \qquad (4)$$

Carrying out the water balance for each cell in separate - for the first cell we have:

$$A_1 S_1 \frac{dH_1}{dt} = R_1(t) - Q_{p1}(t) - Q_{12}(t) \qquad (5)$$

and for the second cell:

$$A_2 S_2 \frac{dH_2}{dt} = R_2(t) + Q_{12}(t) + \alpha \cdot Q_t(t) - Q_{p2}(t)$$
$$- E(t) - Q_r(t) \qquad (6)$$

Where:

A_1S_1, A_2S_2 - The storativities of the confined and shallow aquifers respectively (A-the area and S-the storage coeff.)

R_1, R_2 - The natural recharge to the confined and shallow aquifers respectively.

Q_{p1}, Q_{p2} - The pumpage from the confined and shallow aquifers respectively.

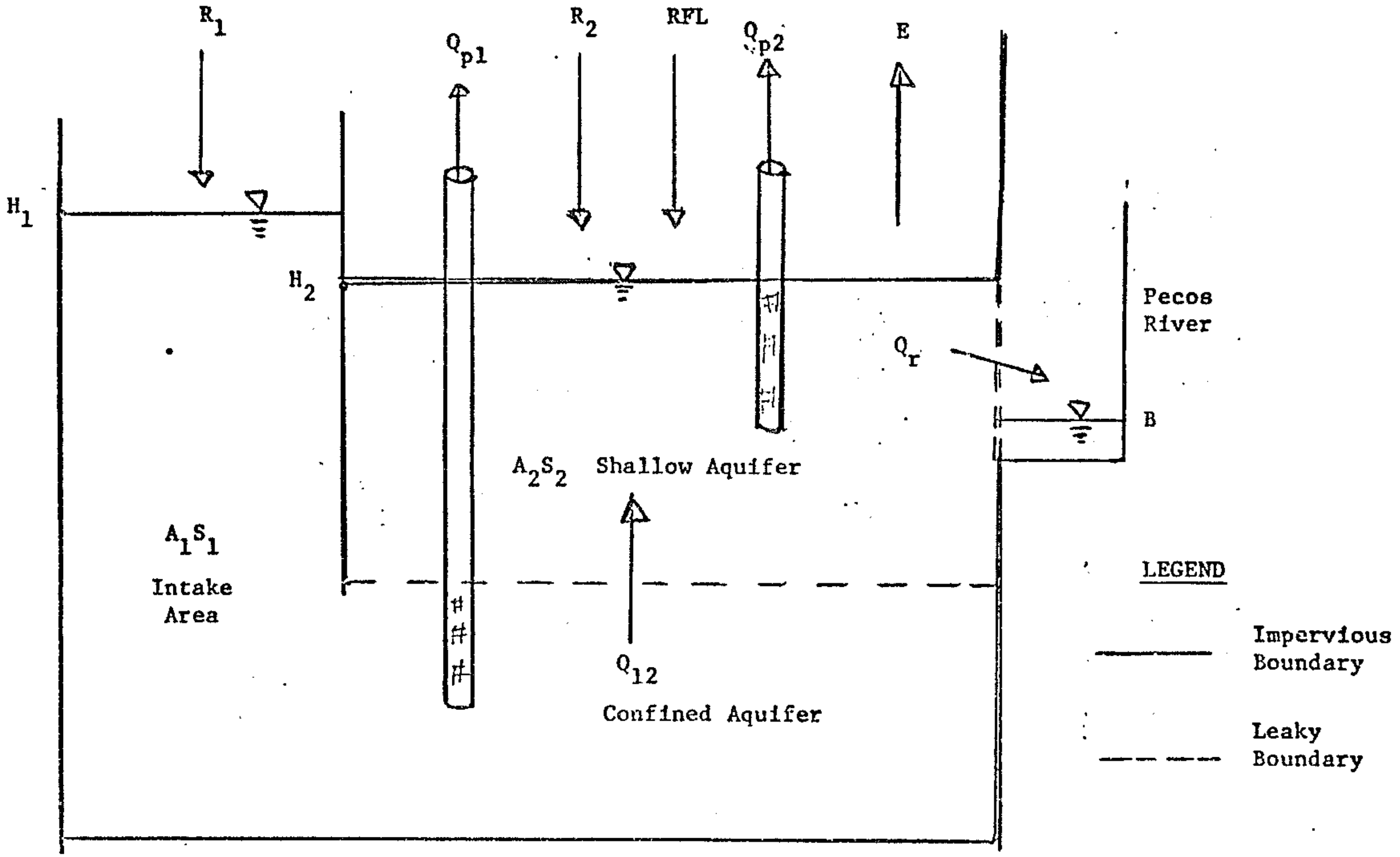

FIGURE 1 - TWO CELL MODEL FOR THE ROSWELL GROUNDWATER BASIN

Q_t - Amount of water applied for irrigation.

α - Return flow coefficient.

E - Evaporation by phreatophytes.

(t) - Time.

Part of the input/output components, which are either stochastic (natural replenishment, and evaporation rate), or controlled by human activities (pumpage, salt cedar covered area, irrigation, etc.), and for which fairly accurate estimates have been provided by previous investigators, may be summed separately as follows:

$$Y_1(t) = R_1(t) - Q_{p1}(t) \tag{7}$$

$$Y_2(t) = R_2(t) + \alpha \cdot Q_t(t) - Q_{p2}(t) - E(t) \tag{8}$$

Since most pumped water is used for irrigation, with only a small addition of water diverted from the river (RDIV), $Q_t(t)$ is approximated by:

$$Q_t(t) = Q_{p1}(t) + Q_{p2}(t) + RDIV(t) \tag{9}$$

Substituting equations (2), (3), (7), (8), and (9) into the water balance equations (5), and (6), and rearranging the terms, we obtain:

$$\frac{dH_1}{dt} = \left[Y_1(t) - k_{12}(H_1(t) - H_2(t))\right] \Big/ A_1S_1 \tag{10}$$

$$\frac{dH_2}{dt} = \left[Y_2(t) - k_r(H_2(t) - B) + k_{12}(H_1(t) - H_2(t))\right] \Big/ A_2S_2 \tag{11}$$

Equations (10), and (11) can be solved numerically by applying the following difference approximation:

$$H_1(t + \Delta t) = H_1(t) + \left[Y_1(t) - k_{12}(H_1(t) - H_2(t))\right] \frac{\Delta t}{A_1 S_1} \qquad (12)$$

$$H_2(t + \Delta t) = H_2(t) + \left[Y_2(t) + k_{12}(H_1(t) - H_2(t)) - k_r(H_2(t) - B)\right] \frac{\Delta t}{A_2 S_2} \qquad (13)$$

Beginning with some measured initial values of H_1 and H_2 at $t = 0$, one can forecast the variations of the water levels with time, provided that the proper values for k_{12}, k_r, A_1S_1, A_2S_2, α, and B were selected, and assuming that the estimated recharge and pumpage functions are exact to the desired accuracy. It should be mentioned here that the time interval Δt should be sufficiently small in order to ensure the stability of the numerical solution.

When steady-state conditions prevail (i.e., dH_1/dt, and dH_2/dt equal to zero) the solution is much easier. Treating B as the reference level of the aquifer system, and applying both continuity and Darcy's law, the steady-state water level at the shallow aquifer would be:

$$H_2 = B + (Y_1 + Y_2)/k_r \qquad (14)$$

Since for the application of this model, the possibility of reverse flow-from the river to the shallow aquifer, was overruled, equation (14) holds only for $H_2 \geqslant B$. In other words, steady-state conditions prevail only when $Y_1 + Y_2 \geqslant 0$, or when pumpage and evaporation do not exceed the natural recharge and return flow from irrigation water.

Similarly, the water level H_1 of the confined aquifer is determined by:

$$H_1 = H_2 + Y_2/k_{12} \tag{15}$$

(b) Preliminary Estimate of the Model Constants - The preliminary estimate of the system's parameters is based on the works of Hantush [1957] and Saleem and Jacob [1971].

(i) k_{12} - The leakage constant - Following Hantush [1957, p.70], the net leakage on January 1954 was estimated to be 12,394 acre-ft./month from the confined to the shallow aquifer. The area weighted average of the water levels difference between the two aquifers was 17.7 feet; thus:

$$k_{12} = Q_{12} \ / \ (H_1 - H_2) = \frac{12,394}{17.7} \times 12 = 8,550 \text{ acre-ft./yr./ft.}$$

(ii) Seepage to the Pecos River (the k_r and B constants) - Following Saleem and Jacob [1971, Table 19] an approximate linear relationship was derived between the discharge to the river (Q_r) and the average water level at the shallow aquifer (H_2):

$$Q_r(t) = 1,200(H_2(t) - 3,348)$$

Thus:

k_r = 1,200 acre-ft./yr./ft.

B = 3,348 ft.

(iii) Storativity - Following Hantush [1957, p.54], a value of 25,000 acre-ft./ft. was determined for the intake part of the confined aquifer. Since the storativity of the confined part is negligible, the storativity of the confined aquifer would be:

$$A_1S_1 = \underline{25,000 \text{ acre-ft./ft.}}$$

The area of the shallow aquifer [Hantush 1957, Table 15, p.70] is 1,233 square miles or 789,120 acres. The storage coefficient S_2 was estimated to be within 10 and 20 percent. Thus the value of A_2S_2 was estimated to be within 10 and 20 percent, that is within 80,000 and 160,000 acre-ft./ft. Accordingly we adopt a value of 120,000 acre-ft./ft.

(iv) α - The return flow coefficient - Following the estimates made by Hantush and Saleem, the return flow coefficient lies within the limits of 20 and 30 percent; the initial guess was therefore 25 percent.

(c) Calibration of the Model - Following the preliminary estimates given above, an attempt was made to calibrate the simplified model, in order to make it reliable enough for prediction purposes. The history of the recorded water levels was reconstructed with the aid of a digital computer, trying various combinations of the parameters, until a reasonable agreement between the computed and measured values was obtained.

The best fit between computed and measured water levels was obtained with the following parameters:

A_1S_1 = 25,000 acre-ft./ft.

A_2S_2 = 110,000 acre-ft./ft.

k_{12} = 8,500 acre-ft./yr./ft.

k_r = 875 acre-ft./yr./ft.

B = 3,340 ft.

α = 27%

The calibrated model can be used for prediction purposes, under both non-steady and steady-state conditions, provided that the distribution of pumpage and irrigation over the basin remains approximately the same.

It is to be emphasized that this particular model can not predict the actual response of the system given drastic changes in the evaporation from phrethphytes, due to their concentrated location along the river channel, relatively far from the pumpage concentrations.

Artificial Recharge and Steady-State Solutions

Let artificial recharge of water to the aquifer be denoted by R_a. Making use of the steady-state equations (14) and (15) and the empirical estimates of the various parameters, we obtain the following steady-state equations:

$$H_2 = \frac{R_a}{875} + 3{,}542 - 0.834\cdot10^{-3}\cdot Q_t \qquad (16)$$

$$H_1 = \frac{R_a}{875} + 3{,}570 - 0.912\cdot10^{-3}\cdot Q_t \qquad (17)$$

In case the artificial recharge is to the confined aquifer, equation (16) remains unchanged, but equation (17) changes as follows:

$$H_1 = R_a\left(\frac{1}{875} + \frac{1}{8{,}500}\right) + 3{,}570 - 0.912\cdot10^{-3}\cdot Q_t \qquad (18)$$