

*Future Quaternary Groundwater
Accessibility in the Grand Prairie — 1993*

Richard C. Peralta, Amin Yazdanian, Paul J. Killian and Robert N. Shulstad

ACKNOWLEDGMENTS

We gratefully acknowledge the secretarial and administrative support provided by Joy Treat and Barbara Taylor; the statistical assistance rendered by Dr. David Marx and Kevin Thompson; the editorial aid of Ronda Bitterli and the valuable counsel and support provided by Dr. Gus Ludwig of the U.S. Geological Survey. We extend our appreciation to Bill Williams and O. B. Wise of the Arkansas Geological Survey, who provided us with data. The leadership and financial support provided by Billy Bryan of the Department of Agricultural Engineering of the University of Arkansas, by John Saxton and Randy Young of the Arkansas Soil and Water Conservation Commission, and by Dr. Les Mack of the Arkansas Water Resources Research Center are also gratefully acknowledged, as is the financial support of the Hartz Seed Company, Producers Rice Mills, Inc., Riceland Foods and the U.S. Department of the Interior.

CONTENTS

| | Page |
|--|------|
| Introduction and Objectives | 1 |
| Previous Studies | 3 |
| Methodology | 3 |
| Determination of the Study Area and Model Selection | 4 |
| Validation and Sensitivity Analysis of a Groundwater Model | 4 |
| Estimation of Data for History-matching | 4 |
| Analysis of the Groundwater Model | 8 |
| Prediction of Groundwater Levels | 10 |
| Results | 13 |
| Future Groundwater Storage and Groundwater Levels | 13 |
| Predicted Cost Increases of Raising Groundwater | 14 |
| Determination of Desirable Aquifer Saturated Thickness | 19 |
| Predicted Saturated Thicknesses | 26 |
| Summary and Conclusions | 26 |
| Literature Cited | 32 |
| Appendix | 34 |

Agricultural Experiment Station, University of Arkansas Division of Agriculture, Fayetteville. John W. Goodwin, Vice President for Agriculture; Preston E. La Ferney, Director. PS1.2M885

The Arkansas Agricultural Experiment Station follows a nondiscriminatory policy in programs and employment.

Future Quaternary Groundwater Accessibility in the Grand Prairie—1993

Richard C. Peralta, Amin Yazdaniyan, Paul J. Killian
and Robert N. Shulstad¹

INTRODUCTION AND OBJECTIVES

Groundwater levels are declining in several areas within Arkansas. Wherever water declines become excessive, wells may become inoperable and water users may be left without an adequate supply. The Grand Prairie is one area that has experienced significantly depressed groundwater levels. It has been a rice-producing region for most of this century. The irrigation water required by rice and, at the present time, by soybeans has been obtained primarily from an aquifer of Quaternary geologic age. This extensive formation underlies much of eastern Arkansas as well as parts of other states.

Figure 1 shows a simplistic west-east cross section of the aquifer near Stuttgart, Arkansas. The western edge is near the Bayou Meto and the eastern edge is near the White River. The top horizontal line is the ground surface. The clear area in the center of the drawing is the aquifer material, consisting of sand and gravel with interspersed clay layers. The shaded area beneath the aquifer depicts relatively impermeable underlying Tertiary clay. The shaded layer above the aquifer is composed primarily of clay with interspersed sand layers.

Figure 1 also displays the potentiometric surfaces (groundwater levels) for 1939, 1959 and 1981. The dramatic decline in groundwater levels with time indicates that the rate at which water has been withdrawn has greatly exceeded the rate at which water has entered the aquifer.

As groundwater levels decline, the cost of raising a unit volume of water to the ground surface increases and aquifer saturated thickness (i.e., the distance between the aquifer bottom and either the potentiometric surface or the top of the aquifer, whichever is lower) decreases. If the saturated thickness becomes too small, an adequate discharge rate is unobtainable from large agricultural wells.

The objectives of this report are the following:

1. To predict groundwater levels in the Quaternary aquifer in 1993.
2. To predict the increase in the cost of raising groundwater to the ground surface that is due to predicted changes in groundwater levels.
3. To predict saturated thicknesses in the Quaternary aquifer in 1993 and to indicate areas where obtaining a satisfactory discharge rate from wells for rice production may be doubtful.

¹Richard C. Peralta, Amin Yazdaniyan and Paul Killian are assistant professor, graduate research assistant and research assistant, respectively, in the Department of Agricultural Engineering. Robert N. Shulstad is a professor in and head of the Department of Agricultural Economics and Rural Sociology.

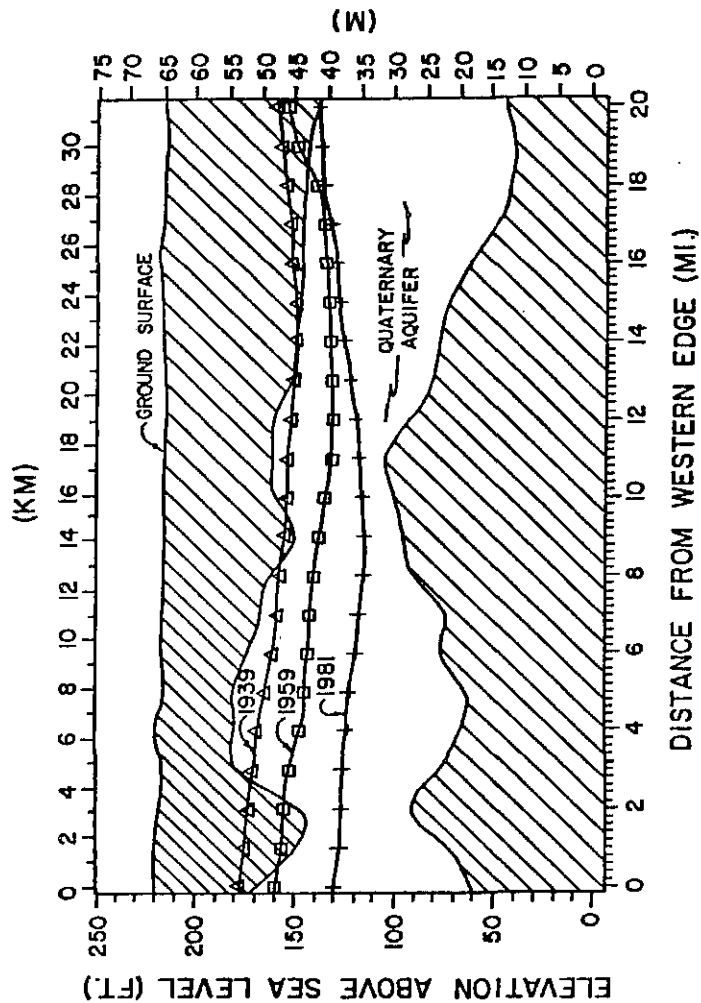


Figure 1. Cross section of the Quaternary aquifer near Stuttgart, Arkansas, showing historic groundwater levels.

PREVIOUS STUDIES

Engler et al. (1945) reported a storage coefficient of 0.3 for the aquifer and a permeability of 1900 gpd per square foot, which corresponds to a hydraulic conductivity of 254 feet per day (77.4 m/day). They indicated that, because of the clay cap overlying the aquifer, the volume of deep percolation moving from the ground surface into the aquifer was negligible.

Sniegocki (1964) reported a permeability of 2000 gpd per square foot, which corresponds to a hydraulic conductivity of 267 feet per day (81.4 m/day), and a storage coefficient of 0.3.

Griffis (1972) developed and validated a nonlinear, two-dimensional groundwater simulation model of that portion of the Quaternary aquifer underlying the Grand Prairie. His estimates of the top and bottom of the aquifer were developed from unpublished data of the University of Arkansas Department of Agricultural Engineering and from a study by Engler et al. (1945). Griffis used an aquifer storage coefficient of 0.3 and a hydraulic conductivity of 267 feet per day. He assumed that deep percolation in the interior of the region was negligible and that the aquifer behaved as if it were everywhere unconfined.

For studying a nearby portion of the Quaternary aquifer, a nonlinear, two-dimensional-flow model used by Broom and Lyford (1981) produced best results when a storage coefficient of 0.3 and a hydraulic conductivity of 270 feet per day (82.3 m/day) were used. Broom and Lyford assumed that the aquifer behaved as if it were unconfined.

METHODOLOGY

The ideal procedure for using a groundwater simulation model for predicting future groundwater levels is composed of the following steps:

1. Use available data to determine the precise study area, select a simulation model and make the best hydrogeologic assumptions possible.
2. Use the selected assumptions, modifying them if necessary, to calibrate the model. In calibration, the model's response to pumping during a specified time period is compared with the historic observed response of the aquifer over the same period. Model response is made to be more in harmony with historic response by improving the estimates of the physical characteristics of the aquifer. The process is continued until the model emulates historic conditions satisfactorily over the calibration period.
3. Test the model over a second time period, the validation period. If the model-predicted water levels again satisfactorily compare with historic observed levels, the model is considered sufficiently validated to be used for predictive purposes. In this step the sensitivity of the model to small changes in the assumptions is evaluated.
4. Select the best assumptions from the validation/sensitivity analysis step and use the model to predict water levels. Prediction is generally limited in time span to the same number of years as validation.

Sufficient accurate data are not always available to perform both calibration and validation for time spans of satisfactory duration. In such situations, when using a generally applicable (as opposed to site-specific) model, validation alone is adequate as long as the hydrogeologic assumptions are not changed significantly during the validation process. That is the case in this study. In the Grand Prairie, water-use information and groundwater-level observations prior to the 1970s are not detailed enough to allow model calibration and validation to the required accuracy. The 10 years between 1972 and 1982 was the longest period of time for which sufficient data could be obtained. For this reason, and because essentially the same estimates of aquifer parameters were used in this study as were used successfully by Griffis (1972), the calibration step was omitted. The validation and sensitivity analysis were accomplished for the 1972–82 era.

Determination of the Study Area and Model Selection

The study area in this report encompasses most of the Grand Prairie (Figure 2). The boundaries were selected following an analysis of spring water levels over a 10-year period. These boundaries, which are approximately the same as those used by Griffis (1972), generally correspond to the White River on the east, the Arkansas Post Canal on the south and the Bayou Meto on the west. The northern border parallels U.S. Interstate 40. The area is divided into cells that are 3 miles by 3 miles in size. The shaded cells in the figure are cells to which Arkansas River water may potentially be diverted (based on unpublished studies of the U.S. Army Corps of Engineers).

A generally applicable, linearized, two-dimensional groundwater model, AQUISIM (Verdin et al., 1981), was selected for our effort. Because of the approximations caused by linearization, the model is appropriate for confined as well as unconfined conditions. Cells are of two types: constant-head (or boundary) cells and internal cells. Constant-head cells, in which the simulated groundwater level is maintained at a constant elevation (head) during a simulation period, comprise the area's periphery.

Validation and Sensitivity Analysis of a Groundwater Model

Estimation of Data for History-matching. Validation was accomplished using the common practice of history-matching. To use this procedure, historic Quaternary groundwater levels, aquifer parameters and withdrawals from and recharge to the aquifer for the 1972–82 validation period had to be estimated.

Historic Quaternary groundwater levels were estimated from data of the U.S. Geological Survey (USGS), which measures groundwater levels in more than 100 wells in the Grand Prairie each spring. An example of the annual report of the levels is that by Edds (1981). From the USGS measurements, the water levels in the center of each cell were estimated for the springs of 1972–82 using the geostatistical technique known as kriging (Sophocleous, 1983). Because of the spacing and number

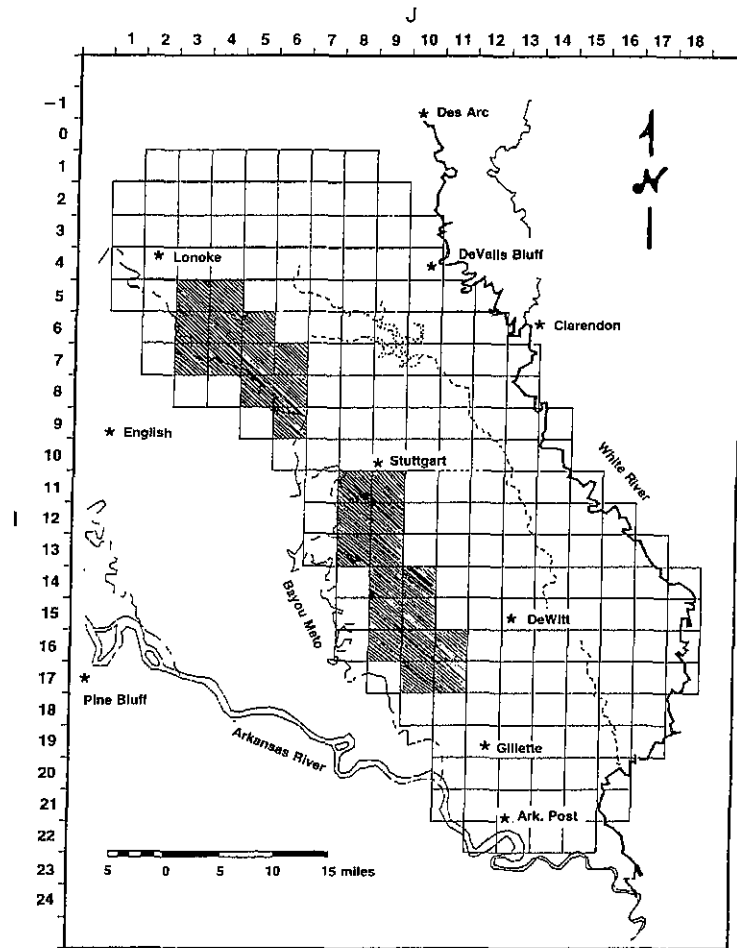


Figure 2. The Grand Prairie study area. Shaded cells are cells to which Arkansas River water may potentially be diverted.

of observation points, the standard error of the estimate of the gridded water elevations was generally between 4 and 11 feet (1.2 and 3.4 m). For the internal cells, the data for 1972 were used as the initial conditions for the validation period. For each constant-head cell, the average spring groundwater level (for 1972-81) at the center of the cell was used as the cell's constant groundwater elevation in simulations conducted for the validation period.

The aquifer parameters used in the model include the elevation of the aquifer top and bottom and the transmissivity and effective porosity in the center of each cell. Elevations of the aquifer top and bottom were developed by kriging from records of water-well construction, and 0.3 was used as an aquifer-wide estimate of effective porosity. In alluvial deposits, hydraulic conductivity, and therefore transmissivity, generally increases with depth as particle size increases. Hydraulic conductivity values reported by previous researchers ranged from 254 to 270 feet per day. Because aquifer water levels have continued to decline with time, 270 feet per day was selected as being the most appropriate hydraulic conductivity value for current use. Transmissivities for each cell in the study area were obtained by multiplying the annual hydraulic conductivity by the distance between the bottom of the aquifer and either the 1972 groundwater level or the top of the aquifer, whichever was lower at that point.

Estimates of the amount of water withdrawn (pumped) from the Quaternary aquifer during the validation period were made for each of the major users of groundwater in the Grand Prairie: irrigated agriculture, aquaculture and municipalities. Amounts withdrawn for aquacultural, rice or soybean production varied from year to year, depending on harvested acreages and climatological differences. Annual municipal use was assumed to be constant during the validation period. For the sake of accuracy, it was necessary to determine the portion of the annual regional groundwater withdrawal that was being withdrawn at each cell in each year. The procedure used to divide the regional groundwater withdrawal into cell-by-cell values, detailed in a report by Peralta et al. (1983), is summarized below.

To estimate rice or irrigated soybean acreage in each cell, we used data from a series of publications of the Arkansas Department of Local Services (1977a,b,c,d) and from the annual Agricultural Statistics for Arkansas reports for 1972-81 (USDA, 1973-82). We assumed that all of the reported harvested rice acreage and 24 percent of the soybean acreage was irrigated. The 24 percent figure was an average derived from unpublished USDA figures for Arkansas, Lonoke and Prairie counties for 1972-81 (D. Von Steen, personal communication). The crop acreage in each cell differed from year to year, depending on county crop acreages. Seasonal estimates of rice or soybean irrigation needs were developed using programs based on simulation of the daily soil water balance and on irrigation scheduling (Peralta and Dutram, 1984). Annual water needs per acre of rice or soybeans varied from year to year, depending on the year's actual weather. Based on information from the Soil Conservation Service, the percentages of these water needs that were actually supplied to the plants were assumed to be 100 percent for rice and 67 percent for

soybeans. Of the supplied irrigation water, only a certain percentage, which was different for each county, was obtained from the Quaternary formation. These percentages were estimated from figures reported by the USGS (Halberg, 1977; Holland and Ludwig, 1981) and from a recent survey reported by Harper (1983). The average annual percentages of irrigation needs being met from the Quaternary aquifer for 1972-81 were 51 percent for Arkansas County, 68 percent for Lonoke County, 67 percent for Monroe County and 65 percent for Prairie County.

The amount of water pumped for rice from the Quaternary aquifer in a particular year and for a particular cell was determined by multiplying the cell's rice acreage for the year by the rice irrigation water needs for that year and by the percentage of those needs being supplied by the aquifer. The amount of water pumped for soybeans in a particular year and for a particular cell was determined in an analogous fashion. The sum of the amounts pumped for rice and soybeans represented the total agricultural pumping for that cell in that year.

Estimates of aquacultural acreage between 1972 and 1975 were obtained from Appendix A of the Arkansas State Water Plan (Arkansas Soil and Water Conservation Commission, 1976) and from information provided by the U.S. Department of the Interior's Fish Farming Experimental Station in Stuttgart, Arkansas (M. Martin, personal communication). Based on information from the USGS (Halberg, 1977), the estimate of annual water use for aquaculture was 7 feet (2.1 m). (This is the same as 7 acre-feet/acre.) Ninety percent of the aquacultural water required between 1972 and 1975 and 100 percent of that required between 1976 and 1982 was judged to have been withdrawn from the Quaternary aquifer.

Estimates of municipal pumping from the Quaternary aquifer were obtained from Appendix B of the Arkansas State Water Plan (Arkansas Soil and Water Conservation Commission, 1978).

The model ensured some recharge to the aquifer by maintaining constant groundwater levels in constant-head cells. Almost all the recharge to the area enters through these cells, either from rivers penetrating the aquifer or from water entering the cells from extensions of the aquifer outside the region. The procedure for estimating constant-head cell elevations is discussed on page 6.

Because a relatively impermeable clay layer overlies the aquifer, we assumed that there was no recharge to the aquifer through most of the internal cells. We tested this assumption by varying the annual deep percolation rate in several 50-year simulations. Each simulation began with 1915 (pre-development) water levels, and it was assumed that no groundwater withdrawals were being made. The pre-development water levels represent an unstressed steady-state potentiometric surface that should remain constant with time. In the simulation in which no deep percolation was assumed to exist, water levels remained essentially as they were input, which is what is expected in a natural, unstressed system. However, when simulating even as little as 0.03 feet of deep percolation per year, simulated water levels increased with time. Therefore, because the steady-state potentiometric surface changed with time under the simulations in which recharge was considered, it is valid to assume that no water

is percolating through the clay layer and into the aquifer.

Our analysis of groundwater levels, however, indicates that streams are providing some recharge to the aquifer in two of the internal cells located in the southern portion of the Grand Prairie. Surface water backs up in these streams because of the locks of the Arkansas River Navigation System. This recharge was simulated by adding negative pumping (discharge is a positive pumping) to the two southern cells—cells (21,12) and (21,13)—where Arkansas River water is ponded. The annual amount of recharge used in these two cells was determined by analyzing spring groundwater levels over a 10-year period. The resulting pumping values for cells (21,12) and (21,13) were -149.7 million and -148.5 million cubic feet (-4.24 million and -4.20 million cubic meters) per year, respectively.

Analysis of the Groundwater Model. The preceding section described the development of our best assumptions concerning aquifer characteristics and inputs and outputs to the aquifer system. There is, however, always error associated with making aquifer-wide estimates of aquifer characteristics and in estimating pumping or recharge. In the model validation and sensitivity analysis step, we wished to determine whether we had identified the best assumptions for use in predicting future water levels. To accomplish model validation and sensitivity analysis, we performed a series of simulation runs. Our "best" assumptions were incorporated into Run 1—the validation run. In this run, a hydraulic conductivity of 270 feet per day, an effective porosity of 0.3 and recharge to the two internal recharge cells were assumed. In addition, 100 percent of the rice irrigation water needs and 67 percent of the soybean irrigation water needs were assumed to be met by irrigation. In order to determine the sensitivity of the model, the hydraulic conductivity, effective porosity and percentage of soybean irrigation water needs met by irrigation were varied in Runs 2-12; all of the rice irrigation water needs continued to be met by irrigation, and recharge to the two internal recharge cells remained the same in these runs.

Table 1 displays the results for this first series of simulation runs. The simulated results that most satisfactorily matched historic data were obtained with Runs 1 and 6. Run 1 (the validation run) underestimated groundwater storage in 1982 by less than 0.5 percent, and the simulated reduction in storage was only 5 percent greater than the observed reduction in storage. The error in predicting storage reduction after 10 years was 2 percent of the total pumping for the 10-year period.

Run 6 had been performed using a hydraulic conductivity of 324 feet per day (98.8 m/day) and an effective porosity of 0.3. In addition, 100 percent of the soybean irrigation water needs were assumed to be met by irrigation. Run 6 simulated actual conditions with the same absolute accuracy as Run 1. In such a situation, where two runs simulate with comparable accuracy, one must determine which set of assumptions should be used for predicting future groundwater levels. In our case, the assumptions of Run 1 are preferred for two major reasons. The first is that 270 feet per day has been historically successful in simulating flow in the aquifer. The second is that for predictive purposes, it is better to be estimating a little less in storage rather than too much.

Table 1. Sensitivity of the model, with recharge in two internal cells assumed.

| Run no. | Model Specifications | | | Sensitivity Measure | | |
|---------|---------------------------------|--------------------|--|---|---|--|
| | Hydraulic conductivity (ft/day) | Effective porosity | % of irrigation needs supplied to soybeans | % deviation of simulated 1982 storage from observed 1982 storage ¹ | % deviation of simulated reduction in storage from observed reduction in storage between 1972 and 1982 ² | % error in predicting storage reduction, 1972-82 (in % of total pumping for the 10 years) ³ |
| 1 | 270 | 0.3 | 67 | -0.3 | 5 | 2 |
| 2 | 270 | 0.3 | 100 | -1 | 14 | 5 |
| 3 | 216 | 0.3 | 67 | -2 | 25 | 9 |
| 4 | 216 | 0.3 | 100 | -2 | 34 | 12 |
| 5 | 324 | 0.3 | 67 | 1 | -14 | -5 |
| 6 | 324 | 0.3 | 100 | 0.3 | -5 | -2 |
| 7 | 270 | 0.25 | 67 | -3 | 54 | 20 |
| 8 | 270 | 0.25 | 100 | -4 | 66 | 24 |
| 9 | 216 | 0.25 | 67 | -5 | 84 | 31 |
| 10 | 216 | 0.25 | 100 | -6 | 97 | 35 |
| 11 | 324 | 0.25 | 67 | -2 | 26 | 10 |
| 12 | 324 | 0.25 | 100 | -2 | 38 | 14 |

¹Calculated as follows: $100(1982 \text{ simulated storage} - 1982 \text{ observed storage}) \div 1982 \text{ observed storage}$.

²Calculated as follows: $-100(1982 \text{ simulated storage} - 1982 \text{ observed storage}) \div (1972 \text{ observed storage} - 1982 \text{ observed storage})$.

³Calculated as follows: $-100(1982 \text{ simulated storage} - 1982 \text{ observed storage}) \div \text{total net pumping from 1972 to 1982}$.

Run 2 was identical to Run 1 except that Run 2 allowed for 100 percent of the soybean irrigation water needs to be met by irrigation instead of the 67 percent allowed by Run 1. Run 2 underestimated 1982 groundwater storage by 1 percent, which is an acceptable value. However, its error in simulating reduction in storage was 14 percent, which does not compare well with the 5 percent error of Run 1. Also, the 5 percent error of Run 2 in simulating storage reduction as a function of total pumping is also not as good as the 2 percent error of Run 1.

A comparison of Runs 1 and 2 permits an observation to be made about the sensitivity of the model to estimated pumping. Because Run 2 allowed for all the soybean irrigation water needs to be met by irrigation, the average annual pumping volume for Run 2 was 1600 acre-feet (0.6 percent) greater than that of Run 1. If we assume that the pumping volume used in Run 1 is a "best" estimate, then the 0.6 percent overestimation of pumping of Run 2 caused a 9 percent increase (14 percent - 5 percent) in error in predicting reduction in storage.

A second series of simulation runs were performed. These simulation runs were identical to those described above except that no recharge to the two internal recharge cells was considered. Because the two internal recharge cells are adjacent to constant-head cells, the effect of the internal recharge cells is highly localized. Results of the second series of simulation runs were at most 1 percent greater (worse) than those of the runs for which recharge at the two internal recharge cells was considered. There-

fore, for purposes of predicting total storage, it makes little difference whether recharge is or is not added to the two southern cells.

The preceding analysis shows that the best assumptions for the 1972–82 validation period were a hydraulic conductivity of 270 feet per day, an effective porosity of 0.3 and a soybean irrigation volume equal to 67 percent of soybean irrigation water needs. Using these assumptions, the simulated change in storage was within 5 percent of the observed change in storage after 10 years. The magnitude of the difference between simulated and observed values is representative of what occurred throughout the validation period.

Figure 3 shows how accurately the best run (Run 1) predicted cell-by-cell groundwater levels. The value in each cell is the difference between simulated and observed (kriged) water levels in 1982 for that cell. A negative value indicates that the simulated level was lower than the observed elevation. The standard error of the estimate of the kriged water levels ranged between 4 and 11 feet for the cells of the study area. A difference between simulated and observed values that was less than the standard error of the estimate of the observed water level was considered insignificant. Differences greater than the standard error of the estimate occurred only in constant-head cells or in cells adjacent to constant-head cells. This can be expected since water levels may change dramatically in cells with good stream–aquifer connection. It can also be expected along the northwestern boundary of the area where aquacultural pumping is causing a steady decline in levels. Therefore, differences between simulated and observed elevations in constant-head cells and in some adjacent cells were not considered important. Figure 3 shows very good agreement between simulated and observed water levels. Figure 4 displays observed (kriged) groundwater elevations and those simulated by Run 1 in contour-map form.

The results of the run that was identical to Run 1 except that it did not include recharge at the two internal recharge cells were the same as those of Run 1 other than in the vicinity of the two internal recharge cells. In the vicinity of those cells, simulated groundwater levels more nearly matched observed groundwater levels when recharge at the two interior cells was considered. Thus, for purposes of predicting groundwater levels, the use of recharge at the recharge cells is preferable.

Prediction of Groundwater Levels

Once the model has been validated, it can be used for predicting future groundwater levels. The simulation of future groundwater levels in interior cells requires *a priori* prediction of groundwater elevations in the constant-head cells during the simulation period. In simulating future groundwater levels, two different sets of constant-head elevations and two different pumping strategies were considered.

In the first set of constant-head elevations tested, we assumed that constant-head elevations will be the same as the average elevations used during the validation period. This set of values is referred to as “average constant-head cell elevations.” In the second set of constant-head elevations tested, we assumed there will be a significant change in elevation in some constant-head cells, especially along the northwestern

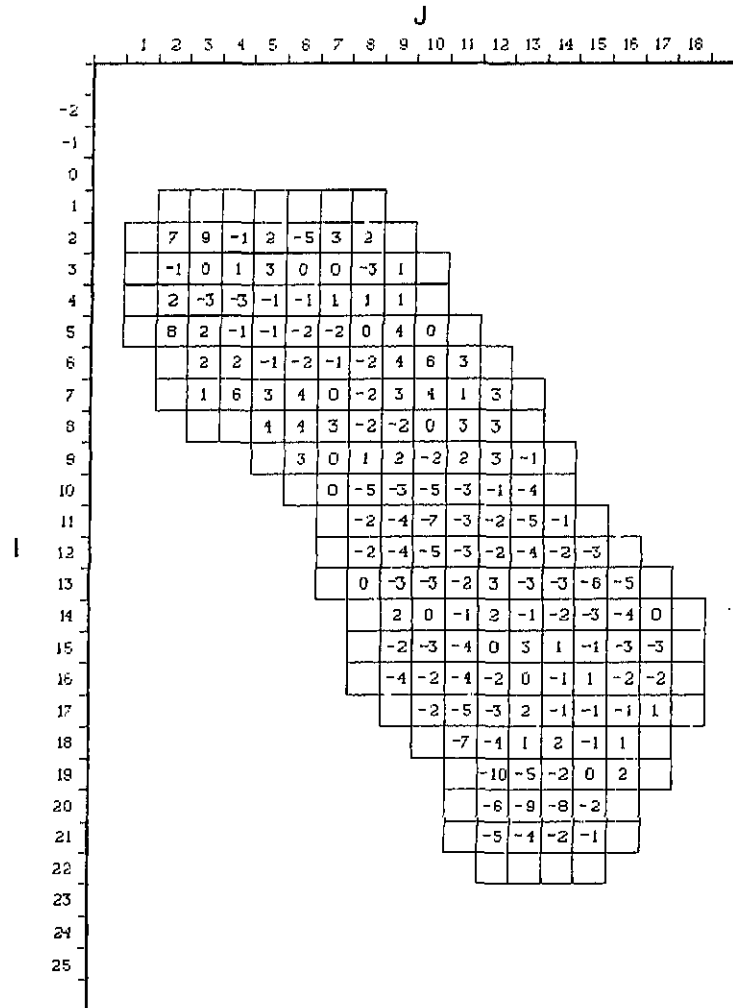


Figure 3. Differences (in feet) between simulated and observed 1982 groundwater levels after 10 years of simulation, Run 1.

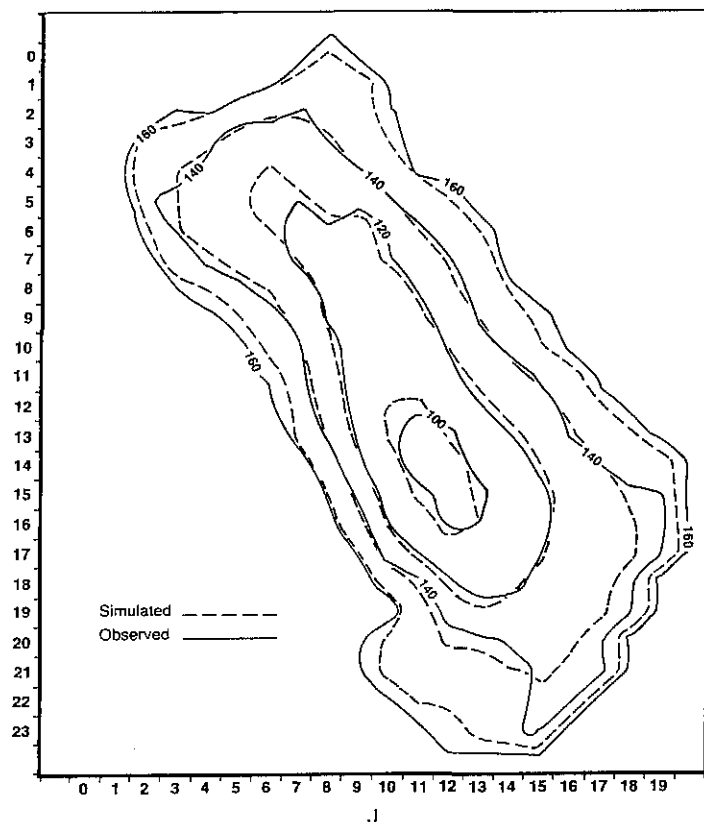


Figure 4. Simulated and observed 1982 groundwater elevations (feet above sea level), Run 1.

boundary. Intensive pumping for aquaculture and increasing irrigation to the north of the study area make this a real possibility. Linear regression analysis was performed on observed water levels (1972–83) in each constant-head cell. An equation was then developed for each constant-head cell to allow prediction of water levels as a function of time. For cells in which we noted an obvious trend, these equations were used to predict water levels in 1986 and 1991. For cells without a trend, average values were most appropriate. This combination is referred to as “projected constant-head cell elevations.” Simulations based on projected constant-head cell elevations used the 1986 values for the first five years and the 1991 values for the last five years of prediction.

In the first of the pumping plans, we assumed that pumping would continue at the current rate. For this, we assumed that 1982 municipal usage and aquacultural and crop acreages would be maintained through 1992. For crops, the average annual water need per acre, based on 15 years of data (Peralta and Dutram, 1984), was used for each year. The same percentages of the total municipal, aquacultural and irrigation water needs were withdrawn from the Quaternary aquifer as were used in the validation run. All the assumptions of Run 1 were used.

In the second pumping plan, we assumed that surface water from the Arkansas River will be available in some cells of the Bayou Meto Watershed by the spring of 1988 (Figure 2). Pumping for the first five years of this plan was the same as that of the first plan. From 1988 on, however, no groundwater was pumped from cells where diverted surface water was available.

Both pumping plans were tested with each of the sets of constant-head cell elevations, giving a total of four scenarios. Scenarios A and B combine the current-use pumping plan with the projected and the average constant-head cell elevations, respectively, and Scenarios C and D combine the surface-water-available pumping plan with the projected and the average constant-head cell elevations, respectively. Scenario A is the most pessimistic and Scenario D is the most optimistic of the four futures.

RESULTS

Future Groundwater Storage and Groundwater Levels

Table 2 presents the predicted net pumping, groundwater storage and reduction in storage after 10 years for each of the scenarios. The values for net pumping take into account recharge in the two interior recharge cells. From these pumping values we can determine that total 10-year pumping for Scenarios A and B, which are based on 1982 acreages and average climatic conditions and which do not allow for diversion of surface water, is 10 percent greater than that observed between 1972 and 1982. However, for Scenarios C and D, for which surface water is available from 1988 to 1993, there is a reduction of 5 percent from the groundwater withdrawals between 1972 and 1982. The difference in total pumping between the first two and the last two scenarios is 381,000 acre-feet (470 million cubic meters), which is 13.5 percent of the pumping for Scenario A or B. If surface water were available for the

Table 2. Trends in volume of groundwater stored in the Grand Prairie Quaternary aquifer.

| Scenario | Scenario Specifications ¹ | | | Groundwater Storage | | Reduction in Storage | |
|----------|--------------------------------------|---|-----------------------------------|---------------------------------|--------|-----------------------|------------------------|
| | Diverted surface water? | Type of constant-head cell elevation used | 10 years Net Pumping ² | Initial | Final | as a % of net pumping | as a % of 1972 storage |
| | | | | ----- 1000's of acre-feet ----- | | | |
| 1972-82 | no | average | 2586 | 18,540 | 17,443 | 42 | 6 |
| A | no | projected | 2832 | 17,255 | 15,676 | 56 | 9 |
| B | no | average | 2832 | 17,255 | 16,094 | 41 | 6 |
| C | yes | projected | 2451 | 17,255 | 15,948 | 53 | 7 |
| D | yes | average | 2451 | 17,255 | 16,358 | 37 | 5 |

¹See pages 10 and 13 for details of the four scenarios.

²These values take into account recharge in the two interior recharge cells.

entire 10-year period, the reduction in net pumping could be estimated at 2 times the 13.5 percent reduction, or 27 percent of 1982 pumping.

Table 2 also shows the percentage of the volume of water pumped during the specified 10-year period that is not replaced by recharge (i.e., the percentage of water that is "mined"). During the observation period (1972-81) the mining percentage was 42 percent. Scenarios A and C, for which boundary conditions are worse than those for Scenarios B and D, result in the higher predicted mining percentages: 56 percent and 53 percent, respectively. Table 2 also shows that for Scenarios A-D, reductions in the volume of water stored in the aquifer would range between 5 and 9 percent.

Figures 5-8 show the projected declines in groundwater elevations between 1983 and 1993 for Scenarios A-D, respectively. Changes greater than 10 feet (3.0 m) are considered significant. In all four figures, declines of at least 20 feet (6.1 m) in the north-central part of the study area are indicated.

Predicted Cost Increases of Raising Groundwater

A significant portion of the cost of procuring and using groundwater is the energy cost associated with raising the water to the ground surface. This energy cost is a function of the depth to water, of the saturated thickness, of well characteristics and of the design and operating pressure of the irrigation system delivering the pumped water. All of these factors influence the total dynamic head (TDH), which is the "effective" distance the groundwater must be raised. A procedure for estimating the energy cost of raising a unit volume of groundwater to the ground surface as a function of TDH is outlined in the Appendix. In the development of the procedure, a 500-gpm (1893-lpm), 15-inch-diameter (38-cm-diameter) well casing and 10-inch (25-cm) discharge diameter were used as the standard. An electric pump/motor system efficiency of 0.5 was assumed, and a current pricing schedule from Arkansas Power

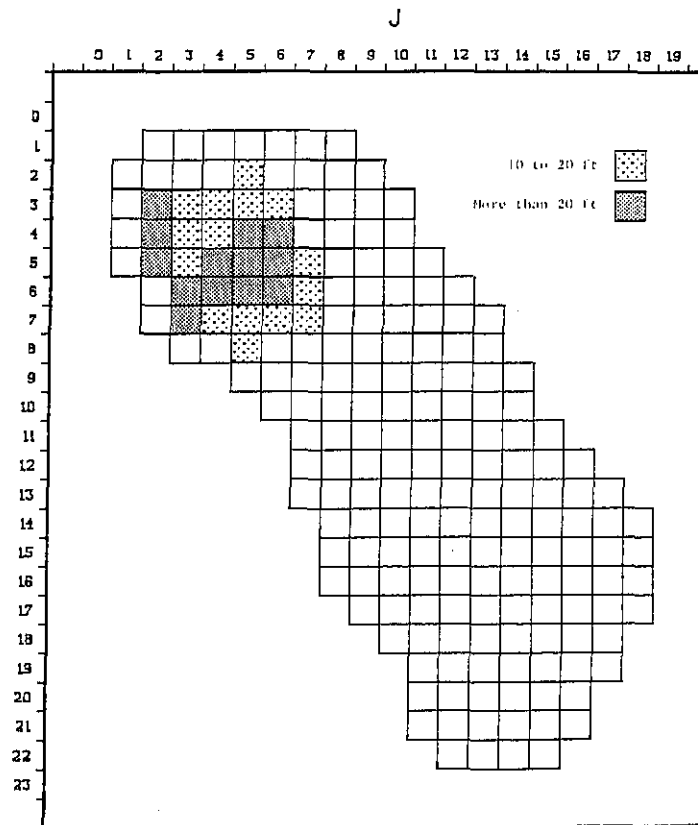


Figure 5. Predicted decreases in groundwater levels (in feet) from 1983 to 1993, Scenario A. (Only decreases of 10 or more feet are shown.)

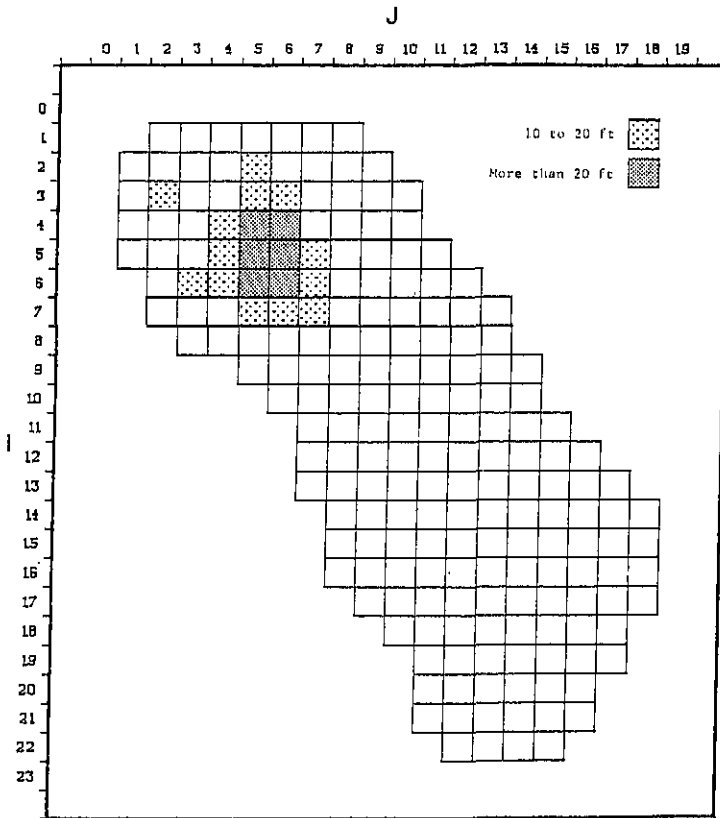


Figure 6. Predicted decreases in groundwater levels (in feet) from 1983 to 1993, Scenario B. (Only decreases of 10 or more feet are shown.)

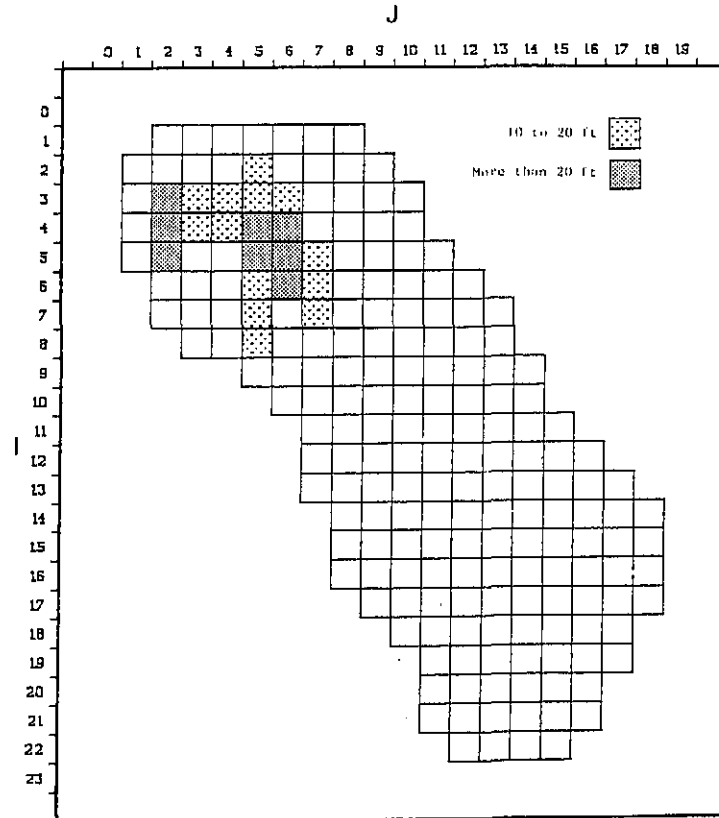


Figure 7. Predicted decreases in groundwater levels (in feet) from 1983 to 1993, Scenario C. (Only decreases of 10 or more feet are shown.)

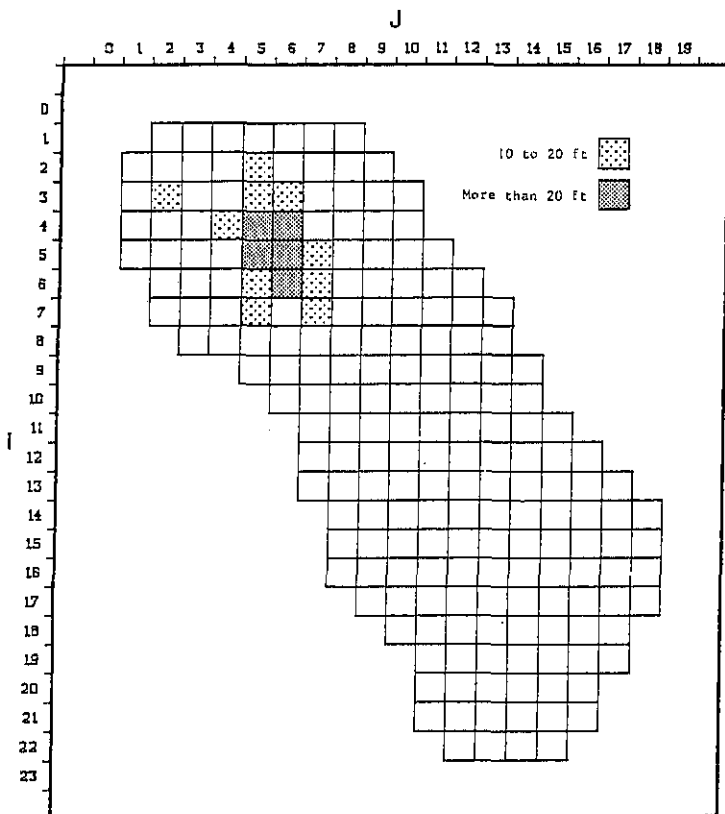


Figure 8. Predicted decreases in groundwater levels (in feet) from 1983 to 1993, Scenario D. (Only decreases of 10 or more feet are shown.)

& Light Company was used. A discharge of 500 gpm was used because this is generally considered to be the minimum desirable discharge rate to support 50 acres (20.3 ha) of rice in the Grand Prairie.

The procedure was used to estimate 1983 and 1993 energy costs of raising groundwater in the Grand Prairie. For the sake of general applicability, no friction losses due to pipe bends aboveground were assigned, nor was an irrigation-system operating pressure specified. Based on 1983 groundwater elevations, cost estimates of raising 1 acre-foot (1233 m³) of groundwater to the surface in each cell varied from \$1 to \$18 per acre-foot (\$0.80 to \$14.60 per 1000 m³) (Figure 9).

Because groundwater levels will decline by 1993, the cost of raising groundwater to the ground surface will increase. In our analysis we assumed that the price for energy will remain the same. Figures 10–13 show how much higher the energy costs for raising 1 acre-foot of groundwater to the surface will be in 1993 than they were in 1983. Because an acre of rice requires 2 acre-feet (2467 m³) of irrigation water per year, the values in Figures 10–13 can be multiplied by 2 to estimate the increase in energy costs that will be caused purely by the lower groundwater levels anticipated in 1993. (This assumes that the price of energy will remain stable.) The maximum expected increase of \$8 per acre (2 acre-feet × \$4/acre-foot) for rice (\$19.80/ha) is small compared with the total reported production costs of \$404 per acre (\$996/ha) for rice (Smith et al., 1983). It does, however, represent a 12 percent decrease in net returns above specified costs.

The current soybean crop budget for the Grand Prairie (Stuart et al., 1983) lists an annual total soybean production cost of \$307 per acre (\$758/ha) and reflects an annual loss for soybean producers. Assuming a 0.58-foot irrigation water need for soybeans, the increase in cost of producing soybeans due to declining groundwater levels could be \$2.32 per acre (0.58 acre-feet/acre × \$4/acre-foot). This increase is small compared with total costs, but it represents a 4 percent increase in loss.

Determination of Desirable Aquifer Saturated Thickness

Because increases in costs of production of rice and soybeans due to declining groundwater levels will not be large when compared with the total cost of production, such cost increases alone will probably not provide much motivation to water users to seek alternative sources of water supply. Decreases in saturated thicknesses, however, could strongly motivate water users to seek alternatives to groundwater. When the drawdown in the vicinity of a pumping well exceeds about two-thirds of the saturated thickness for which the well was designed, the efficiency of raising the water decreases and the cost of raising a unit volume begins to increase dramatically (Universal Oil Products Company—Johnson Division, 1966).

The depth of the drawdown is related to the aquifer material, the well design and the pumping rate. Figure 14 shows the variation in drawdown that would occur in a hypothetical 500-gpm well being pumped to meet the irrigation needs of 50 acres of rice during 1973, which had a climatically typical growing season in the Grand Prairie. The initial saturated thickness for this well was 24.2 feet (7.4 m). The

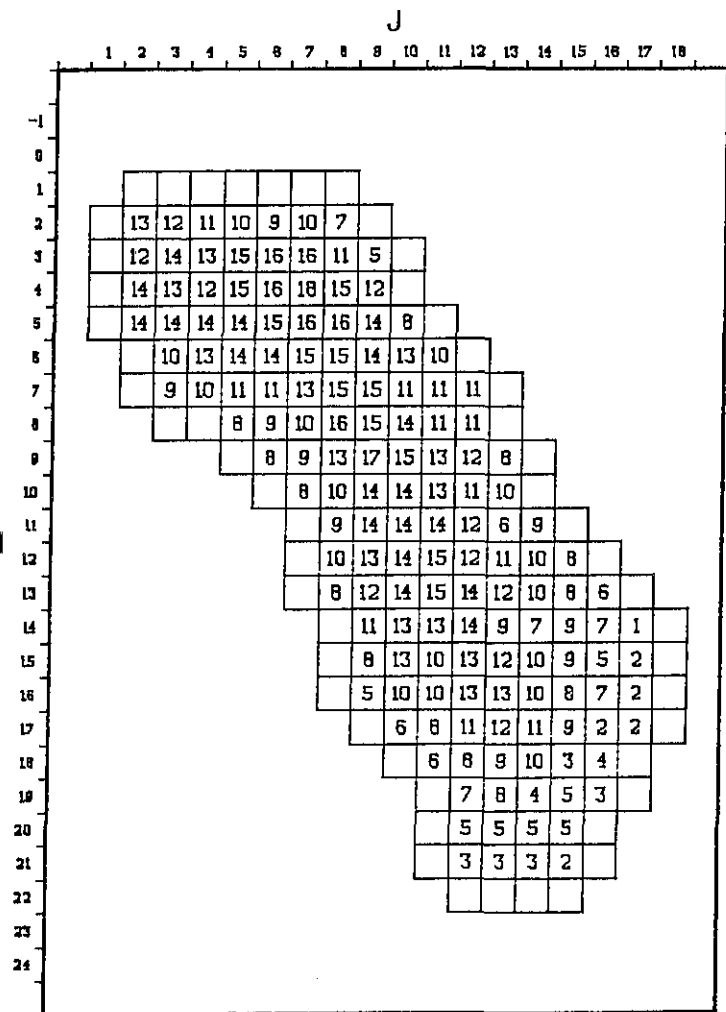


Figure 9. Energy cost (in dollars) of raising 1 acre-foot of groundwater to the ground surface (based on 1983 groundwater elevations).

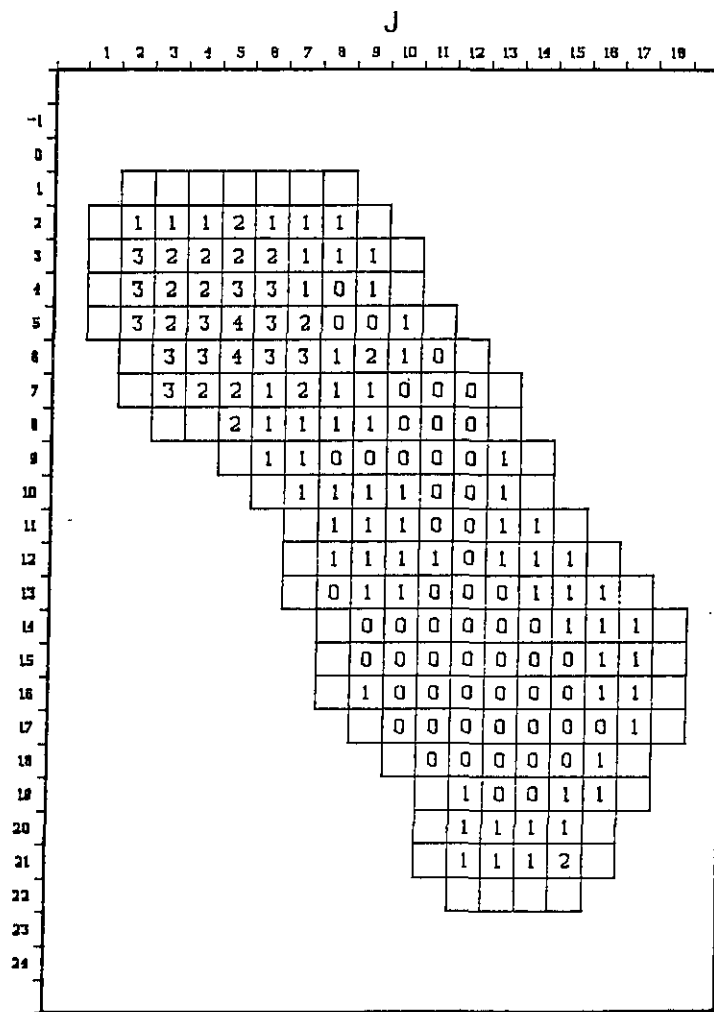


Figure 10. Increase in energy cost (in dollars) of raising 1 acre-foot of groundwater to the ground surface by 1993, Scenario A.

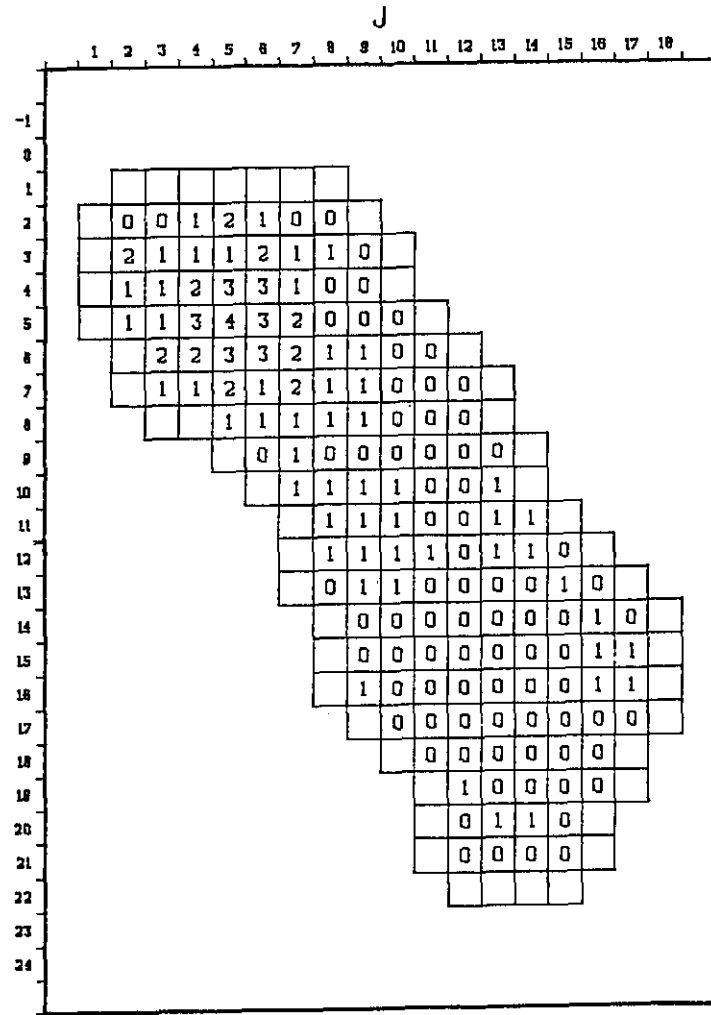


Figure 11. Increase in energy cost (in dollars) of raising 1 acre-foot of groundwater to the ground surface by 1993, Scenario B.

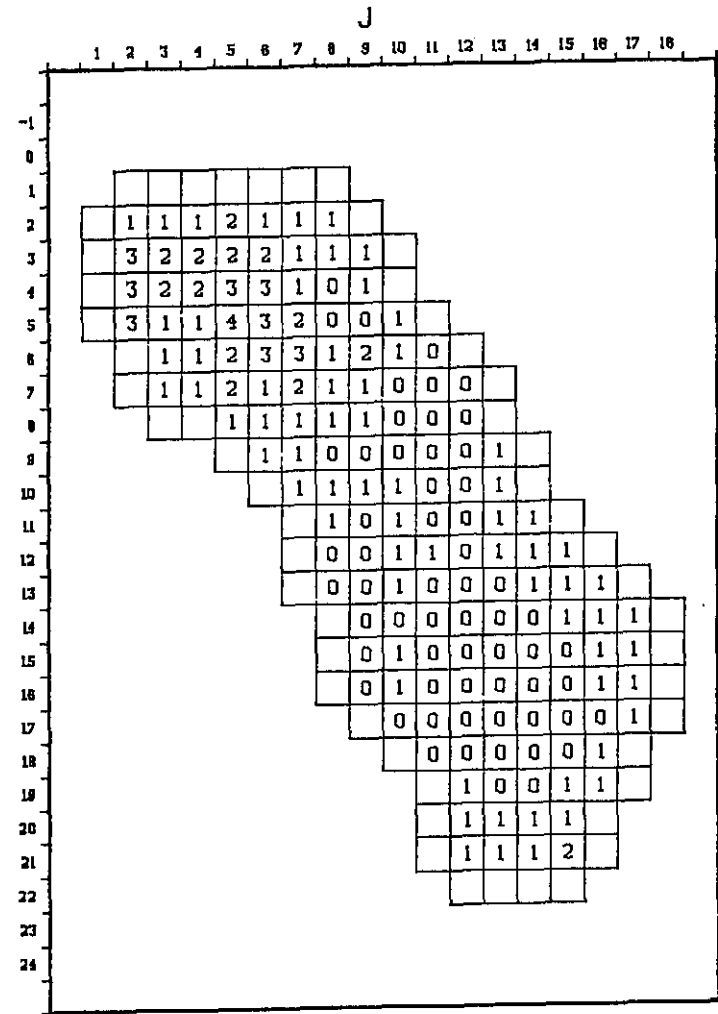


Figure 12. Increase in energy cost (in dollars) of raising 1 acre-foot of groundwater to the ground surface by 1993, Scenario C.

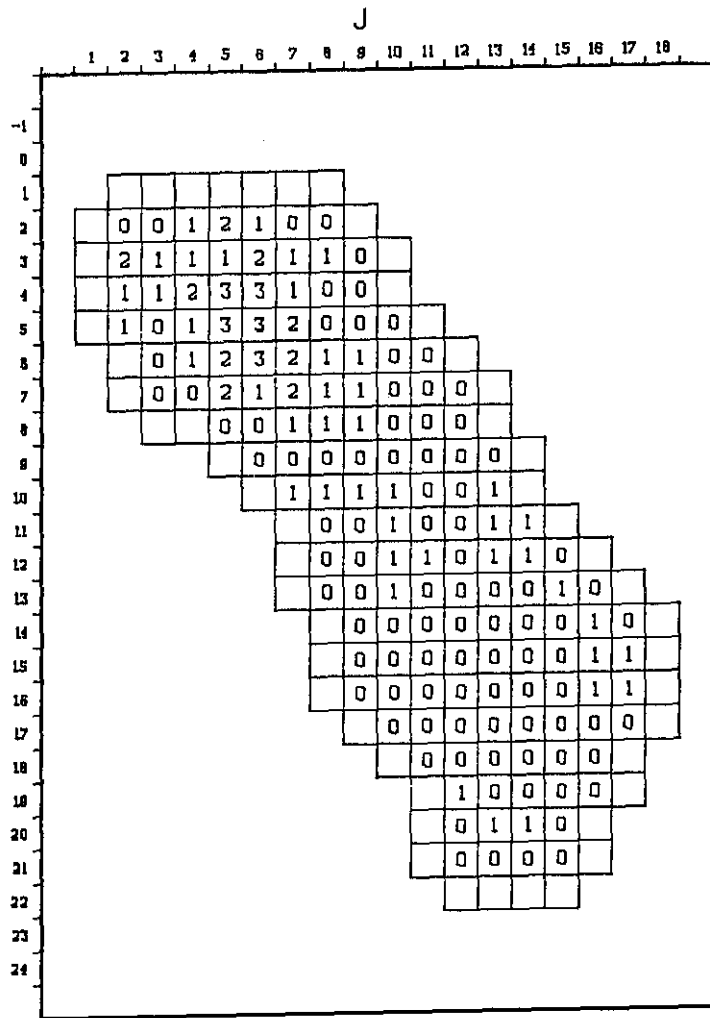


Figure 13. Increase in energy cost (in dollars) of raising 1 acre-foot of groundwater to the ground surface by 1993, Scenario D.

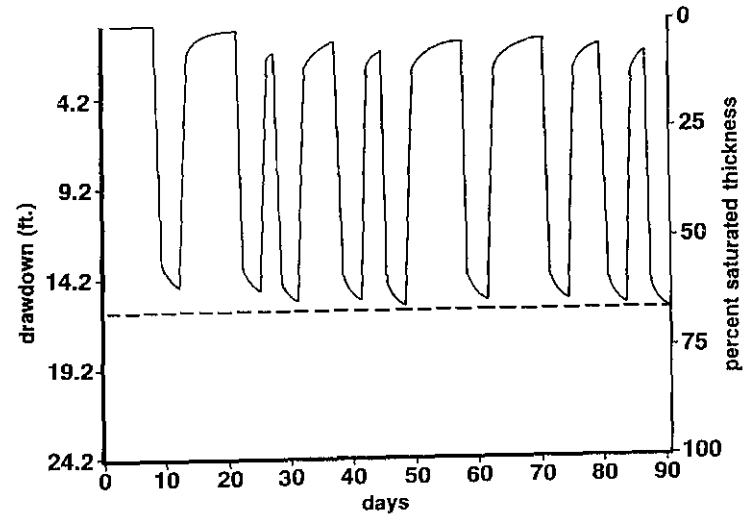


Figure 14. Variation of drawdown with time for a hypothetical 500-gpm well pumping to meet the irrigation water needs of 50 acres of rice during the summer of 1973.

maximum simulated drawdown is 16 feet (4.9 m). If the initial saturated thickness were less than 24.2 feet, the drawdown in the well would be even greater and would exceed two-thirds of the initial saturated thickness. In that case the efficiency of the pump would be less than previously estimated and the energy cost per unit volume would increase. Thus, for a single 500-gpm well not affected by the drawdown of other wells, the minimum desirable saturated thickness for 1973 climatic conditions would be about 24 feet. It should be noted that the simulated drawdowns in Figure 14 were developed assuming an initially horizontal water table. The existence of a steep gradient may change the desirable saturated thickness because of the altered rate of inflow into the cone of depression.

The most severe drought in recent years occurred during the 1980 growing season. Climatic conditions and the resulting irrigation needs from 1980 were used in a simulation similar to that described above. The minimum desirable saturated thickness for a well not affected by other wells during 1980 climatic conditions would be 25 feet (7.6 m). Once again, an initially horizontal water table was assumed. It should be noted that the 1980 climatic conditions required a pumping schedule similar to the four-days-on, two-days-off schedule described in the Appendix and that both sets of simulations indicated that 25 feet is about the minimum desirable saturated thickness for 500-gpm wells supporting 50 acres of rice in the Grand Prairie. If a

steep hydraulic gradient exists in the vicinity of the well, a saturated thickness of less than 25 feet may be acceptable.

Cells for which estimated saturated thicknesses are less than 25 feet in 1983 are indicated in Figure 15. In interpreting these results, the following should be considered. The saturated thickness in the area of concern is the distance between the water table and the bottom of the aquifer. The water levels are interpolated from measurements obtained at randomly spaced observation wells. The standard error of the estimate of the interpolated values is generally ± 4 to ± 11 feet (± 1.2 to ± 3.4 m). Also, the elevation of the aquifer bottom is not known with complete certainty, having been approximated from estimates of the ground-surface elevation and from well-construction records. The elevation of the ground surface for a particular location is generally estimated from topographic maps having a contour interval of 5 feet (1.5 m). Thus, ground-surface elevations are known within about 5 feet. In addition, estimates of the distance between the ground surface and the bottom of the aquifer are dependent on records from randomly spaced wells. Even where an accurate well-construction record exists, the bottom of the aquifer is not always clearly defined. In some locations, interspersed layers of sand and clay make estimation of the elevation of the bottom of the Quaternary aquifer difficult. As a result of these factors, the estimate of saturated thickness for the center of a cell is accurate within about 20 feet (6.1 m). In addition, one should note that a difference of 30 feet (9.2 m) or more in the elevation of the aquifer bottom can easily occur within a cell. Thus, the values shown are valid averages but may not reflect the exact situation for a particular well within a cell.

Predicted Saturated Thicknesses

In 1983 there were six cells with a saturated thickness of less than 25 feet (Figure 15). These are cells in which water users may find it difficult to obtain 500 gpm from a well throughout a growing season. Most of the cells with insufficient saturated thickness are in the north-central part of the study area.

Figures 16–19 show the cells that have a predicted saturated thickness in 1993 of less than 25 feet for Scenarios A–D, respectively. All scenarios are similar in that they show an increasing area of uncertain Quaternary groundwater availability (cells with a saturated thickness of less than 25 feet). There are 19 such cells in Scenario A, 17 in Scenario B, 16 in Scenario C and 15 in Scenario D. (Fifteen cells represent an area of 135 square miles, which is the equivalent of 86,400 acres or 35,000 ha.) In such cells, an alternative source of irrigation water will probably be needed if rice production is to be continued.

SUMMARY AND CONCLUSIONS

Between 1972 and 1982 the volume of groundwater stored in the Quaternary aquifer dropped from 18.5 million to 17.4 million acre-feet (2.28×10^{10} to 2.15×10^{10} m³). This represents a 6 percent decline from the 1972 storage. Predicted

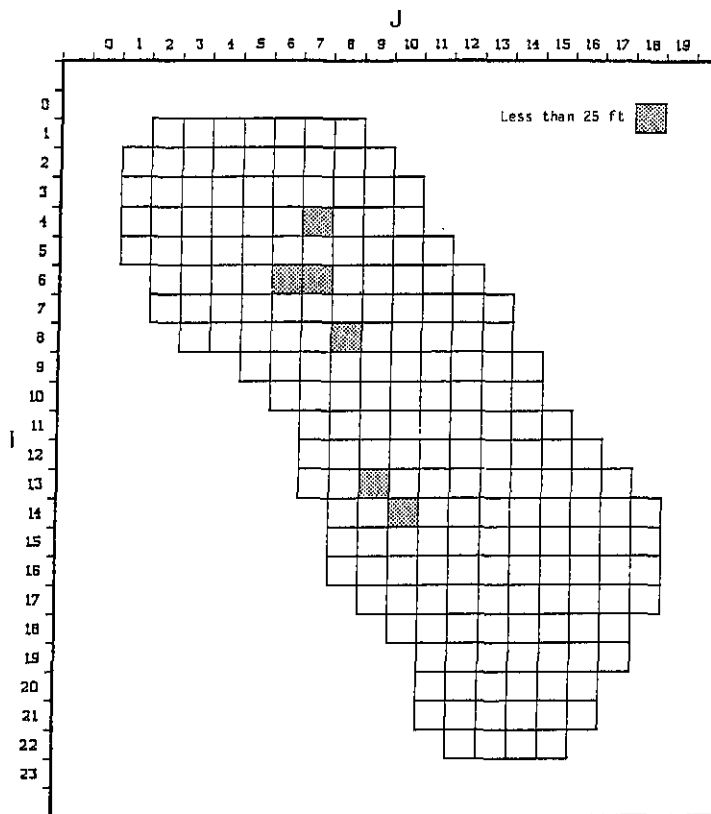


Figure 15. Cells in the Quaternary aquifer that have a saturated thickness of less than 25 feet (shaded cells), 1983.

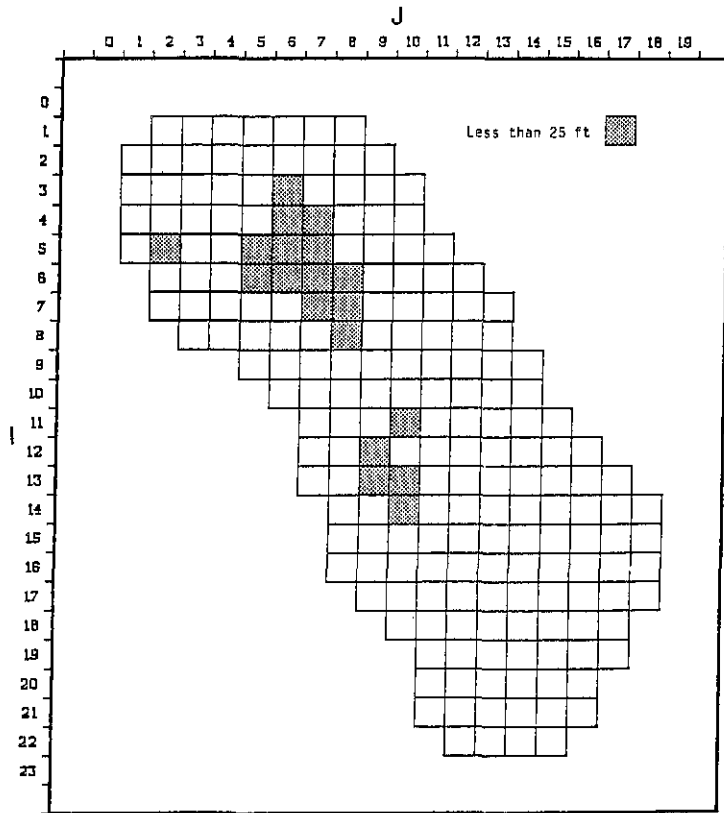


Figure 16. Cells in the Quaternary aquifer that are predicted to have spring, 1993, saturated thicknesses of less than 25 feet (shaded cells), Scenario A.

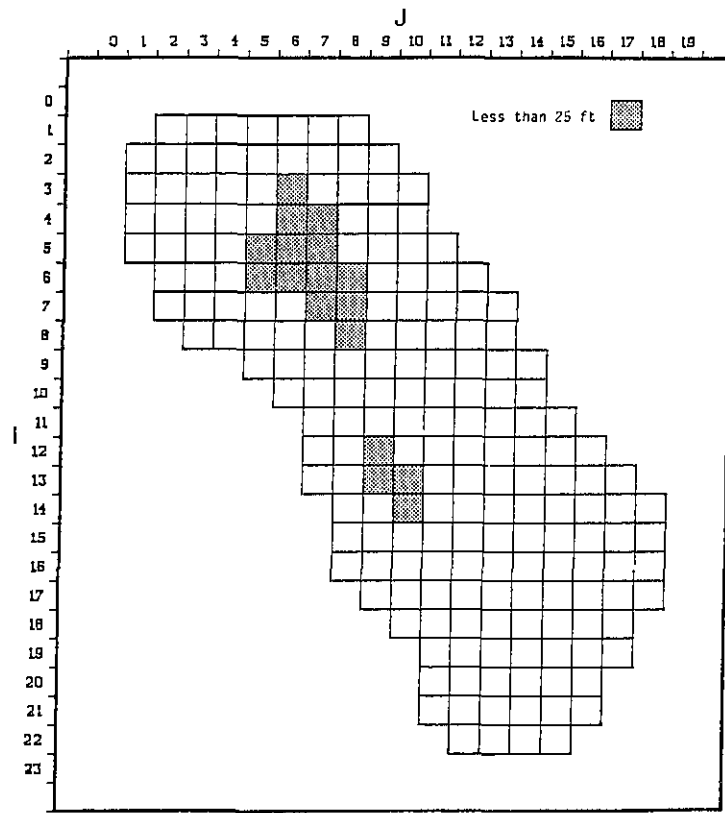


Figure 17. Cells in the Quaternary aquifer that are predicted to have spring, 1993, saturated thicknesses of less than 25 feet (shaded cells), Scenario B.

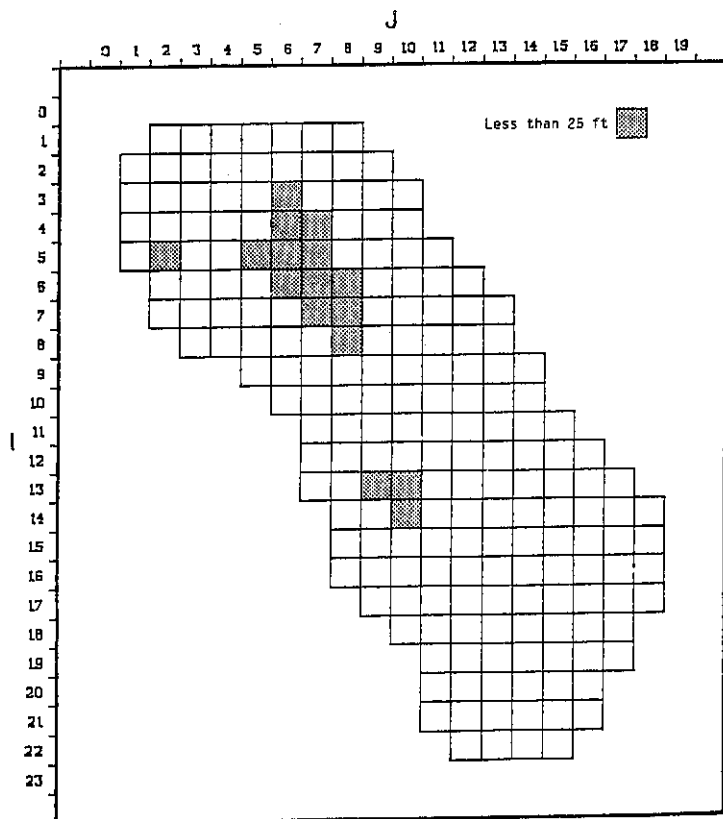


Figure 18. Cells in the Quaternary aquifer that are predicted to have spring, 1993, saturated thicknesses of less than 25 feet (shaded cells), Scenario C.

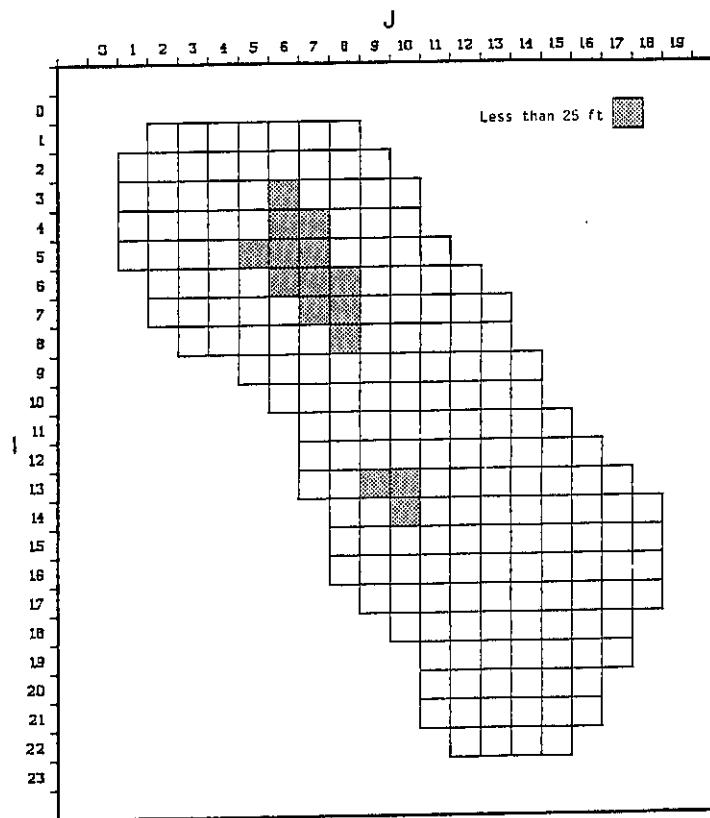


Figure 19. Cells in the Quaternary aquifer that are predicted to have spring, 1993, saturated thicknesses of less than 25 feet (shaded cells), Scenario D.

decreases in storage between 1983 and 1993 range from 5 percent to 9 percent of the 1972 storage volume.

Groundwater levels in the Quaternary aquifer will continue to drop, especially in the north-central part of the Grand Prairie. Declines of up to 28 feet (8.5 m) can be expected by 1993. The decline in the water-table elevation will cause an increase in the cost of raising the water to the ground surface for use. Based on 1983 water levels and current prices from Arkansas Power & Light Company, the cost of energy for pumping groundwater to the ground surface in 1983 ranged from \$1 to \$18 per acre-foot (\$0.80 to \$14.60 per 1000 m³) within the study area. Assuming that energy prices remain the same, the increase in the cost of energy for pumping could reach \$4 per acre-foot (\$3.20 per 1000 m³). Because rice on the average requires 2 feet (61 cm) of irrigation water per season, the cost of producing 1 acre (0.405 ha) of rice could increase by \$8 due to declining water levels. This is not a large percentage of the total production costs, but it does represent a 12 percent reduction in profits. For soybean producers in the Grand Prairie, who are already operating at annual losses according to current soybean crop budgets, the maximum increase in pumping costs of \$4 per acre-foot due to declining water levels represents a 4 percent increase in losses for producers.

In 1983 there were approximately 54 square miles (34,560 acres or 14,000 ha) in which the ability to obtain a 500-gpm yield from the Quaternary aquifer throughout the growing season was doubtful. By 1993 that area will at least increase in size to 135 square miles (86,400 acres or 35,000 ha). It may be as large as 171 square miles (109,440 acres or 44,300 ha).

One observation that can be made is that the increase in pumping costs due to declining groundwater levels will not be prohibitive. Thus, the increasing costs do not provide a very strong signal to water users, who, as a result, may continue to pump until their portion of the aquifer has inadequate saturated thicknesses and Quaternary groundwater is no longer available to them. In such a situation, if there is no adequate available alternative source of water, rice production may eventually be replaced by production of crops that require less water.

LITERATURE CITED

1. Arkansas Department of Local Services. 1977a. Arkansas County. Arkansas Department of Local Services, Little Rock, AR.
2. Arkansas Department of Local Services. 1977b. Lonoke County. Arkansas Department of Local Services, Little Rock, AR.
3. Arkansas Department of Local Services. 1977c. Monroe County. Arkansas Department of Local Services, Little Rock, AR.
4. Arkansas Department of Local Services. 1977d. Prairie County. Arkansas Department of Local Services, Little Rock, AR.
5. Arkansas Soil and Water Conservation Commission. 1976. Arkansas state water plan, Appendix A. Arkansas Soil and Water Conservation Commission, Little Rock, AR.
6. Arkansas Soil and Water Conservation Commission. 1978. Arkansas state water plan, Appendix B. Arkansas Soil and Water Conservation Commission, Little Rock, AR.
7. Broom, M. E. and F. P. Lyford. 1981. Alluvial aquifer of the Cache and St. Francis river basins, northeastern Arkansas. U.S. Geological Survey Open-File Report no. 81-476, USGS, Little Rock, AR.
8. Edds, J. 1981. Ground-water levels in Arkansas, spring 1981. U.S. Geological Survey Open-File Report no. 81-1114, USGS, Little Rock, AR.
9. Engler, K., D. Thompson and R. Kazman. 1945. Groundwater supplies for the rice irrigation in the Grand Prairie region, Arkansas. Ark. Agr. Exp. Sta. Bull. no. 457.
10. Griffin, C. L. 1972. Groundwater-surface water integration study in the Grand Prairie of Arkansas. Arkansas Water Resources Research Center Publ. no. 11, Univ. of Arkansas, Fayetteville, AR.
11. Halberg, H. N. 1977. Water use in Arkansas. 1975. Water Resources Summary Number 9, Arkansas Geological Commission, Little Rock, AR.
12. Harper, J. K. 1983. An economic analysis of on-farm water management strategies to reduce groundwater demand in the Grand Prairie region, Arkansas. Unpublished Master's thesis, Department of Agricultural Economics and Rural Sociology, Univ. of Arkansas, Fayetteville, AR.
13. Holland, T. W. and G. Ludwig. 1981. Use of water in Arkansas, 1980. Water Resources Summary Number 14, Arkansas Geological Commission, Little Rock, AR.
14. Jensen, M. E. (ed.). 1981. Design and operation of farm irrigation systems. American Society of Agricultural Engineers, St. Joseph, MI.
15. Peralta, R. C. and P. Dutram. 1984. Assessment of potential irrigation needs in the Bayou Meto Watershed. Ark. Agr. Exp. Sta. Rep. Series no. 285.
16. Peralta, R. C., R. Arce and T. Skergan. 1983. Evaluation and accessing of data for a water resources simulator. Arkansas Water Resources Research Center Publ. no. 91. Univ. of Arkansas, Fayetteville, AR.
17. Smith, D. A., C. Farler, R. W. Hale, C. A. Stuart Jr., C. R. Garner, D. Dorland and R. E. Coats Jr. 1983. Arkansas rice budgets, 1983. Univ. of Arkansas Cooperative Extension Service Report MP 206.
18. Sniegocki, R. T. 1964. Hydrogeology of a part of the Grand Prairie region, Arkansas. Geological Survey Water-Supply Paper 1615-B, U.S. Department of the Interior, Washington, DC.
19. Sophocleous, M. 1983. Groundwater observation network design for the Kansas Groundwater Management District, U.S.A. J. Hydrology 61:371-389.
20. Stuart, C. A., Jr., C. Farler, D. A. Smith, C. R. Garner, R. Hale, D. Dorland and R. E. Coats Jr. 1983. Arkansas soybean budgets, 1983. Univ. of Arkansas Cooperative Extension Service Report MP 208.
21. U.S. Department of Agriculture. 1973-82. Agricultural statistics for Arkansas [annual reports covering the years 1972-81]. Ark. Agr. Exp. Sta. Rep. Series no. 211, 216, 221, 228, 237, 241, 246, 253, 262 and 268.
22. Universal Oil Products Company—Johnson Division. 1966. Groundwater and wells. Universal Oil Products Company, St. Paul, MN.
23. Verdin, K. L., H. J. Morel-Seytoux and T. H. Illangasekare. 1981. User's manual for AQUISIM: FORTRAN IV programs for discrete kernels generation and for simulation of an isolated aquifer behavior in two dimensions. HYDROWAR Program, Colorado State Univ., Ft. Collins, CO.

APPENDIX

Estimation of the Energy Cost of Raising 1 Acre-Foot of Groundwater to the Ground Surface

The unit price a utility company charges a user often decreases as the level of use increases. This is the case in the Grand Prairie. For example, the cost of pumping only 1 acre-foot of groundwater during a season is greater than one-onehundredth of the cost of pumping 100 acre-feet. Thus, it is necessary to assume a seasonal pumping volume in order to properly estimate the average cost of lifting an acre-foot of groundwater to the ground surface at a particular location. The following procedure assumes that a representative well provides irrigation water for 50 acres (20.3 ha) of rice and that 100 acre-feet (1.2 million cubic meters) of water is pumped during a single growing season. The well is assumed to have a 15-inch-diameter casing, a 10-inch-diameter discharge and a discharge of 500 gpm (1893 lpm).

Before the cost of lifting groundwater to the ground surface can be calculated, the total dynamic head (*TDH*) must be estimated. The *TDH*, which is the effective distance (in feet) through which groundwater must be raised, is calculated using Equation (1) (Jensen, 1981):

$$TDH = H_p + H_f + H_s + H_w \quad (1)$$

where H_p = the contribution to *TDH* due to the operating pressure of the irrigation system delivering the groundwater to the crops, in feet.

H_f = the friction loss in the pipe calculated by the Hazen-Williams equation, in feet.

H_s = static lift, i.e., the difference in elevation between the ground surface at the well and the water table at the well when the well is not pumping, in feet.

H_w = the average *additional* drawdown (during pumping days) of the groundwater surface at the well casing caused by pumping, in feet.

Since in this study we consider only the costs associated with the hydraulic system between the bottom of the well and the ground surface, H_p is equal to zero feet. H_f is negligible for the lengths of pipe we are considering. H_s is readily calculated for any point for which the elevations of the ground surface and water table are known and can therefore be estimated for the center of each cell.

To estimate H_w , simulations of the drawdowns resulting from pumping a well at 500 gpm for a range of initial saturated thicknesses were performed. An initially horizontal water table was assumed. Alternating periods of four days of pumping followed by two days without pumping were used throughout the irrigation season.

The results are presented in Figure 20¹. The equation that best fits the curve describing the relationship between H_w and initial saturated thickness (*T*) is:

$$H_w = 309.44T^{-0.929} \quad (2)$$

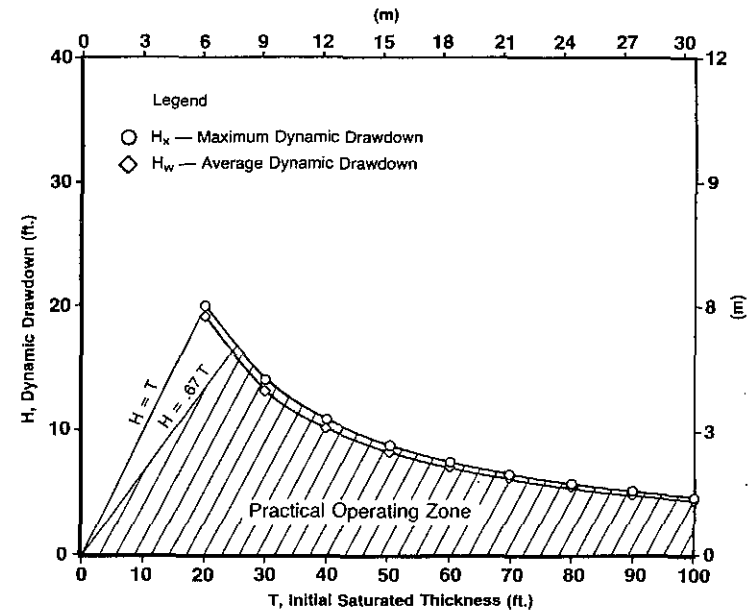


Figure 20. Dynamic well drawdown vs. initial saturated thickness for a 500-gpm well pumping on a seasonal schedule of four days on, two days off.

¹Also shown in Figure 20 is a curve relating *T* and the maximum simulated drawdown, H_{max} , during the pumping season. In general, when drawdown exceeds two-thirds of the initial saturated thickness, pumping-plant efficiency decreases and the cost of raising a unit volume of water begins to increase significantly. Thus, the range of practical drawdowns (shaded area) is bounded to the left by the line at which dynamic drawdown, H , equals two-thirds of the initial saturated thickness, *T*. Note that this line intersects the H_{max} curve at a *T* value of 25 feet (7.6 m), indicating that 25 feet is about the minimum desirable saturated thickness for a single well pumping at this schedule and not experiencing interference with other wells. The line at which H equals *T*, which represents an absolute left-hand bound on the range of feasible situations, is also shown. Its intersection with the H_{max} curve indicates that maximum drawdown will reach the bottom of the aquifer if the initial saturated thickness is 20 feet (6.1 m). Thus, 20 feet represents a lower limit on acceptable initial saturated thickness. It must be noted that this value was created assuming an initially horizontal water table. A steeply sloping regional water table and the resulting recharge to a cone of depression could reduce the necessary initial saturated thickness. It is also important to realize that the drawdown at a 1000-gpm well is greater than that from a 500-gpm well.

Once TDH is known, the power P required to raise water to the surface can be estimated from the following equation (Jensen, 1981):

$$P = Q(TDH) \div kc \quad (3)$$

where P = necessary power, in horsepower.

Q = well discharge, in gpm.

k = 3960 gpm-ft/hp.

c = system efficiency, which is equal to the product of the pump and motor efficiencies.

In our study we assumed that Q was 500 gpm and c was 0.5. Therefore, Equation (3) becomes:

$$P = 0.25TDH. \quad (4)$$

It takes 1098.2 hours to pump 100 acre-feet at 500 gpm. The energy required to lift this amount is (1098.2 hours)(0.25 hp/ft)(TDH). After converting this to kilowatt-hours, we have:

$$E_1 = 204.73TDH \quad (5)$$

where E_1 is the total energy required to raise 100 acre-feet of water, in kilowatt-hours.

We use Equations (1) and (2) to estimate TDH for a representative well supporting 50 acres of rice at the center of any cell in the Grand Prairie. Equation (5) is used to estimate the total energy required for this well during a growing season. Seasonal energy cost, C , for pumping can now be calculated. A recent rate schedule from Arkansas Power & Light Company shows that a higher rate is charged for the first E_1 kilowatt-hours of energy used than for the remaining amount of energy ($E_1 - E_1$) used:

$$C = r_1E_1 + r_2(E_1 - E_1) \quad (6)$$

where r_1 = rate of charge for the first E_1 kilowatt-hours of energy used and

r_2 = rate of charge for the amount of energy used in excess of E_1 .

According to the rate schedule, r_1 is equal to \$0.08241/kwh, r_2 is equal to \$0.06027/kwh, and E_1 is equal to (268 kwh/kw load)(0.7457 kw load/hp)(P). Substituting the right-hand side of Equation (4) for P in the expression for E_1 gives:

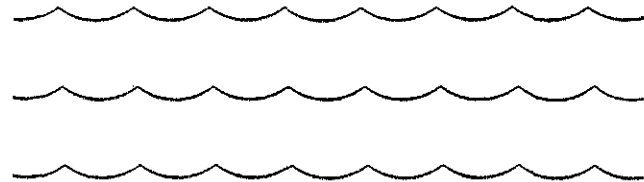
$$E_1 = 49.96TDH. \quad (7)$$

The values for r_1 and r_2 and the expressions for E_1 and E_1 from Equations (7) and (5) can now be substituted into Equation (6) to obtain an expression relating TDH to C , the cost of raising 100 acre-feet of groundwater from the aquifer to the ground surface. Dividing this expression by 100 to obtain the cost of raising 1 acre-foot, C_1 , gives:

$$C_1 = 0.1345TDH. \quad (8)$$

Thus, if the total dynamic head in a cell is 100 feet, the energy cost of raising groundwater to the surface is \$13.45 per acre-foot.

RL 37



*Future Quaternary Groundwater
Accessibility in the Grand Prairie — 1993*

Richard C. Peralta, Amin Yazdanian, Paul J. Killian and Robert N. Shulstad