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Investigation of the Feasibility of the Development of a Water Resources Management Model for the High Plains Area of Oklahoma

Submitted to

The Oklahoma Water Resources Research Institute
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by

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ABSTRACT

INVESTIGATION OF THE FEASIBILITY OF THE DEVELOPMENT OF A WATER RESOURCES MANAGEMENT MODEL FOR THE HIGH PLAINS AREA OF OKLAHOMA

The purpose of this study was to determine the feasibility of applying a groundwater management model to the Ogallala aquifer of the Oklahoma Panhandle. The Texas Tech Model was applied to a portion of the Oklahoma Ogallala, and parametric studies were made to determine the sensitivity to variability in input data. Parameters varied were permeability, coefficient of storage and flow from wells. The model proved sensitive to changes in the coefficient of storage.

Also studied were the legal, economic, and physical factors affecting groundwater in Oklahoma. It is concluded that the laws of Oklahoma will allow a management agency to control the use of groundwater resources. A discussion of a managerial organization is included.

An interdisciplinary approach in the development of a management model was made in the early stages of this research. An interdisciplinary model is proposed, which includes the physical, economic, and legal aspects of aquifer management.

A new program was written to generate Theissen Polygons. This program executes about ten times faster than the Texas Tech program. An original algorithm is used.

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MANAGEMENT ORGANIZATION.

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I. DESCRIPTION OF RESEARCH PERFORMED

The overall objective of this research was to study the applicability of an existing mathematical management model to the Ogallala groundwater system of the Oklahoma Panhandle. Specific objectives were:

(1) to determine the physical, legal, and economic model constraints applicable to the Oklahoma study area,

(2) to consider the impact of the different Oklahoma water resources development plans on the groundwater supplies of the study area,

(3) to apply an existing model to a portion of the study to predict movement of water in the Ogallala formation,

(4) to determine the sensitivity of the existing computer model to changes in input data,

(5) to discuss a possible managerial organization to control the use of the water resources of the study area.

INTRODUCTION

Water depletion trends, developed over the last few years, clearly indicate the direction of future changes in any region which depends on a groundwater basin for its major source of water. The major questions involved relate to the time, location, the magnitude of the changes to be expected, and how the effects of these changes can be managed to mitigate the adverse adjustments in the economy. Obviously, water shortages because of depletion of a groundwater supply would have far reaching individual and areal impacts. It is possible to ease the impact of future changes, providing there is early acceptance of the inevitable nature and magnitude of these changes. California, a state subject to water shortages, has the first regulatory system attempting to devise better methods to manage and protect its resource of water.

The Ogallala formation is a groundwater basin, and investigators have found that the Texas High Plains portion of the Ogallala formation is being depleted. Included in this area are the three counties located in the Oklahoma Panhandle. It is this restricted area that is being considered in this report. See Figures 1 and 2.

A digital computer model has been developed for part of the state of California to aid in the management of its water resource system. Likewise, investigators are currently developing a computer management model to aid in the management of the Texas High Plains groundwater reservoir. This groundwater management model is a mathematical representation of the movement of water as a result of both natural flow and flow from wells. The model is responsive to economic and legal constraints affecting the real system as well as physical conditions. These constraints are combined with constraints set by a regulatory board to control the amount of water each user takes from the system. The model then

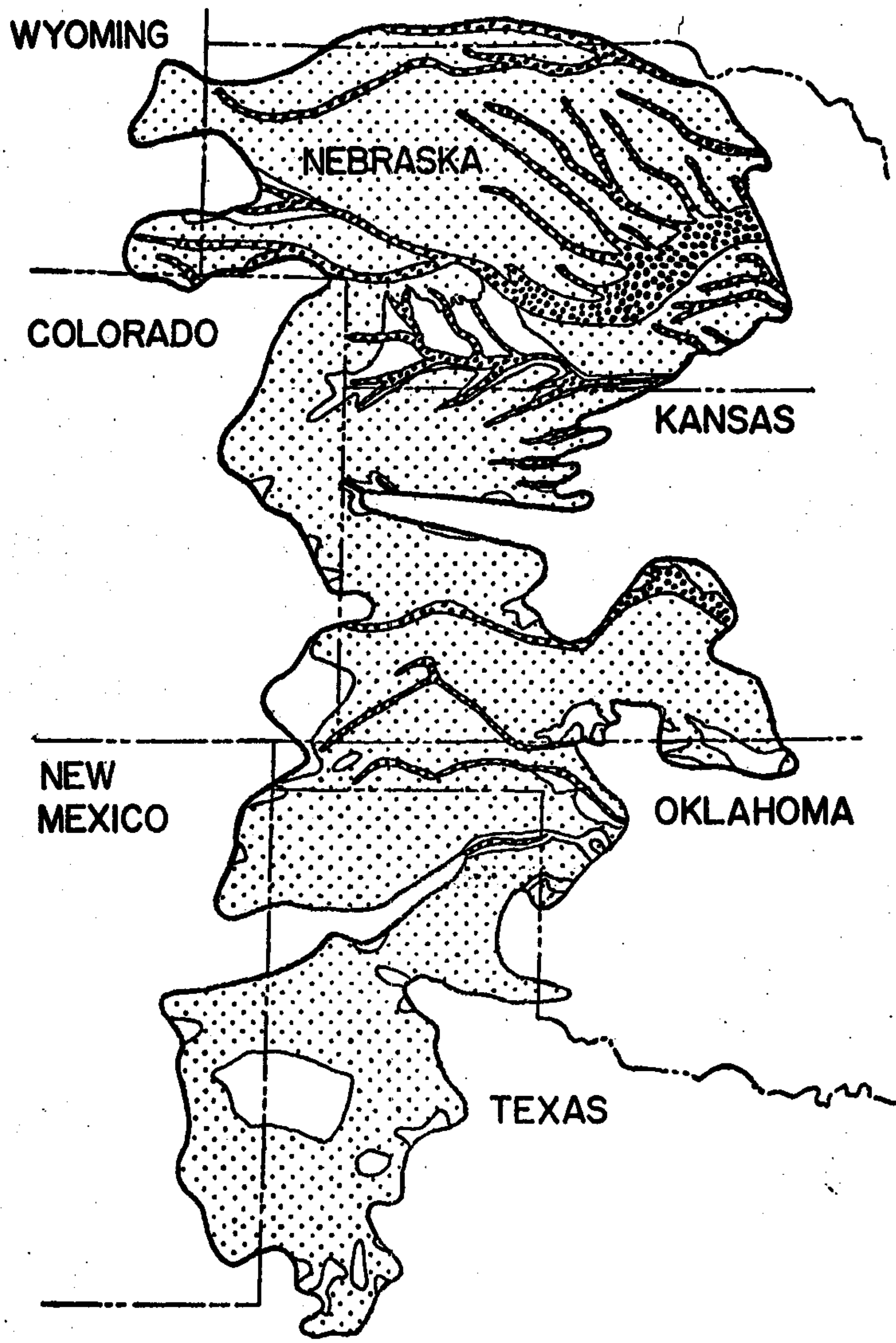

Figure 1. The High Plains Region

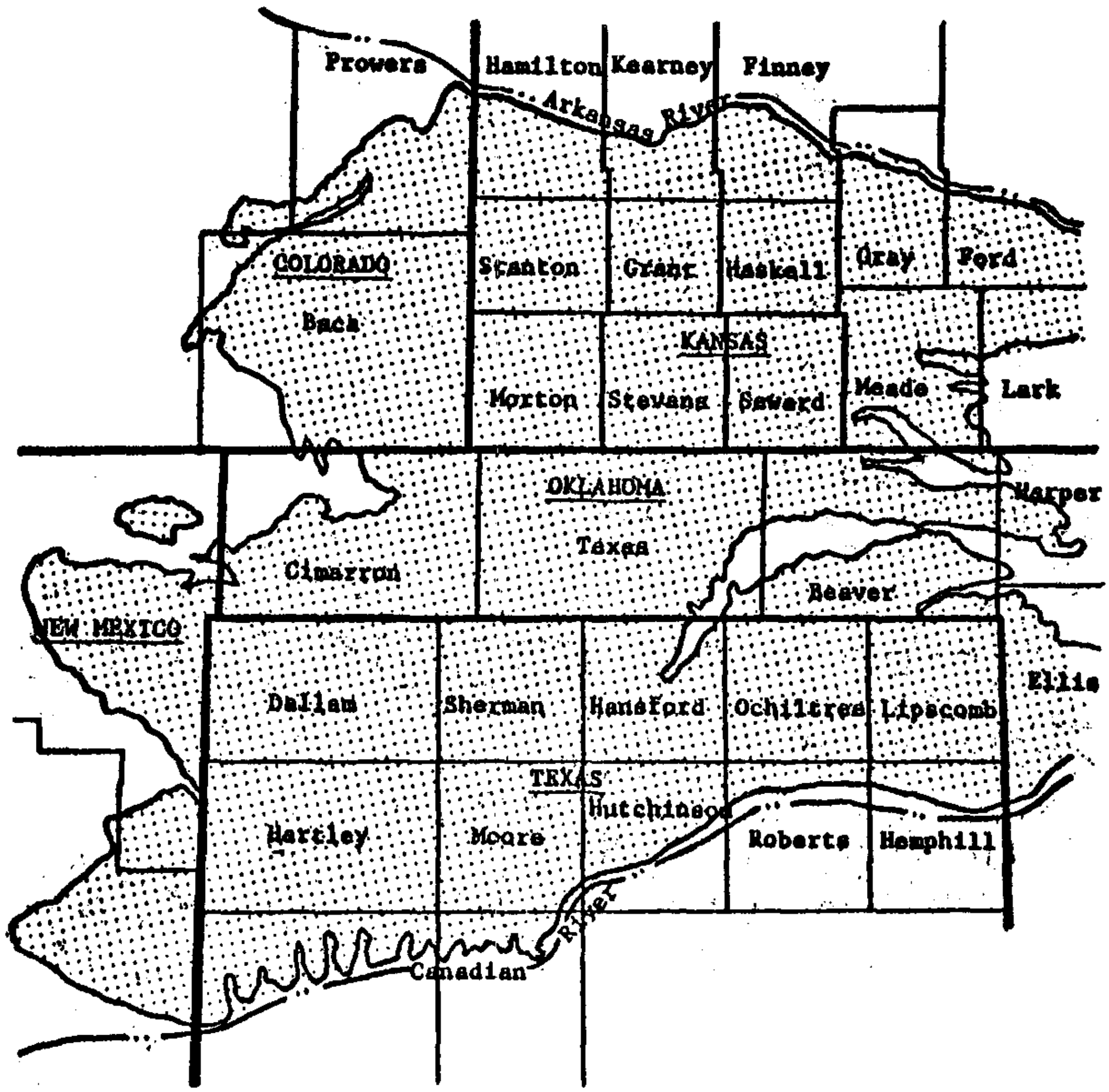

Figure 2. The Central High Plains

projects such data as the amount the water table has lowered each year, and the economic life of the reservoir. Thus, the two major questions relating to the time and location will be answered.

Economic models to evaluate the impact of water resources development on an area have also been devised. Eventual physical exhaustion is feared, and economic exhaustion would occur shortly thereafter. Economic exhaustion occurs when declining water tables increase the cost of pumping water from the aquifer to the point where the total cost exceeds the total return from its use. The fact that there is such a possibility in the long run supply of water for irrigation is established. An economic model consisting of two multi-stage sequential decision models has been developed to test whether the rates of ground water depletion projected from current data are optimal. In this manner, the magnitude of the changes to be expected in the long run can be measured.

Anytime changes in the way of conducting some activity is proposed, human reactions are generated which may preclude the institution of the proposed changes. In this instance, the first requirement is convincing the people involved that a real problem exists, and it looms on the relatively near horizon. Then it will be necessary to communicate accurately the alternatives available, and encourage active particiaption in the choice of an alternative.

CONSTRAINTS AND CONSIDERATIONS

The application of a management model to the water resources of the Oklahoma Panhandle involves the physical properties of the area, the legal framework of the State pertaining to water, the economics of the region under consideration, and the human attitude of those persons vitally involved in the area. For the development of the management model, these constraints or considerations should be identified and recognized individually and then in a framework of interdependencies.

Physical Constraints

Indepth studies of the Texas High Plains portion of the Ogallala formation reveal that, in 1968, water withdrawn as groundwater from the Ogallala was almost twice as much as the total water usage from all the surface storage in the area. Most of the present withdrawals is for irrigation purposes; about 22% is for municipal and industrial use, and a small percentage is used in water-flooding of oil fields for secondary recovery. Economically, per volume consumed and dollar returned, water-flooding is the most important and profitable use of the water, with municipal and industrial uses second, and irrigation uses the least profitable.

Unfortunately, the withdrawals far exceed recharge rates, and a number of estimates are available as to just how fast the aquifer is being depleted--all of them are alarming.

The ratio of withdrawals to recharge is so high that Ogallala water in the Texas Panhandle has been recognized as a wasting asset by the Internal Revenue Service, and granted depletion allowance credit. Recharge has been estimated as high as 39% and as low as 0.174%. In any case, the decline of the water table in the Ogallala formation is widely recognized and has been presented by Federal officials as a glaring example of bad water management.

There is a computer model, developed at Texas Tech University and based on the California Model, which can be used to predict future water levels in the Ogallala formation. Well tests will provide the data for the inputs to the program. Thus, how much water is available and how fast it is being depleted will be estimated with reasonable accuracy.

Legal Considerations

Since this report is restricted to an area located in the Oklahoma Panhandle, the concern is with laws of Oklahoma dealing with groundwater. Initially, it must be determined whether state laws allow an agency to manage a groundwater reservoir or whether the right to groundwater is given to landowners, regardless of use. This determination will dictate the type of management system to be used. Oklahoma groundwater law states that the Water Resources Board has the power to appropriate groundwater. Thus it is assumed that since the Water Resources Board has control over the appropriation of the water, it also has the power to manage the system.

Another important aspect of groundwater law is the priority to water rights of appropriators of groundwater with respect to their type of beneficial use. Some method of ranking beneficial uses of water is also required. It is very important in groundwater management programs to rank users in terms of priorities as to use. It is especially crucial in times of water shortages to give the management agency a method for determining the users most entitled to the water. Title 82 of the Oklahoma Statutes, as amended in 1963, establishes the priority of claims for appropriation of groundwater, excluding domestic use. The Act defines domestic use as use of water by a natural individual or by a family or household for household purposes, for farm and domestic animals up to the normal grazing capacity of the land, and for the irrigation of land not exceeding three acres for gardens, orchards, and lawns. The management agency would use these priorities as a basis for operating the groundwater aquifer.

Thirdly, it must be determined whether the law allows mining of the resource. Mining of groundwater is defined as using more water from an aquifer than the average annual recharge. If mining of the aquifer is allowed, then at some time in the future a point would be reached when use of groundwater would not be economical. The exact time when this point in the future is reached is the objective of the management model. A prohibition of mining results in a very restrictive constraint on the operation of the aquifer by allowing an equivalent drawdown of only 0.3 inches per year. This would make it impossible to use the Ogallala aquifer to any great extent, and preclude the use of a management model. It is believed the groundwater law of Oklahoma implies that waste of the groundwater in Oklahoma is prohibited. Waste is defined as "taking or using groundwater in any manner so that water is lost for beneficial use, permitting any groundwater to reach a pervious stratum and be lost in caverns or otherwise pervious materials encountered in a well, appropriating, taking or using water in excess of the safe annual yield measured by the average annual recharge of the area owned or leased, and drilling of wells in locations which substantially reduces the yield of water." It appears this definition of waste would prohibit mining of the Ogallala aquifer. It is noted that to date, the ruling defining waste has not been applied to the Ogallala aquifer, thus it is assumed this ruling could be changed to allow management of the State's groundwater resources.

The final area of groundwater law considered is that concerning conjunctive use of the groundwater reservoir. Conjunctive use is defined as using a groundwater reservoir in conjunction with surface water to achieve the most economical operation of the aquifer. This would include such factors as artificial recharge and interbasin transfer. Recharge water is defined here as water that will be placed in the aquifer by artificial means. It is sometimes possible constraint on the operation of the aquifer by allowing an equivalent drawdown of only 0.3 inches per year. This would make it impossible to use the Ogallala aquifer to any great extent, and preclude the use of a management model. It is believed the groundwater law of Oklahoma implies that waste of the groundwater in Oklahoma is prohibited. Waste is defined as "taking or using groundwater in any manner so that water is lost for beneficial use, permitting any groundwater to reach a pervious stratum and be lost in caverns or otherwise pervious materials encountered in a well, appropriating, taking or using water in excess of the safe annual yield measured by the average annual recharge of the area owned or leased, and drilling of wells in locations which substantially reduces the yield of water." It appears this definition of waste would prohibit mining of the Ogallala aquifer. It is noted that to date, the ruling defining waste has not been applied to the Ogallala aquifer, thus it is assumed this ruling could be changed to allow management of the State's groundwater resources.

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A review of the legal considerations indicates no serious constraints upon a groundwater management model. The ruling prohibiting mining of water appears to lack consistent application, and revision of it should not meet much resistance. The fact the Water Resources Board has control over the appropriation of the water implies a public agency system, with influence by public opinion, will be used as the vehicle for the management model.

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Economic Considerations

The value of water in any region depends almost entirely on the use to which the water is put. It is important to estimate the net value of the resource in relation to its use. The value of water for irrigation is much less than the value of water for industrial or domestic purposes. The lowest return value of irrigation water obtained was $9/acre-foot for low value crops on poor soil, and the highest value was $32/acre-foot for high value crops on good soil.

The feasibility of alternative water resources for an area is determined by the economic system of the area. A more expensive supply of water can be allowed for a region that is primarily industrial than a region that is primarily agricultural.

Agriculture is the major industry upon which much of the economic development of the study area has been dependent. In recent years, cattle feeding in the study area has been characterized by rapidly increasing numbers of large-scale commercial feedlots. This rapid development in the cattle feeding industry has tremendously increased the demand for feed grains, hay, and silage. As this development is expected to continue for the foreseeable future, the irrigated production of these crops is expected to increase very rapidly.

Developments of the past decade clearly indicate that the water table of the Ogallala formation in the study area will decline and the groundwater storage will inevitably diminish in the future. As the water table declines, the unit cost of pumping water will increase and, sooner or later, it will be uneconomical to pump water for irrigation purposes. This implies that resources once committed to irrigated production will have to revert to dryland farming. The adjustment from irrigated to dryland farming will result in serious primary and secondary reductions of income in the study area. The primary reduction of income entails the higher net returns per acre of production foregone and some of the resources abandoned in switching to dryland farming. The secondary reduction of income involves the losses attributed to reduced land prices and the economic slump created through the multiplier effect by the reduction of demand for inputs and services that complement irrigated crop production in the study area.

It is reasonable to assume that under the present uncontrolled system, irrigators are making individual decisions on a short run basis. It is possible that this is the optimal policy in the long run, but this requires testing and indepth study before such determination can be made. With this as the objective, an economic model was developed wherein Model I represented the minimum irrigation development that can be expected, and Model II represented the maximum irrigation development. These two models each tested the results for a hundred-year period assuming (A) the present uncontrolled system remains in effect, and (B) a situation in which decisions on the intertemporal allocation of groundwater in the study area are made by all irrigators acting as a body through a public agency. Thus the total expected discounted net returns in the long run are maximized and considered optimal.

The solutions of Model I, minimum irrigation development, indicated no uneconomic mining of the Ogallala formation for the study area. The policy implication was that restrictive measures on pumping groundwater are not necessary. The solutions of Model II, maximum irrigation development, indicated more dire circumstances. In fact, if irrigation development occurs as projected by Model II, the population of the area should be concerned about uneconomic mining of groundwater as early as 1990. The policy implication was that some control measures other than well spacing may be necessary to regulate the extraction of groundwater from the Ogallala formation to conform to those rates which will maximize the study area's net income over a longer period of time.

The models assume that maximizing net returns of the study area is the relevant objective. Actually, from a national viewpoint, economic stability and income redistribution are relevant objectives as well as economic efficiency. A trade-off between these objectives would further support the decision to institute a management system for controlling the withdrawal of water from the Ogallala formation.

Human Relations Considerations

Historically, water has been considered a free and unlimited public good, somewhat the same as air. Of course, there are costs connected with its acquisition and transporting from place of origin to place of utilization, but its existence and continued supply is assumed and unquestioned. Consequently, it is used with abandon, often wasted, with little or no thought of its being depleted. If water is desired, the constraint upon getting it is largely that of the cost of drilling it and transporting it to the place of utilization. Its utilization is largely determined by the economic value of the production it supports, after human needs, of course, based upon a cross-sectional analysis. Time is not a factor, because, it is assumed, there will always be enough water.

In the study area, there has been and is a considerable increase in irrigation and, as long as it is economically feasible to conduct irrigated farming, irrigation systems will be installed and the increase will continue. Human nature is such that today is given prime consideration over tomorrow until it is demonstrated that what was believed to be future uncertainties are, in fact, certainties. As a result, much of what is currently being said about the limited reserves of the groundwater source in the Oklahoma Panhandle is not believed.

Any activity which requires more than just a few participants needs some form of management of organization. Participants are human, thus human relations are relevant. Coercion is a form of management, but seldom, if ever, as successful as management with consensus. Thus, it is argued here, that human factors with respect to a proposed control system for water management in the Oklahoma Panhandle, must be considered. The most important human factors are participation, motivation, communication, and attitudes. If these four factors can be positively developed, the management of the system will surely benefit, whereas negative attitudes and participation would retard the system, if not defeat it.

THE OKLAHOMA WATER PLAN

There have been proposed some large scale plans to meet the future water requirements of Oklahoma. The Oklahoma Plan, a plan developed by the Department of the Interior, Bureau of Reclamation, is one such plan. This plan proposes to transport water from the southeast part of the State to the areas that need water. The plan proposes to provide an additional source of water to supplement or replace groundwater when needed in the study area.

The management model will provide a definite means for evaluating the effect of this additional source of water. Presently the only economic requirement resulting from the Plan study is that the cost of the water fall within the $9.00/acre-ft to $32/acre-ft range for agricultural areas.

Such plans as the Oklahoma Plan could have a definite short term impact on the use of groundwater in High Plains Area; since, current philosophy is to use the groundwater supply from the Ogallala to develop the local economy to such an extent that the local economy and the state will be able to afford the high cost of the imported water.

Since there is no definite data available on the costs

average annual lake evaporation ranges from [illegible]
per year.

In the Oklahoma Panhandle, wells can produce from 500 to more than 1000 gallons per minute. This makes the Ogallala a valuable water supply for irrigation purposes. As a result, more and more wells are being developed. The High Plains of Texas experienced the same growth in the early 1960's.

There is very little surface water available in the Oklahoma Panhandle. Most of the surface water available is

of the imported water, the impact on the Panhandle area could not be evaluated. However the management model would be invaluable in making these evaluations.

APPLICATION OF THE TEXAS TECH MANAGEMENT MODEL TO A PORTION OF THE OKLAHOMA PANHANDLE

The Study Area

The Ogallala groundwater aquifer is an extensive formation located throughout portions of Nebraska, Kansas, Colorado, New Mexico, Oklahoma, and Texas, as shown in Figure 1. The formation is dissected in Kansas by the Arkansas River, and in Texas and Oklahoma by the South Canadian River.

The portion of the Ogallala for the Oklahoma Panhandle was used in this study. In this area the formation consists of interbedded sands, siltstone, clay, lenses of gravel, thin limestone, and caliche. Portions of the aquifer are capable of storing and transmitting large volumes of water.

In the Oklahoma Panhandle, the Ogallala groundwater formation is the main source of water. This area of the state is engaged primarily in agriculture and ranching. As a result there are large volumes of water used from the formation daily. Also, the Ogallala aquifer is the primary source of water for municipalities.

In the Oklahoma Panhandle, the Ogallala aquifer ranges in thickness from 0 to more than 700 ft. The depth to water ranges from 150 to 250 ft. The average annual precipitation of this area ranges from 16 to 20 inches per year, while the estimated. The portion of the aquifer in the Texas High Plains appears to be similar to that in the Oklahoma Panhandle, and therefore the values of the aquifer constants will be used here. The value used for transmissibility was 400 gpd/ft^2, and the value used for the storage coefficient was 0.15.

To facilitate the application of the Texas Tech computer program to a case study in the Oklahoma Panhandle, a small section was chosen. The specific area chosen was Township 2 North, Range 14 East of the Cimarron Meridian in Texas County, Oklahoma. There are thirty-five wells in the area. The locations were estimated as the center of the closest one-quarter of a section. The pumpage of all wells could not be obtained, so values of Q from the wells were estimated and then varied in the model. This township is one of the more dense areas for irrigation wells in the Oklahoma Panhandle. This is, therefore, one of the more critical areas.

The Grid System

The data generation program was developed to aid in setting up the grid system. The grid system used in this study was a system of irregular polygons developed by bisecting the lines connecting a center node to an adjacent node. When this is done for all adjacent nodes and the bisectors are connected, a boundary results that separates the center node from all adjacent nodes. Average values of permeability, storage coefficient, and flow can then be set for each node that will

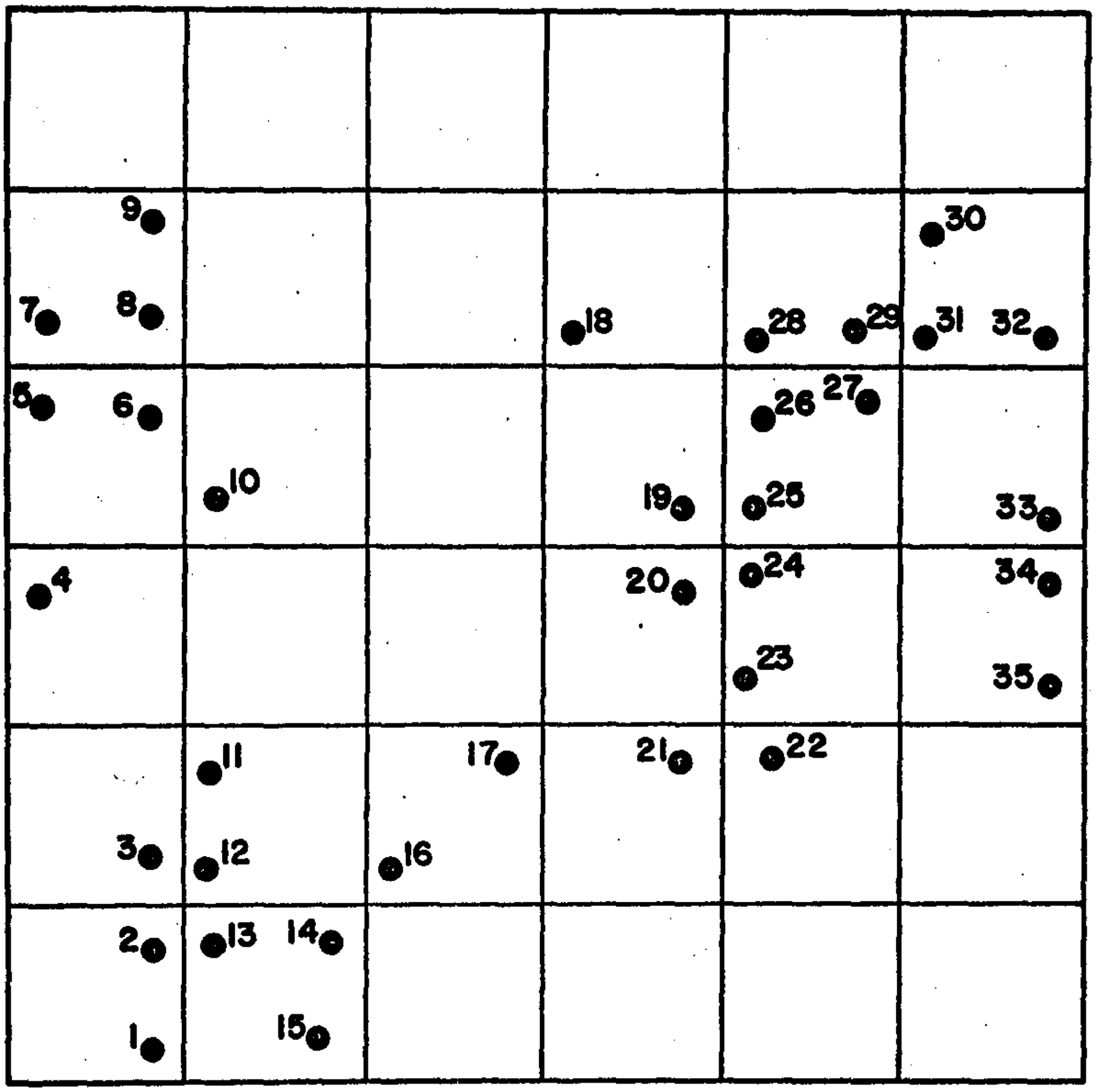

Figure 3. Location map for thirty-five wells - Township 2 North, Range 14 East, Cimarron Meridian, Texas County, Oklahoma.

apply only to the polygon associated with the node.

The program developed in this study was used to calculate the length between nodes, the width of all faces of each polygon, and the surface area of each polygon. This data was then input to the Texas Tech University Model.

The most difficult problem encountered in using the data generation program was that of establishing boundaries in the program. This was accomplished by assuming "boundary" nodes outside the boundary that were equidistant from the boundary as a node inside. The perpendicular bisector then approximately defined the boundary in the program.

This program was then applied to the 35 wells in the study area. The areas of all of the nodes are shown in Table I.

Some nodes had large areas and flow paths associated with them. This resulted from sparse density of wells in some sections of the study area. For example, the nearest well to node 18 was a full mile, and the area associated with that node was almost four square miles.

Another set of data required for the program were elevations in the study area. These included elevations of the nodes, bottom of the aquifer at the nodes, and water table at the nodes.

The Computer Model

The Texas Tech University computer model was used to predict the level of the water table in 1975. The base values used for the first run were: P = 400 gpd/ft^2, Q = 800 gpm, and

TABLE I

DATA OUTPUT OF POLYGON GENERATION PROGRAM AREA OF POLYGON

Node	Area (Square Miles)	Area (Acres)
1	0.59	377.6
2	0.50	320.0
3	0.83	531.2
4	1.02	652.8
5	0.38	243.2
6	0.48	307.2
7	0.37	236.8
8	0.75	480.0
9	3.10	1984.0
10	2.17	1388.8
11	1.19	761.6
12	0.34	217.6
13	0.31	198.4
14	0.44	281.6
15	1.28	819.2
16	2.00	1280.0
17	2.19	1401.6
18	3.94	2521.6
19	0.88	563.2
20	0.84	537.6
21	1.27	812.8
22	2.67	1708.8
23	0.56	358.4
24	0.50	320.0
25	0.37	236.8
26	0.35	224.0
27	0.54	345.6
28	1.50	960.0
29	1.00	640.0
30	1.37	876.8
31	0.35	224.0
32	0.50	320.0
33	0.60	384.0
34	0.50	320.0
35	1.91	1222.4

S = 0.15. The results of this computer run are contained in Table II. The reason that the water table rose at some nodes, i.e., negative values, was that the computer model, through the relaxation methods, balances the water table after each iteration. This should simulate the natural movement of water within the aquifer due to the balancing of the hydraulic gradient of the water table. To check the accuracy of this effect, the net drawdown of each node and the total water use was computed. This value was checked against the total outflow from the wells and found to agree within a $\pm$ two percent error. During all runs of the computer program, the natural recharge was not included because of the negligible amount.

PARAMETER SENSITIVITY

A series of parametric studies was made with the computer program to determine the sensitivity of the program to values of Q, S, and P. In each run, two of the variables were held at the base value, while one of them was varied through a certain range. The reason for this was to determine how accurate field determinations of these values must be. After the program was run for five years, the values of drawdown were compared to values of drawdowns obtained from the base values of P, Q, and S. These values were compared to a range of the residual value in the program. The residual term in the computer program is in a range within which the sum of the inflows and outflows at each node must balance. This term is required because the approximation technique, at best, gives an approximation of the inflows and outflows.

The residual term used for runs involving changes in P was 2.0 acre-ft per time step, which is equivalent to a maximum of 1.0 ft of error in five years. However, for runs involving Q and S, the program became unstable and this value had to be increased to 4.0 acre-ft/time step, or an equivalent of 2.0 ft of drawdown in five years. The results of these computer runs are shown in Tables II through VIII.

From the results of the computer runs for the parametric studies, when permeability was varied by 12.5 per cent, the difference in the drawdown compared to the base value was within the residual error. Also, when the permeability was varied by 25 per cent, only a few nodes were outside the range of the residual error. Therefore, the program is considered insensitive to a range of permeabilities.

When the storage coefficient was first run, a residual error of 2.0 acre-ft/time step caused the program to become unstable. The residual error was then increased to 4.0 acre-ft/time step. The storage coefficient was then allowed to vary within a 33 per cent range of the base value. The results show that the differences in drawdown fell outside the range of the residual error. Therefore, the program is sensitive to storage coefficient.

Varying the flow from wells required that the residual term be increased to 4.0 acre-ft per time step. The flow was first varied by 12.5 per cent. This resulted in very little change in drawdown. Even a range up to 40 per cent failed to exceed the residual error. Therefore, it can be concluded that the program is very insensitive to Q.

TABLE II

DRAWDOWN - BASE VALUES*

Node	H (1970)	H (1975)	h**
1	3100.0	3093.0	7.0
2	3092.0	3090.5	1.5
3	3103.0	3095.0	8.0
4	3115.0	3110.0	4.4
5	3110.0	3107.2	2.8
6	3110.0	3108.0	2.0
7	3100.0	3105.8	-5.8
8	3105.0	3109.1	-4.1
9	3125.0	3112.5	12.5
10	3110.0	3108.0	2.0
11	3075.0	3076.9	-1.9
12	3075.0	3074.0	1.0
13	3065.0	3070.5	-5.5
14	3060.0	3055.2	4.8
15	3055.0	3055.9	-0.9
16	3040.0	3043.5	-3.5
17	3040.0	3043.3	-3.3
18	3150.0	3141.7	8.3
19	3090.0	3081.6	8.4
20	3060.0	3062.8	-2.8
21	3050.0	3048.4	1.6
22	3055.0	3051.7	3.3
23	3045.0	3046.2	-1.2
24	3045.0	3048.7	-3.7
25	3040.0	3056.1	-16.1
26	3065.0	3070.7	-5.7
27	3045.0	3055.2	-10.2
28	3090.0	3090.5	-0.5
29	3080.0	3076.5	3.5
30	3075.0	3070.4	4.6
31	3060.0	3064.2	-4.2
32	3045.0	3054.2	-9.2
33	3030.0	3035.0	-5.0
34	3030.0	3030.5	-0.5
35	3025.0	3028.7	-3.7

*P = 400 gpd/ft^2, S = 0.15, Q = 800 gpm

**Positive value indicates drawdown.

TABLE III

SENSITIVITY OF PROGRAM TO CHANGE IN PERMEABILITY*

Selected Nodes	H (1970)	H (1975)	h	h- h(base) (Abs.Val.)
	Permeability = 300 gpd/ft^2			
2	3092.0	3090.8	1.2	0.3
4	3115.0	3111.4	3.6	0.8
6	3110.0	3107.9	2.1	0.1
8	3105.0	3108.6	-3.6	0.5
10	3110.0	3108.4	1.6	0.4
22	3055.0	3052.3	2.7	0.6
24	3045.0	3047.1	-2.1	1.6
26	3065.0	3069.1	-4.1	1.6
28	3090.0	3090.4	-0.4	0.1
30	3075.0	3071.2	3.8	0.8
	Permeability = 350 gpd/ft^2			
2	3092.0	3090.6	1.4	0.1
4	3115.0	3111.0	4.0	0.4
6	3110.0	3107.9	2.0	0.0
8	3105.0	3108.9	-3.9	0.2
10	3110.0	3108.2	1.8	0.2
22	3055.0	3052.0	3.0	0.3
24	3045.0	3047.9	-2.9	0.6
26	3065.0	3069.9	-4.9	0.8
28	3090.0	3090.5	-0.5	0.0
30	3075.0	3070.8	4.2	0.4

*S = 0.15, Q = 800 gpm.

TABLE IV

SENSITIVITY OF PROGRAM TO CHANGE IN PERMEABILITY*

Selected Nodes	H (1970)	H (1975)	h	h- h(base) (Abs.Val.)
		Permeability = 450 gpd/ft^2		
2	3092.0	3090.3	1.7	0.2
4	3115.0	3110.2	4.8	0.4
6	3110.0	3108.0	2.0	0.0
8	3105.0	3109.3	-4.3	0.2
10	3110.0	3107.8	2.2	0.2
22	3055.0	3051.4	3.6	0.3
24	3045.0	3049.4	-4.4	0.7
26	3065.0	3071.4	-6.4	0.7
28	3090.0	3090.5	-0.5	0.0
30	3075.0	3070.1	4.9	0.3
		Permeability = 500 gpd/ft^2		
2	3092.0	3090.1	1.9	0.4
4	3115.0	3109.8	5.2	0.8
6	3110.0	3108.0	2.0	0.0
8	3105.0	3109.5	-4.5	0.4
10	3110.0	3107.6	2.6	0.6
22	3055.0	3051.1	3.9	0.6
24	3045.0	3050.1	-5.1	1.4
26	3065.0	3072.1	-7.1	1.4
28	3090.0	3090.5	-0.5	0.0
30	3075.0	3069.8	5.2	0.6

*S = 0.15, Q = 800 gpm.

TABLE V

SENSITIVITY OF PROGRAM TO CHANGE IN STORAGE COEFFICIENT*

Selected Nodes	H (1970)	H (1975)	h	h- h(base) (Abs.Val.)
	Storage Coefficient = 0.10			
2	3092.0	3088.9	3.1	1.6
4	3115.0	3108.7	6.3	1.9
6	3110.0	3108.7	1.3	0.7
8	3105.0	3113.1	-8.1	4.0
10	3110.0	3107.1	2.9	0.9
22	3055.0	3048.8	6.2	2.9
24	3045.0	3050.5	-5.5	1.8
26	3065.0	3072.4	-7.4	1.7
28	3090.0	3090.2	-0.2	0.3
30	3075.0	3069.0	6.0	1.4
	Storage Coefficient = 0.20			
2	3092.0	3091.2	0.8	0.7
4	3115.0	3111.6	3.4	1.0
6	3110.0	3108.6	1.4	0.6
8	3105.0	3111.0	-6.0	1.9
10	3110.0	3108.5	1.5	0.5
22	3055.0	3052.4	2.6	0.7
24	3045.0	3047.5	-2.5	1.2
26	3065.0	3069.6	-4.6	1.1
28	3090.0	3090.6	-0.6	0.1
30	3075.0	3071.3	3.7	0.9

*Permeability = 400 gpd/ft^2, Q = 800 gpm.

TABLE VI

SENSITIVITY OF PROGRAM TO CHANGES IN Q*

Selected Nodes	H (1970)	H (1975)	h	h- h(base) (Abs.Val.)
		Q = 500 gpm		
2	3092.0	3091.1	0.9	0.6
4	3115.0	3110.9	4.1	0.3
6	3110.0	3108.5	1.5	0.5
8	3105.0	3109.6	-4.6	0.5
10	3110.0	3108.1	1.9	0.1
22	3055.0	3051.8	3.2	0.1
24	3045.0	3049.3	-4.3	0.6
26	3065.0	3071.4	-6.4	0.7
28	3090.0	3090.7	-0.7	0.7
30	3075.0	3070.7	4.3	0.3
		Q = 600 gpm		
2	3092.0	3090.9	1.1	0.4
4	3115.0	3110.8	4.2	0.2
6	3110.0	3108.3	1.7	0.3
8	3105.0	3109.5	-4.5	0.4
10	3110.0	3180.1	1.9	0.1
22	3055.0	3051.8	3.2	0.1
24	3045.0	3049.1	-4.1	0.4
26	3065.0	3071.1	-6.1	0.4
28	3090.0	3090.7	-0.7	0.2
30	3075.0	3070.6	4.4	0.2

*Permeability = 400 gpd/ft^2, S - 0.15.

TABLE VII

SENSITIVITY OF PROGRAM TO CHANGES IN Q*

Selected Nodes	H (1970)	H (1975	h	h- h(base) (Abs.Val.)
		Q = 700 gpm		
2	3092	3090.7	1.3	0.2
4	3115.0	3110.7	4.3	0.1
6	3110.0	3108.1	1.9	0.1
8	3105.0	3109.3	-4.3	0.2
10	3110.0	3108.0	2.0	0.0
22	3055.0	3051.7	3.3	0.0
24	3045.0	3048.9	-3.9	0.2
26	3065.0	3070.9	-5.9	0.2
28	3090.0	3090.6	-0.6	0.1
30	3075.0	3070.5	4.5	0.1
		Q = 900 gpm		
2	3092.0	3090.3	1.7	0.2
4	3115.0	3110.5	4.5	0.1
6	3110.0	3107.8	2.2	0.2
8	3105.0	3108.9	-3.9	0.2
10	3110.0	3107.9	2.1	0.1
22	3055.0	3051.6	3.4	0.1
24	3045.0	3048.5	-3.5	0.2
26	3065.0	3070.5	-5.5	0.2
28	3090.0	3090.4	-0.4	0.1
30	3075.0	3070.3	4.7	0.1

*Permeability = 400 gpd/ft^2, S = 0.15.

TABLE VIII

SENSITIVITY OF PROGRAM TO CHANGES IN Q*

Selected Nodes	H (1970)	H (1975)	h	h- h (base) (Abs.Val.)
		Q = 1000 gpm		
2	3092.0	3090.1	1.9	0.4
4	3115.0	3110.4	4.6	0.2
6	3110.0	3107.6	2.4	0.4
8	3105.0	3108.8	-3.8	0.3
10	3110.0	3107.8	2.2	0.2
22	3055.0	3051.6	3.4	0.1
24	3045.0	3048.3	-3.3	0.4
26	3065.0	3070.3	-5.3	0.2
28	3090.0	3090.3	-0.3	0.2
30	3075.0	3070.3	4.7	0.1

*Permeability = 400 gpd/ft^2, S = 0.15.

MANAGERIAL ORGANIZATION

With water demands of various kinds emerging in the Oklahoma Panhandle, and the apparent limited supply of groundwater, the need for a water development institution is becoming increasingly evident. The haphazard growth of a water development institution for the Panhandle can be avoided, if steps are taken now to design the organization to fit the particular circumstances in existence. Organization for water resource development is viable only if it operates within the context of the physical, social, and political setting.

It is assumed the goal of a management model for the Panhandle is to maximize net social satisfaction. It can be said that an objective of our society is to maximize welfare. Welfare is a concept which cannot be defined precisely, and is extremely difficult to measure. Welfare is concerned with the quality, as well as quantity, of satisfactions derived over time. An additional concern is the "fair" distribution of satisfactions among the members of society. Our culture supports a political system based upon the belief that individual views should weigh heavily in deciding upon the course of public action. It upholds a philosophy that respects minority views and desires. Therefore, in considering the design of organizational arrangements for water management, the basic question is whether the design promotes the realization of maximum welfare.

The pattern of satisfactions flowing from water resources depends upon the decisions that people make about the way water should be managed. Water development institutions should provide decision-making machinery which will promote welfare maximization. Ideally, this machinery will (1) express relative values as they apply to satisfactions received and satisfactions foregone in any proposed management action, (2) identify as nearly as possible the point where the marginal returns from the use of a given amount of resources fails to match the marginal returns from feasible alternative uses, and (3) operate to constrain allocation of resources beyond this point.

A groundwater management model could be instituted through a public agency system or a market system. The market system, in theory, provides a simple, automatic, and democratic method for individuals to express their values and for the productive machinery to identify marginal utilities and respond with an efficient allocation of resources. In essence, users would compete for the supply and, in cases of shortages, the supply would go to the user who receives the largest value for the resource. However, in the case of water resources, the market system often fails to allocate resources to achieve maximum social satisfactions, and the government thus becomes involved, substituting the political process for market forces.

This study is concerned with a vital resource which is in short supply. In this particular study, it is difficult, if not impossible, to place a market price on some of the services people derive from the water resource. The water being used for irrigated farming is resulting in growth and prosperity of a community that could never be supported by dryland farming in this particular area. Other industries connected with agriculture, such as commercial feeders and packing houses, are being fostered. Without an adequate water supply for irrigation, the economy would surely revert to a subsistence level. From a national viewpoint, the benefits of such a water supply are immeasurable, and yet the cost of such a water supply could easily exceed what the people of that area could pay for it. Thus the market system, based upon economic efficiency, would certainly fail to maximize welfare. As a result, a public agency system is recommended. Its purpose is to supply the area with an economical water supply available in needed quantities to all. Public opinion, through the political process, will thus affect policy decisions rather than the pricing mechanism which operates in the market system. In this situation, government intervention promises a closer approach to welfare maximization than a private institution can.

The organizational arrangements necessary for water management will be affected by physical interdependencies. Physical interdependencies may result in advantages and disadvantages to others. These are externalities which the organization will attempt to internalize. Unless the externalities are internalized, all considerations necessary to the selection of optimum management schemes may not be included in the decision process. The attempt to internalize economic consequences leads to a concept of comprehensive development in water resources policy. Another physical characteristic involved is the indivisibility of certain water services. For instance, a flood control project will protect all in the flood plain and it is almost impossible to exclude those who benefit but do not wish to pay. Thus, it is necessary to resort to a government taxing authority to support a provision for flood control.

The groundwater source in the Oklahoma Panhandle is the Ogallala formation. The portion of this groundwater basin which is being depleted is that underlying the Texas High Plains, which includes portions of Texas, Oklahoma, and Kansas. The study area under consideration is the Oklahoma Panhandle; therefore, it is apparent that the activities pursued by Texas and Kansas would also have an effect upon the optimum use of the groundwater supply. Thus any public agency entrusted with the responsibility of managing the groundwater supply for the Oklahoma Panhandle would find it necessary to form a coalition with similar agencies in Texas and Kansas, if it is to be successful at managing the water supply for optimum production.

Another decision facing the management agency is the artificial recharge of the aquifer. This would involve the acquisition of water from another area and the transportation to a point of recharging facilities. If an aquifer is recharged, the increased supply will be available to all properties overlying the aquifer, namely portions of Texas and

Kansas, as well as the Oklahoma Panhandle. This further supports the need for an agency, either Federal or a coalition of state agencies, that would manage the water for the entire area rather than only a portion of the area overlying the groundwater basin under study. The decision-making process requires that organization arrangements embrace a geographic area large enough to consider the practical effects of physical interdependencies and economies of scale.

Central to organizational design, is the problem of how to motivate governmental institutions to make welfare maximization decisions. The private market does have the virtue of permitting each individual to express his choice through the way he spends his money. Government decisions, however, theoretically reflect the wishes of the majority. The question, then, becomes how to assure that majority decisions do not veto all minority desires and, at the same time, that a vocal minority does not command the governmental decision process to the disadvantage of a majority.

With respect to the Oklahoma Panhandle, the place for the public agency to start in its effort to make welfare maximization decisions is with the legal priority of claims for appropriation of groundwater. Granted, there may be a need for some changes in the priority rankings, but they will still provide a starting point. Further, it will take an act of the Senate Legislature to change these rankings, therefore, the agency is legally bound to observe these rankings. Some form of economic analysis, such as a cost-benefit study, can be developed which will indicate economic efficiency of alternative uses of the water. These studies in conjunction with non-quantifiable considerations can be submitted to the governing body. Such economic analyses provide additional information for judging alternatives, but it is the political process which makes the final judgment. This is not presented as a solution to the problem of motivating governmental agencies to make welfare maximization decisions, but it is hoped that it improves the situation somewhat.

The management of the water services in this study may be thought of as involving four processes: (1) the planning of production facilities and other measures, (2) the installation of facilities and measures planned, (3) the operation of facilities, and (4) the distribution of services produced.

Initially, it must be determined that the computer model developed at Texas Tech University can be used to predict the future water levels in the groundwater basin. A significant amount of data must be gathered and numerous tests conducted to prove the workability of the model. It appears reasonable to assume a workable model is feasible, since there is one currently in operation in California.

Once a workable model is devised, actual data will be used and predictions will be made. Meanwhile, a priority of water use appropriations will be instituted based upon those written into the law. Since this is a public agency authorized by Oklahoma state law, the agency will have police powers. Despite this, however, the management of the water supply will be smoother and easier if it has the active participation of the residents of the area. A selling job is needed. The people need to be convinced of the problems faced and the alternatives available. If they can be motivated to work together for the good of the entire area and for future generations, the need for police powers would be nonexistent. In addition, it would be necessary to communicate assurances that an adequate water supply will be available for qualified purposes.

The operation of the facilities will also profit by active participation of the populace. As mentioned earlier, it becomes important to internalize the externalities. If this was not possible during the planning or installation stages, it is now most important. The probable method of accomplishing this is a cooperative agreement with its counterparts in Texas and Kansas.

It is during the operations that the decision faced by the public agency is one of output. In essence, a pricing decision is nonexistent. The public agency will not put a price on the water withdrawn, but rather control the amount to be withdrawn. The cost of the water to the users will be that of pumping and transporting the water.

The proposed flow chart for output decisions is shown on Figure IV.

Through the use of the computer model, the reserves in the groundwater basin will be measured. The economic models will be used to predict the preferred long-run usage. A

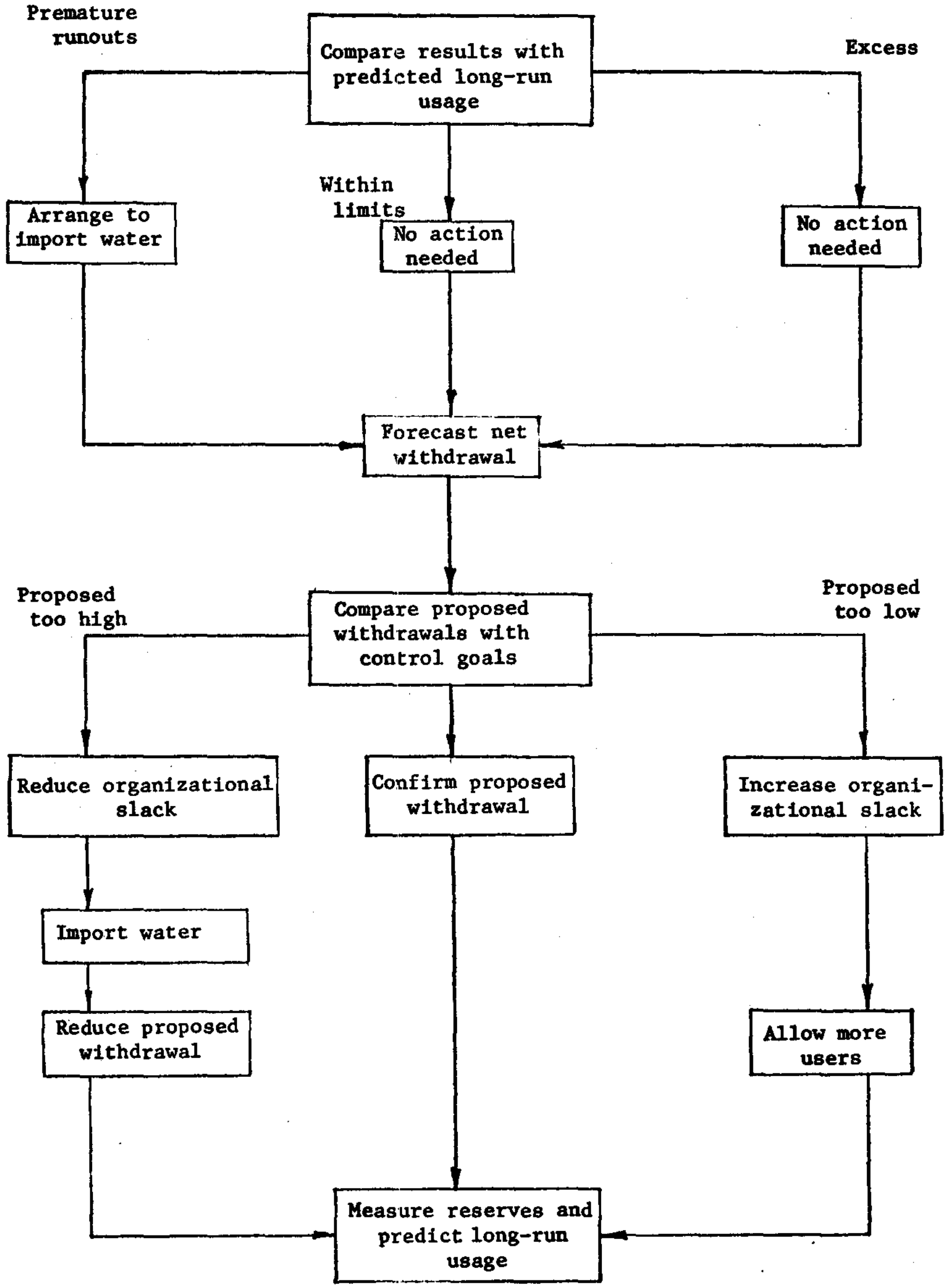

Figure IV. Flow Chart of Withdrawal Decision comparison of the two will indicate one of three possibilities. Either excess reserves are developing over that predicted in the long run, or the trend is approximately equal to that determined to be optimum or premature runouts are likely to occur. The first two cases would require no action, whereas the third would generate a decision to import water and proceed with recharging the aquifer with the imported water.

It is noted that it has been determined there is no legal restriction on the practice of importing water that cannot be fulfilled. The existence of a supply of water available for importation would constitute another externality which the organization would want to internalize. It is anticipated the water needed would be imported from areas in Southeastern Oklahoma. The most probable means of bringing the water supply under the agency's control is through contract negotiations. Thus, the agency would attempt to avoid the major uncertainty factor facing it.

The next step is the forecasting of net withdrawals for the following period. This forecast would be based upon the gross withdrawals for the prior period, adjusted for whatever factors may be anticipated in the current period that did not occur in the previous period, less an anticipated recharge through natural processes, such as rainfall. This forecast is then compared with the control goals in effect. The comparison may show the forecasted withdrawals are too high, too low, or are on target.

If the proposed forecast of net withdrawal is too high, the reaction may simply be to reduce organizational slack. Organizational slack is defined here as the disparity between the water available to the organization and the demands for that water presented by the area residents when compared to the long-range control goals for the water in question. Thus, if prior periods resulted in lower net withdrawals than conceived by the master plan, some excess reserves (or organizational slack) would be available to cover proposed excess withdrawals in the current period. If no organizational slack exists, a decision to import water may be generated. The third and most stringent action that may be presented is a reduction in the proposed net withdrawals. This reduction would follow the priority rankings as set by Oklahoma statutes.

If the comparison shows the proposed net withdrawals are too low, either organizational slack, as defined previously, would be increased or new users, such as industry and additional irrigated farm land, may be accepted. This last possibility would have to be weighed carefully. It would be necessary to determine that the forecasted net withdrawal as compared to the control goals was a new and permanent trend rather than an isolated circumstance which would more than likely correct itself or even reverse itself in the ensuing period. It is imperative that it be recognized the input of more users will affect the predicted usage in the long run.

If the comparison indicates the proposed net withdrawals for the current period are in line with the master plan, the only action needed is to confirm the proposed net withdrawal forecast.

As the period draws to a close, the reserves would be measured, the long run usage predicted using updated information, and the results would be compared with the control goals.

The distribution of the water would be basically a case of fulfilling the demands of the residents of the area. It is naturally anticipated the demand will exceed the supply. Therefore, distribution will be controlled with no need for motivation. The extent of control will be determined by predicted reserves and the optimum usage of that water over the long-run.

II. SUMMARY AND CONCLUSIONS

Summary

Many states are now reaching the point where water resource plans for the entire state are needed for their effective management. Although some states have taken steps to implement laws and techniques for the management of their water resources, many states still lack effective tools to implement a management program. One objective of this study was to determine the legal and economic framework under which this state can manage the Ogallala groundwater aquifer.

It appears that until the ruling of waste is redefined, legally the Ogallala aquifer cannot be used to any great extent. However, to date the state agencies have not applied this ruling to the Ogallala aquifer. It then seems that this ruling could be changed to allow a basis to manage the State's groundwater resources.

Other than this, the law tends toward management of the groundwater resources. For example, the law gives a state agency, the Water Resources Board, the power to administer groundwater law and the right to appropriate groundwater. The law also gives the Water Resources Board the power to administer matters pertaining to the operation of groundwater reservoirs such as artificial recharge. With very few legal changes, the Water Resources Board could also become the management agency for applying the groundwater management model.

The mathematical model proved to be a suitable program after some small changes. The greatest problem arising from the use of this program was input data other than that pertaining to the grid system. Sets of data are contained in the results that were used for this study. The most critical data was determined to be the data involving the physical aspects of the groundwater aquifer, Q, S, and P.

As a result of the inaccuracy of the physical data, a parametric study was made on Q, S, and P. The results show that the program is relatively insensitive to variation in Q and P, but quite sensitive to variations in the storage coefficient, S. This implies that tests will have to be made to determine the storage coefficient.

It has been established that the groundwater supply in the Oklahoma Panhandle is being depleted. It appears reasonable to predict that some form of control over the withdrawal of the water from the groundwater basin will be necessary.

It is vital that such control does not retard the economic growth of the area, and, further, assures the economy can be sustained at a natural level. Thus a rational organization is required.

There is little doubt that solutions to the technical problems are imperative, but it is also important to consider organizational aspects that may be involved. An attempt is made here to describe an organization that will promote rational decision-making. In essence, it is a simple organization. It is concerned primarily with the rate of output. There is the complementary function of acquiring and transporting a subsidiary source of water, but there is no price decision involved.

Considering the fact that controls would be placed upon an item generally considered a "free good," there is the possibility police powers will be necessary to enforce the controls considered desirable. Because of this as well as the reasons stated earlier, a public agency is recommended over a market system. However, the police powers, hopefully, would not have to be exercised; rather, the populace will be aware of the very real need for the controls and will support the objectives of the agency in controlling the withdrawal from the groundwater basin.

Conclusions

The feasibility of a management model for the High Plains Area of Oklahoma has been established. Now is the time to proceed with the development and application of the model.

III. INTERDISCIPLINARY DEVELOPMENT OF A GROUNDWATER MANAGEMENT MODEL

In late May of 1970, a group of faculty members from OSU was assembled to investigate the feasibility of developing an interdisciplinary approach to groundwater management in the Oklahoma area. This group was composed of Professors Vernon Eidman from Agricultural Economics, Douglas Kent from Geology, Richard DeVries and William Dawkins from Civil Engineering and Glen Laughlin from Administrative Sciences and Business Education. Preliminary meetings of this group of faculty resulted in presentation of a proposal to the Oklahoma State Research Institute entitled, "An Interdisciplinary Investigation of Legal, Economic and Physical Aspects of Ground and Surface Waters in the Oklahoma Panhandle to Develop a Feasible Management Model." This proposal was submitted in April of 1970. The project was funded as a part of A-024-OKLA. and commenced on June 1, 1970.

The interdisciplinary group met in early June and subsequently on the average of twice weekly until late July. During the course of these meetings, the groundwater situation in Oklahoma was discussed with particular emphasis on the Ogallala formations in the Central High Plains. A review of the various factors affecting groundwater management in this area was conducted. This review consisted of a description of the geology to be found in that area presented by Professor Kent; economic factors, including current research efforts related to agricultural economy in the Central High Plains area, was presented by Professor Eidman; a review of current research and mathematical modelling of groundwater aquifers and computer applications of these models was discussed by Professors DeVries and Dawkins; and, a review of legal aspects of groundwater management was presented by Professor Laughlin. Following these presentations, the group visited the Central High Plains area on July 10, 1970, and discussed the groundwater situation in the Central High Plains area with water users, management personnel, and legal and governmental agencies in that area. The group also conducted an aerial reconnaisance of the entire Central High Plains area. Discussions were also held with representatives of the U.S. Geological Survey and the Oklahoma Resources Board.

Concurrently with the reports by the individual members of the Interdisciplinary group, and the meetings with the governmental agencies, a literature survey was conducted and a bibliography related to all areas of the project was compiled. The selected bibliography is included as Appendix A.

As a result of the interdisciplinary study groups review of the problems encountered, it was unanimously agreed that a comprehensive water resources management model of the high plains of Oklahoma could be designed. This comprehensive model should include consideration of economic constraints, water law, the geological and hydrological features of the area and should be capable of being integrated with present and future water plans including the possibility of interbasin transfer of aquifer recharge water.

Attached as Appendix B is a model proposal which the authors feel would provide the framework for such a comprehensive study.

IV. AN OPTIMAL THIESSEN POLYGON GENERATING PROGRAM

The group at Texas Tech has used Thiessen polygons in calculating the flow of groundwater. One polygon is associated with each "node" (in this case, each node is a well). These polygons are determined by the positions of the nodes and the boundary of the set of nodes. For this reason the polygons are in a sense naturally adapted to a given problem, permitting fewer polygons to be used than if simple rectangles were used, as is often done.

The computer program written at Texas Tech to generate the polygons is time consuming; after some optimization had been done, the generation of Thiessen polygons for a set of 343 wells required about 65 minutes on an IBM 360/50 computer.

For his report for the Master's degree in computer science at OSU, Mr. Ben Shelton has written a faster program to do the same task. An original algorithm of Mr. Shelton's invention is used. The program executes about eight to ten times faster than the Texas Tech program. The report gives a good description of the method, the format of the data, etc. The program is well documented internally with comment cards (the program is written in the FORTRAN language). The program is available for use at Texas Tech and at OSU. Except for these two installations the program is a proprietary package owned by Mr. Shelton, and all rights are reserved.

Mr. Shelton was aided and supervised by Dr. John Chandler, Assistant Professor of Computer Science, Oklahoma State University.

V. PROJECT RELATED PUBLICATIONS

1. Lamirand, Thomas J., "Application of a Management Model to the Ogallala Groundwater Aquifer of the Oklahoma Panhandle," unpublished Master's Thesis, School of Civil Engineering, Oklahoma State University, Stillwater, Oklahoma, 1971.
2. Lamirand, Thomas J., and Richard N. DeVries, "Sensitivity of a Groundwater Management Model to Aquifer Constants for the Ogallala Groundwater System of the Oklahoma Panhandle," Proceedings of the 22nd Annual Oklahoma Industrial Waste and Pollution Control Conference and Advanced Water Conference, Oklahoma State University, Stillwater, Oklahoma, 1971.
3. DeVries, Richard N., "Deep Disposal Wells and the Ogallala Aquifer," Presented at the American Society of Civil Engineers National Water Resources Conference, Phoenix, Arizona, 1971.

VI. PROJECT PERSONNEL

The following personnel received financial support from this project:

1. R. N. DeVries, Associate Professor of Civil Engineering, Principal Investigator.
2. W. P. Dawkins, Associate Professor of Civil Engineering.

3. D. C. Kent, Assistant Professor of Geology.
4. G. E. Laughlin, Professor, Department of Business Education and Administrative Services.
5. A. J. Lassker, Graduate Student.
6. G. R. Guhl, Graduate Student.
7. G. D. Steele, Undergraduate Student
8. J. A. Tatchio, Secretary.

The following personnel contributed much, although not receiving financial support from the project:

1. V. R. Eidman, Associate Professor of Agricultural Economics.
2. J. P. Chandler, Assistant Professor of Computer Science.
3. T. J. Lamirand, Graduate Student.
4. W. R. Loo, Graduate Student.
5. B. Shelton, Graduate Student.

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APPENDIX A

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APPENDIX B

At the conclusion of the interdisciplinary session of Project A-024-OKLA., the participants agreed that it was both feasible and desirable to conduct a major research program aimed toward developing a comprehensive water resources management model for the high plains of Oklahoma. This study should include as a minimum participation from the disciplines of law, geology, hydrology, and economics.

A model of such a proposal is herewith appended.

OBJECTIVES OF PROPOSED STUDY

Water depletion trends developed over the last few years clearly indicate the direction of future changes in any region which depends on a groundwater basin for its major source of water. The major questions involved relate to the time, location, the magnitude of changes to be expected, and how the effects of these changes can be managed to mitigate the adverse adjustments in the economy. If these questions can be answered, individual and areal impacts of depletion can be eased, providing there is early acceptance of the inevitable nature and magnitude of these changes. To that end, there is serious need for research designed to identify, explore, and develop procedures and criteria for evaluating adjustment alternatives that will ease the impact of prospective changes in all sectors of the economy.

The general objective of this study is to develop the interdisciplinary methodology for constructing and operating a multipurpose groundwater management model.

Specific objectives are:

1. To develop a digital computer model for a groundwater system to predict available water resources when the system is subjected to prescribed water withdrawal rates.

2. To develop a procedure which includes the legal and economic constraints that will determine water withdrawals and resulting production levels of primary sectors of the economy for alternative management plans.

3. To develop an interindustry input-output model that utilizes the production levels and legal constraints from 2 above to determine the effects (income level, employment level, and services required) on the secondary sectors of the economy.

4. To utilize the above methodology to analyze and evaluate alternative legal, economic, and physical constraints to facilitate water management within the Central High Plains as a specific study area.

The Central High Plains is defined for this study as the area bounded on the North by the Arkansas River, on the South by the Canadian River, and on the East and West where the Ogallala formation has been removed by erosion. These boundaries conform to those reported by Irwin and Morton [1]* and are illustrated in FIGURE 1.

RESEARCH PLANS

Mathematical management models have been developed which describe the physical capabilities of a water resources system. Economic models to evaluate the impact of water resources development on an area have also been devised, and legal studies determining the implications of policy changes have been made. Generally, these studies have been conducted by investigators within an individual discipline. The approach typically uses very simplified models for the portion of the work lying within the discipline of the principal investigator. This study differs in that it combines the disciplines of civil engineering, geology, agricultural economics, and law to develop mathematical models to construct a complete management model. The objectives of this study will be accomplished as follows.

RESEARCH PLANS FOR OBJECTIVE 1

In order to develop a model of a groundwater system, it is necessary to have a thorough understanding of the vertical and horizontal distribution of aquifer variables and constants. It is generally known that many unconfined aquifers are composed of a wide variety of clastic sediments which are often irregularly distributed as lenses and channels. In addition, many unconfined aquifers are recharged both from the surface and subsurface.

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*References cited are shown in APPENDIX A.

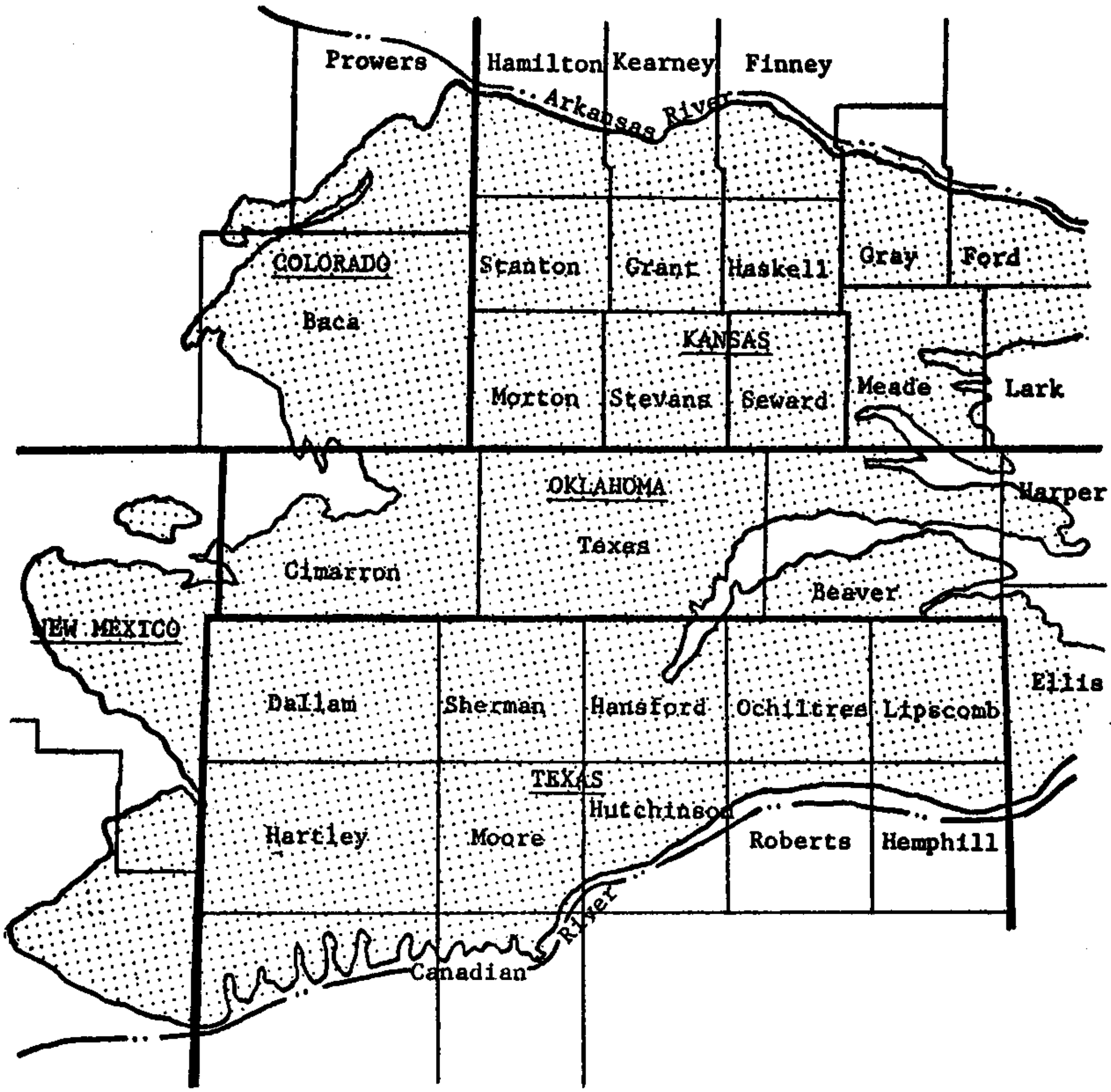

Figure 1. The Study Area

A variety of boundary conditions can be found which will lead to different rates of recharge. Physical conditions as described above are found in the High Plains Ogallala aquifer. The geology of areas such as the High Plains has been over generalized in the past. Therefore, physical constants, variables, and boundary conditions which represent an aquifer will be evaluated before the mathematical model is developed. Data and technology developed for groundwater studies and modeling will be obtained from the United States Geological Survey, Texas Tech University, the Texas Water Commission, and applicable irrigation districts.

The mathematical model will be based on the techniques developed by Texas Tech University [2], General Electric Tempo [3], and Freeze and Witherspoon [4]. Applicability of these techniques will be evaluated by consultation with the respective research groups referred to above (See APPENDIX C). The model will be composed of an array of nodes having properties and location based on the stratigraphy and hydraulic characteristics of an unconfined, nonhomogeneous, multi-layered aquifer. A detailed evaluation of flow at vertical and horizontal boundaries will be included. Subsurface flow into the aquifer from underlying or adjacent confined aquifers will be treated as a component of a leaky aquifer or as a direct inflow from localized boundaries where no impermeable separation exists between unconfined and confined aquifers. Flexibility for including parameters describing legal and economic management aspects will be incorporated in the model design. The principal effort will be to develop the most general mathematical model which is consistent with available computational capabilities. Oklahoma State University's IBM 360/65 digital computer will be used in the development of the management model.

During the first year of the study, the representatives from the disciplines of engineering and geology will establish and incorporate the physical parameters into a mathematical model. In the second year, selected and synthesized data will be used in the model to test the response to various legal, economic, and physical constraints. In the final year, real data will be substituted in the model to evaluate the operational capabilities of the combined management model for the specific study area.

RESEARCH PLANS FOR OBJECTIVE 2

A model to determine water withdrawal and production levels will be composed of data from representative firms for each subregion in the study area. This model will be based on the area programming model developed in OWRR Project B-010-Oklahoma [5]. However, it will be expanded to include the relevant legal constraints identified in this study and will be related to the physical model developed under Objective 1. An investigation of present applicable law and administrative policies pertaining to groundwater use in Texas, Oklahoma, Kansas, New Mexico, and Colorado will be implemented through study of judicial, legislative, and administrative sources at federal and state jurisdictional levels. The economic and technical information to construct this model is available from the above mentioned OWRR study. However, to include the effects of legal constraints and to provide estimates of water withdrawal rates by subregions of the study area, a different structure of the model is required. Legal constraints become more important in determining water withdrawal rates as the availability of water diminishes.

The investigation of present legal and administrative rules and policies will be completed during the first year of this study. Estimates of production within the primary sector of the economy for use by this model will also be developed during the first year.

During the second, year, the study will concentrate on recommended changes in legal constraints. Alternative legal and administrative rules and policies relevant to groundwater use will be devised, as may be suggested by interdisciplinary analyses, to facilitate water management.

Proposed groundwater codes and changes in administrative regulations will be examined. Other alternative legal constraints will be developed from analysis of legal literature. In addition, personal conferences will be conducted with water users in the various sectors of the economy and with legislators, lawyers, and administrative personnel interested in the use and control of water. The model of the basic production sectors incorporating the appropriate legal alternatives will be structured and tested during the second year.

RESEARCH PLANS FOR OBJECTIVE 3

A survey of cattle feedlots and nonfarm business will be combined with information from previous studies of the farming sector to develop a detailed interindustry input-output model of the study area. The primary sector of the economy will be divided into categories such as irrigated food grains, irrigated feed grains, irrigated forages, dryland food grains, dryland feed grains, dryland forages, and cattle feeding. This breakdown will enable a detailed analysis of the impact of alternative uses of water on the economy of the area. The studies by Emerson [6] for Kansas and by Masucci [7] for U. S. Agriculture will be particularly useful in developing this model.

The sector breakdowns will be developed during the first half of year one. A schedule to obtain the necessary information to complete an interindustry transactions table will also be developed during the first year. The survey will be completed early in the second year. This survey information will be combined with data available from previous studies to complete the transactions table. The corresponding technical coefficient matrix and interdependence coefficient matrix will also be developed during the second year.

RESEARCH PLANS FOR OBJECTIVE 4

The models developed under the above three objectives will be used jointly to evaluate alternative water management plans. After specifying a legal and economic alternative to be analyzed, the model developed under Objective 2 will be used to determine water withdrawals and production levels. This will be used to specify input data for the other two models discussed under Objectives 1 and 3. Water withdrawals by subregion of the study area will be provided as input for the aquifer model. The resulting production levels will be used as input data for the interindustry input-output model.

The aquifer model will provide input required to determine pumping costs and water availability for the following time period. The input-output model provides a basis for judging the adjustment required in other sectors of the economy to sustain the production levels.

PERIOD OF RESEARCH PERFORMANCE

The project proposed is for a period of three years with a suggested starting date of July 1, 1971. This proposal requests funds for the first year's effort, from July 1, 1971 to June 30, 1972. Funds for the second and third year of the project will be requested at the appropriate times. Preliminary estimates of funding required for the second and third year of the project are included in this proposal as APPENDICES D and E.

RELEVANCY OF THE PROPOSED RESEARCH TO WATER RESOURCES PROBLEMS

This interdisciplinary study encompasses sections of Priorities 1, 3, 6, and 8 as stated in the OWRR Research Letter dated June 12, 1970.

PRIORITY 1

This study will provide both a basis and a mechanism to evaluate alternative means of augmenting and conserving groundwater supplies for water resources planning and management effectiveness. Also, water rights doctrines will be evaluated as they affect the process of decision making, user attitudes, and water management practices and policies for the specific study area.

PRIORITY 3

Mathematical modeling and simulation as well as optimizing principles will be assessed and further employed in relation to the economic and legal planning of groundwater resource development.

PRIORITY 6

Methodologies will be developed for estimating future demands in time and place with full consideration given to economic relationships between supply and demand as well as the impact of new technologies for the specific study area in the Central High Plains.

PRIORITY 8

Development and evaluation will be made of management methods and techniques which will serve to protect the groundwater resource from degradation and to insure its availability and safety for domestic, municipal and agricultural uses.

BACKGROUND INFORMATION

GENERAL

This study group has reviewed current techniques and data used in groundwater investigations and mathematical modeling. During the summer of 1970, the feasibility of developing a practical management model for the Central High Plains was confirmed following site visits and personal interviews in the Central High Plains area. This effort was carried out as a part of the Oklahoma Water Resources Research Institute Project A-024-Oklahoma. A continuation of the project, currently underway, involves an analysis of controlling parameters in a sub-area of the Central High Plains.

ENGINEERING AND GEOLOGY

Mathematical modeling of the flow of water within an aquifer has been the subject of many articles appearing in the literature in recent years. In each case, the researcher has directed his attention toward a particular aspect of the overall problem and, as a result, has limited the generality of his model. In every case, however, the basis of the model is the same in that Darcy's law relating velocity of flow to hydraulic head is used in conjunction with continuity of flow and quantity of water available to describe the flow process. These models differ in the method of describing the aquifer and in indicating whether the flow process is in the steady or nonsteady state. It is infeasible to describe every reported attempt at the solution of the problem; however, a limited number of articles described below will provide useful background information on digital computer modeling.

Freeze and Witherspoon [4] have described both analytical and numerical procedures for solution of steady state conditions in a three-dimensional, nonhomogeneous aquifer. Since they conclude that the numerical solution process is clearly the more versatile of the two, only that part of their development will be described. The equations of flow and continuity are cast in finite-difference form with numerical values of flow parameters (permeability and water table elevations) being supplied at finite points (or nodes) throughout the aquifer. Solution of the finite-difference equations for hydraulic potential at each node permits determination of the direction and quantity of flow throughout the aquifer.

Kleinecke [3] and Claborn et al [2] have approached the solution of the transient flow problem by considering the aquifer to be composed of an assemblage of vertical prisms of irregular polygonal cross-section. The shape of the prism cross-section is determined according to a prescribed arrangement of nodes which are usually observation wells. Each prism is characterized by a storage coefficient, uniform head, depth to the bottom of the aquifer, and permeability. The effects of inclusions such as impermeable lenses or confining aquifers can be accounted for only implicitly by adjusting the descriptive parameters for each polygon. The finite difference form of the flow and continuity equations is utilized to solve for the head at each node. Results of the application of the model to actual aquifers are reported along with a discussion of the empirical data necessary to determine the characteristic parameters for each prism.

In an effort to reduce the computational effort encountered in the more general description of the aquifer used by Freeze and Witherspoon, and to provide for more explicit determination of the effects of relatively impermeable layers within the aquifer, Bredehoeft and Pinder [8] have developed a quasi three-dimensional model for analysis of a multi-layer system. This model accounts for communication between confined and unconfined aquifers by limiting flow in the confining layers to the vertical direction while permitting only horizontal flow in the other strata.

ECONOMICS

The Arizona study by Martin et al [9], utilizing both an electric analog model of the aquifer and a linear programming model of the farming sector, provides a methodological background for combining the models developed under

Objectives 1 and 2 of this study. Likewise, Emerson's interindustry analysis of Kansas [6] provides a useful background study for developing the sector breakdowns and data collection procedures in the study area. However, none of the previous studies has developed a truly integrated set of models to analyze the effect of alternative government policies on groundwater and the economy of the area.

A related ongoing OWRR project, B-010-Oklahoma, will be useful in developing the proposed study. Much of the background information on the resources of the area, relative importance of water use by the various sectors of the economy, as well as some preliminary projections of water use over time, provide an excellent starting point for the research proposed in this study. The proposed interdisciplinary project will result in a comprehensive management model, whereas the ongoing project (B-010-Oklahoma) provides projections of water use and the resulting production levels for the agricultural sector of the area economy.

LEGAL

A recent case decision [10] has recognized that water extracted from "closed" aquifers is a mineral resource eligible for cost depletion credit for income tax purposes. Present Oklahoma law [11] defines the taking of groundwater in excess of its natural recharge as waste. Thus, such depletion credit is inconsistent with Oklahoma's water use policy.

Groundwater laws and administrative policies are continuously being reevaluated and restated. For example, the Oklahoma Water Resources Board is developing a groundwater code to be proposed to the 1971 State Legislature. Rules, regulations, and modes of procedures applicable in Oklahoma [12] must be reviewed to correlate them with the philosophy of the proposed groundwater code.

Hearings before the Oklahoma Corporation Commission have reviewed the question of injection of waste water below fresh water aquifers in the High Plains area of Oklahoma. The results of these hearings are expected to reflect certain attitudes of economic interests which are directly related to water use and conservation.

The groundwater aquifer in the area of study underlies portions of five states, each of which may respectively govern groundwater use. A comparative analysis of relevant state laws, rules, and administrative policies will suggest systems and approaches to groundwater resource management laws. The study of the water laws of Wisconsin, Iowa, Michigan, Minnesota, and Illinois by Beuscher and Ellis [13] provides an excellent pattern for the study of state laws affecting the Central High Plains.

EXTENSION OF KNOWLEDGE

The proposed project will fill gaps in available knowledge in several ways. First, the interdisciplinary approach provides a series of three correlated models that will be useful in estimating the impact of water resource development strategies in other geographic areas. Second, it will be useful in analyzing alternative administrative proposals and possible interstate water compacts for the study area. Third, it will provide information that can be used by business and community leaders in planning for the economic adjustments anticipated in the area. It will also be a contribution to related research and extension programs in rural economic development.

QUALIFICATIONS OF PRINCIPAL INVESTIGATORS

Resumes for the principal investigators are shown in APPENDIX B.

TIME AND EFFORT OF THE PRINCIPAL INVESTIGATORS

Other research, if any, conducted by the principal investigators coincidentally with the proposed project will not exceed one-quarter time.

The portion of each principal investigator's time to be devoted to this project is indicated in TABLE II of the financial section of this proposal.

PROPOSED PROJECT FINANCIAL PLAN

See OWRR Forms C-1, C-2, C-3, C-4, C-5 and accompanying budget tables. The overall project budget is shown in TABLE I. TABLE II provides a breakdown of salary costs.

COST AND PRICING DATA

Not Applicable

INDIRECT COSTS AND EMPLOYEE BENEFITS

The indirect cost rate of 51.2% was established by negotiations between Oklahoma State University and the Department of Defense Audit Agency. It is the predetermined rate for the period of July 1, 1970, through June 30, 1971. If a new predetermined rate has not been negotiated by July 1, 1971, the rate of 51.2% will be used as a provisional rate. The address of the current audit agency, effective July 1, 1970, is HEW Audit Agency, 1114 Commerce Street, Room 1017A, Dallas, Texas 75202.

The employee benefits--hospitalization insurance, major medical and life insurance, and retirement benefits--are secured directly by the University. The entire premium for all faculty members and most staff members is paid directly by the University; no payroll deductions are made to cover any portion of this expense. The costs for employee benefits and F.I.C.A. are estimated as a separate cost item at a rate of ten percent of direct salaries for staff members and 4.8 percent of that portion of direct salaries for students employed full time.

NOTICE OF RESEARCH PROJECT (NRP)

An original and three copies of an NRP for the proposed project has been enclosed with the proposal package.

TRAINING

The proposed project will provide an excellent opportunity for qualified graduate students to participate in research activity. Three graduate associates, candidates for the Ph.D. degree, and five graduate assistants, candidates for the M.S. degree, will be employed half-time for 10 months and full-time for the two summer months.

PUBLICATION OF RESEARCH RESULTS

Research results will be published in scientific journals such as the Water Resources Research (American Geophysical Union), Water Resources Bulletin (American Water Resources Association), Journal of the Hydraulics Division

(American Society of Civil Engineers), Oklahoma Law Review (School of Law, Oklahoma University), Oklahoma Bar Journal (Oklahoma Bar Association), and the American Journal of Agricultural Economics (American Agricultural Economics Association).

NON-FEDERAL CONTRIBUTION TO THE RESEARCH EFFORT

OSU is making a contribution to this project in the amount represented by the difference of indirect costs calculated as 41.2% of direct salary costs and the indirect costs associated with the federally audited overhead rate of 51.2% of salaries.

SUBMITTAL OF PROPOSAL TO OTHER FUNDING SOURCES

This proposal has not and will not be submitted to funding organizations other than OWRR.

RESEARCH TIME PERIOD

This proposal is to be considered valid for the period of October 1, 1970 through June 30, 1971.

PROPRIETARY INFORMATION

This proposal contains no information to be considered as proprietary.

APPENDIX A

REFERENCES CITED

REFERENCES CITED

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