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DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
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AN APPRAISAL OF PUMPING EFFECTS ON THE EDGELEY AQUIFER, LA MOURE COUNTY, NORTH DAKOTA, AS DETERMINED BY A DIGITAL MODEL

Open-File Report 79-748

Prepared in cooperation with the
North Dakota State Water Commission

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By M. R. Burkart

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ABSTRACT

A finite-difference digital model simulated hydrologic conditions in the Edgeley aquifer, which is an unconfined glacial-drift aquifer. The calibrated model supported the hypothesis that under natural steady-state conditions, recharge is from precipitation and discharge is through evapotranspiration. This hypothesis was further supported by comparing simulated water levels to observed water levels collected during a 3-year period of irrigation withdrawal.

Predictions of the effects of continued withdrawal of currently allocated water were made. One prediction using recharge equal to 25 percent of the average annual precipitation showed that an equilibrium between pumping and recharge would be established within 10 years and water levels would be 2 to 4 feet below 1977 levels. A second prediction included a 2-year drought of one-half the average recharge from precipitation. This prediction also showed equilibrium within 10 years, but water levels would be 3 to 5 feet below 1977 levels. Predictions using additional withdrawals based on allocation requests were indeterminate.

INTRODUCTION

The Edgeley aquifer is the principal source of water for irrigation in the Edgeley area. Plans and requests were pending for the Edgeley municipal supply as well as additional irrigation development. Therefore, a study to evaluate the effects of present and long-term withdrawal was requested by the North Dakota State Water Commission in 1977.

The aquifer is in southwestern LaMoure County, southeastern North Dakota (fig. 1), north of the city of Edgeley (population 888; U.S. Bureau of the Census, 1971).

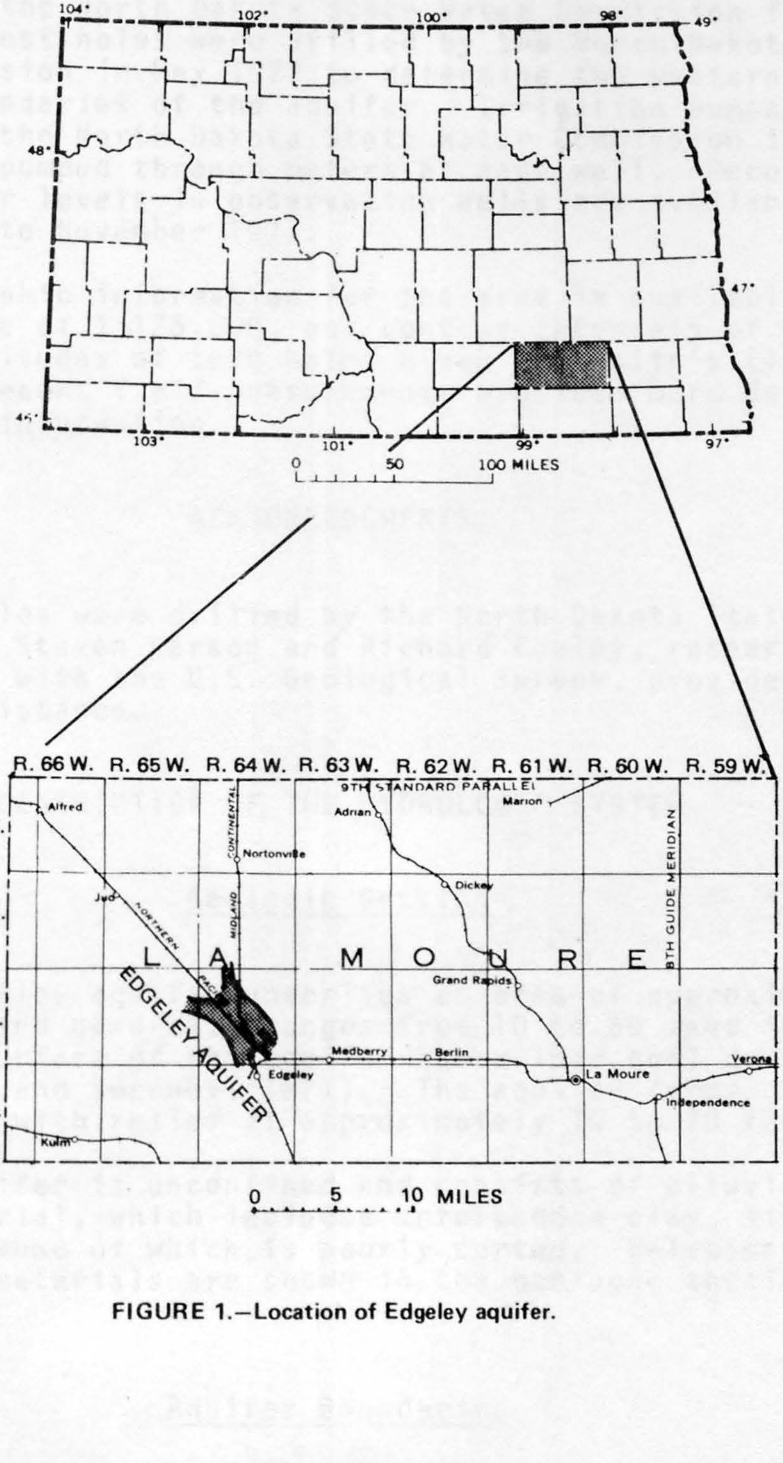

FIGURE 1.—Location of Edgeley aquifer.

The geologic and hydrologic information for initial simulation attempts was adapted from Naplin (1976), Schmid (1973), and the North Dakota State Water Commission files. Additional test holes were drilled by the North Dakota State Water Commission in May 1977 to determine the western and northern boundaries of the aquifer. Irrigation pumpage data provided by the North Dakota State Water Commission include total water pumped through meters at each well. Records of monthly water levels in observation wells are available from August 1973 to November 1977.

Topographic information for the area is available at a maximum scale of 1:125,000, and contour intervals of 20 feet. However, altitudes of test holes given in Naplin's (1976) report and recent field measurements provided more detailed topographic information.

ACKNOWLEDGMENTS

Test holes were drilled by the North Dakota State Water Commission. Steven Larson and Richard Cooley, research hydrologists with the U.S. Geological Survey, provided programming assistance.

DESCRIPTION OF THE HYDROLOGIC SYSTEM

Geologic Setting

The Edgeley aquifer underlies an area of approximately 3,600 acres and generally ranges from 10 to 60 feet in thickness. The surface of the aquifer has a loam soil developed on it (Thompson and Sweeney, 1971). The aquifer forms a topographic high with relief of approximately 10 to 20 feet.

The aquifer is unconfined and consists of alluvial and outwash material, which includes interbedded clay, silt, sand, and gravel, some of which is poorly sorted. Relationships among these materials are shown in the geologic sections in figure 2.

Aquifer Boundaries

The lateral boundaries of the aquifer are of two basic types; (1) an impermeable boundary of till (fig. 2), and (2) a permeable boundary of thin alluvial sand and gravel in narrow channels extending beyond the limits of the study area.

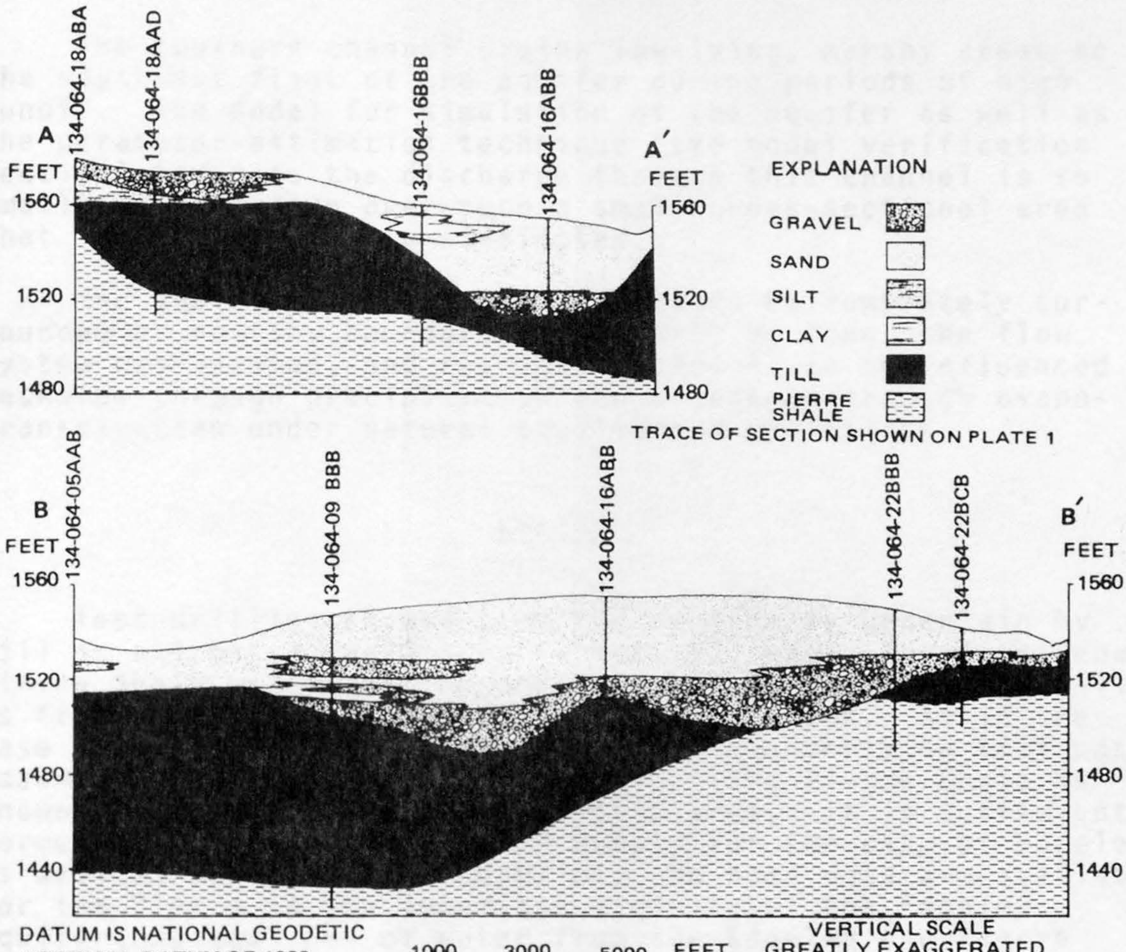

FIGURE 2.—Geologic sections through Edgeley aquifer (modified from Naplin, 1976).

The channels extending west, north, and south of the aquifer (pl. 1, in pocket) were treated alternately as constant-head and constant-flux boundaries during early simulations of natural steady-state conditions. However, test drilling for this study showed that the channel material in the west and north was less than 10 feet thick. The material was dry except during periods of high precipitation and(or) snowmelt.

The southern channel drains low-lying, marshy areas on the southwest flank of the aquifer during periods of high runoff. The model for simulation of the aquifer as well as the parameter-estimation technique (see model verification section) indicate the discharge through this channel is so small and is active over such a small cross-sectional area that its effects can be eliminated.

The aquifer is therefore assumed to be completely surrounded by no-flow boundaries. As will be seen, the flow system was assumed, and reasonably proved, to be influenced by recharge through precipitation and discharge through evapotranspiration under natural equilibrium conditions.

Leakage

Test drilling showed that the aquifer is underlain by till in all but a small area in sec. 22, where the Cretaceous Pierre Shale underlies the aquifer. Where present, the till is from a few feet to more than 100 feet thick. As in the case of the lateral till boundaries, the underlying till was assumed to be relatively impermeable. The Pierre Shale is known to be highly fractured in this area. It is sufficiently permeable to provide the water supply for the city of Edgeley as well as numerous farm supplies. No head data are available for the Pierre in the immediate vicinity of the Edgeley aquifer, so analyses of water from the Edgeley and Pierre aquifers (Armstrong, 1978) were compared to determine if any hydraulic connection exists.

The Piper diagram in figure 3 shows distinct differences between water from the Pierre and Edgeley aquifers with one exception. One Edgeley sample (number 8, fig. 3) is in the same sodium field as the Pierre samples. From the Piper diagram it can be interpreted that this sample is not affected by leakage from the Pierre, as Pierre water has more chloride and sulfate and sample 8 is clearly in the bicarbonate field with other Edgeley samples. Also, because sample 8 was taken from a well where one of the thickest sections of till separates the Edgeley aquifer from the Pierre Shale, it does not appear to be related to leakage from the Pierre aquifer.

No.	Well number	Dissolved solids (mg/L)
	Pierre aquifer	
1	129-065-35ADC	8,630
2	132-065-36ABB	2,740
3	133-064-03 [a/]	1,470
4	133-064-32CAA	3,380
5	133-066-03DAC	1,680
6	134-064-35BBC	1,400
	Edgeley aquifer	
7	134-064-05AAB	333
8	134-064-09BAB	823
9	134-064-09BBB	367
10	134-064-09CAC2	358
11	134-064-15CBB5	308
12	134-064-16ABB1	419
13	134-064-16DAA2	314
14	134-064-16DAD	331
15	134-064-22BCB	945

a/ Composite sample from several Pierre wells used by the city of Edgeley.

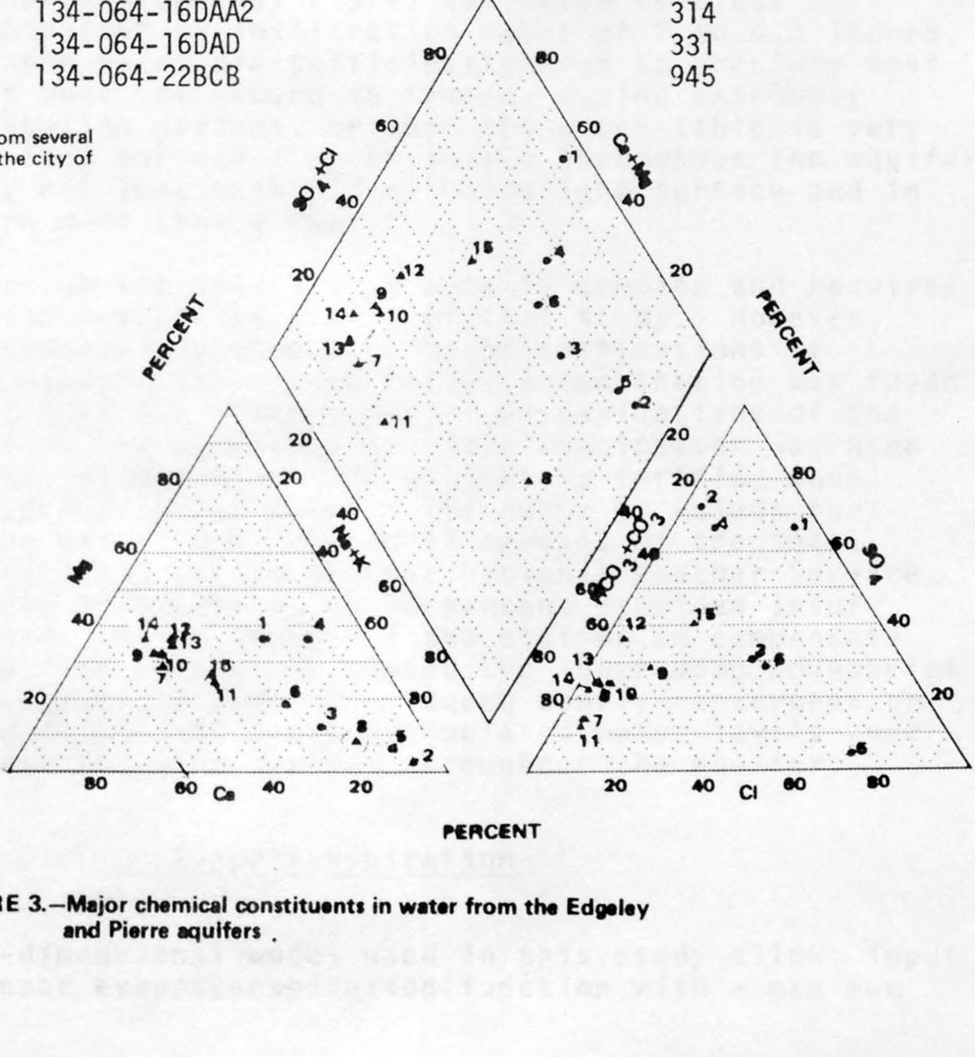

FIGURE 3.—Major chemical constituents in water from the Edgeley and Pierre aquifers .

The above evidence is not conclusive, but was considered sufficient to assume there is no vertical leakage from the Pierre prior to stress applied by irrigation withdrawals. However, because inadequate head data exist, it will be difficult to determine the rate of leakage if any does or will occur.

Sample 15 (fig. 3) is from a well within 1,500 feet of the Pierre contact with the Edgeley aquifer. This sample had the highest percentage of calcium, magnesium, and sulfate of the Edgeley samples. This well may be one to consider monitoring for quality changes which may indicate leakage from the Pierre.

Areal Recharge

The soil developed on the aquifer is porous and permeable. Thompson and Sweeney (1971) estimated vertical permeability equivalent to infiltration rates of 2 to 6.3 inches per hour. These rates are sufficiently high to preclude most runoff except when the ground is frozen, during extremely heavy precipitation periods, or when the water table is very close to the land surface. Water levels throughout the aquifer are generally not less than 2 feet below land surface and in most areas are more than 4 feet.

Flow through the unsaturated zone is complex and requires data collection beyond the limits of this study. However, through experimentation with a range of combinations of recharge and evapotranspiration rates, a combination was found that at least does not violate empirical evaluations of the aquifer and soil characteristics. This combination was used in calibrating the model and was ultimately verified when stress was applied to the model. The range of values for areal recharge was between 20 and 30 percent of the total annual precipitation (18.74 inches; National Weather Service, 1977). The use of values below 20 percent provided insufficient recharge to the center of the aquifer to compensate for flow away from the center toward the lower head boundaries. Values in excess of 30 percent produced poorly convergent or nonconverging conditions because simulated water levels were at or very near the land surface throughout the aquifer.

Evapotranspiration

The two-dimensional model used in this study allows input of only a linear evapotranspiration function with a maximum rate at land surface and a zero rate at a fixed depth. The average annual maximum potential evaporation rate in an area including the Edgeley aquifer is about 32 inches (Meyers, 1962). Ripple, Rubin, and van Hylckama (1972) describe a technique by which homogeneous soil types such as those at Edgeley may be evaluated for rates of evaporation. Calculations based on this technique show that evaporation can occur at rates close to the potential rate for depths to the water table of as much as 7 feet depending upon soil permeabilities. It was necessary to vary rates and depths of effective evapotranspiration using various recharge rates to arrive at a balance between the two rates that simulated observed steady-state head values.

A range of values for maximum evapotranspiration from 25 to 30 inches per year were found to be in balance with the range of recharge rates described above. Maximum depths of 6 to 10 feet for the effects of evapotranspiration proved to fit best with observed steady-state conditions.

Hydraulic Conductivity

Initial estimates of hydraulic conductivity were based on data from an aquifer test by Schmid (1973) in the SE¼ sec. 15, T. 134 N., R. 64 W. The distance-drawdown plot of these data (corrected for unconfined conditions) was analyzed and a range of values for transmissivity of 3,500 to 6,300 feet squared per day was obtained. Using an average saturated thickness of 30 feet, the range of conductivities in the area of the test is 117 to 210 feet per day. The values that were ultimately used in the simulation varied throughout the aquifer. The variation was based on a weighting factor representing the ratio of sand, gravel, and silt and natural steady-state saturated thicknesses.

Specific Yield

Data from the aquifer test conducted by Schmid (1973) also were used to calculate specific yield. A range of values from 0.049 to 0.158 was calculated using transmissivities of 3,500 and 6,300 feet squared per day, respectively, and the distance-drawdown curves related to each. Simulations utilizing specific yields within and beyond this range demonstrated the following: (1) generally values greater than 0.25 produced a time lag between calculated drawdown and recovery and observed drawdown and recovery near pumping wells, and (2) values less than 0.10 produced an area of drawdown much larger than was observed. The optimum value for transient simulations was determined to be 0.16.

Withdrawal Stresses

In 1975, four irrigation wells began producing water from the Edgeley aquifer. Two located in 134-064-09C withdrew 184 acre-feet and two located in 134-064-16D withdrew 116 acre-feet in 1975. In 1976, these wells produced 337 acre-feet and 205 acre-feet, respectively. The average application for irrigation was approximately 9 inches in 1975 and 16 inches in 1976.

In 1977, a fifth irrigation well was installed in the aquifer in 134-064-16A. This well produced 65 acre-feet, the two wells in sec. 9C produced 220 acre-feet, and the wells in sec. 16D produced 135 acre-feet. The average application was approximately 9.5 inches in 1977.

The city of Edgeley has installed two wells in 134-064-15CBB and it has an allocation of 115 acre-feet per year. This allocation combined with irrigation allocations could result in a total withdrawal from the aquifer of 505 acre-feet per year.

Permit applications for additional withdrawal of 225 acre-feet by existing systems have been held in abeyance by the North Dakota State Water Commission. In addition, there are permit requests totaling 520 acre-feet per year for new irrigation systems. If the aquifer were developed to the maximum requested, the annual withdrawal would be 1,250 acre-feet.

NUMERICAL MODEL

The model used to simulate the Edgeley aquifer was the two-dimensional finite-difference model developed by Trescott and others (1976). This model was chosen over the three-dimensional model developed by Trescott (1975) for two reasons. First, the system studied involves only one aquifer and one confining layer. Therefore, it is possible to define the flow system adequately within the two-dimensional model. Second, the two-dimensional model allows greater flexibility for balancing evapotranspiration and areal recharge rates, the principal external influences on this aquifer.

Mathematical Technique

The model used produces an approximate solution to a generalized form of the ground-water flow equation:

$$\frac{\partial}{\partial x}\left(K_{xx}b\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}b\frac{\partial h}{\partial y}\right) = S_y\frac{\partial h}{\partial t} + W(x,y,t) \qquad (1)$$

where

x and y are the coordinate axes (L),
K_{xx} and K_{yy} are the principal components of the hydraulic conductivity tensor (Lt^{-1}),
h is the hydraulic head (L),
b is the saturated thickness of the aquifer (L),
S_y is specific yield of the aquifer (dimensionless),
t is time, and
W(x,y,t) is the volumetric flux of recharge or withdrawal per unit surface area (Lt^{-1}).

Equation 1 assumes colinearity of coordinate axes and principal components of the hydraulic conductivity tensor. In addition, the transmissivity tensor has been replaced by the variable product of hydraulic conductivity and saturated thickness.

In order to solve equation 1 for the Edgeley aquifer it was necessary to subdivide the aquifer into rectangular blocks in which the aquifer properties were assumed to be uniform. The continuous derivatives in equation 1 are replaced by finite-difference approximations for the derivative at a point at the center of each block (node). The result is a set of N equations with N unknown heads where N is the number of nodes representing the aquifer.

The W(x,y,t) term in equation 1 comprises the areal recharge rate due to precipitation, withdrawal rates from wells, and the depth-variant evapotranspiration rate.

Further details of the mathematics and documentation of the basic program used in the simulation can be found in Trescott, Pinder, and Larson (1976).

Equilibrium Model Calibration

Calibration of the model under equilibrium conditions was accomplished by simulating a steady-state, nonstressed, water-table surface interpreted from heads observed in August 1973 (Naplin, 1976).

The boundaries of the model do not coincide with the exact configuration of the aquifer. Because of the rectangular configuration of the nodes it was necessary to model the bounding channel areas on the west and north as straight appendages rather than the sinuous pattern representing the real aquifer. For this reason some test holes penetrating the aquifer lie outside the model limits.

The aquifer is discretized by a variably spaced grid of 23 by 30 block-centered nodes (pl. 1). The blocks are designated by their row and column coordinate numbers. The grid spacing varies from 500 to 3,000 feet. Aquifer boundaries are defined by no-flow boundaries along the margins and no leakage from underlying till and(or) Pierre Shale. Areal recharge is considered uniform over the aquifer at a rate of 4.69 inches per year (25 percent of the average annual precipitation). The only natural flow out of the system is through evapotranspiration. The values of evapotranspiration that produce the best correlation with the observed data are 27 inches per year maximum when the water table is at or above the land surface and a minimum of zero at a depth of 8 feet or more below land surface. The aquifer thickness distribution used in the simulation is shown in figure 4.

Hydraulic conductivity was estimated for segments or zones of the aquifer according to the different materials as determined through test drilling. The average value used was 131 feet per day with a range of 82 to 164 feet per day (fig. 5). For purposes of equilibrium calibration, the specific yield was set at zero to eliminate the term in equation 1 which includes the time derivation. This imposes a steady-state solution.

The results of the calibration are summarized in table 1, which shows heads measured at observation wells and heads calculated for blocks containing the observation wells. The maximum absolute difference between observed and calculated heads is 2.0 feet, the minimum is 0.1 foot, and the median is 0.6 foot.

An attempt was made to verify the relationship of calculated steady-state heads to the parameters input during calibration. This attempt involved a program written by Richard Cooley (oral commun., 1977) that solves the flow equation for hydrologic parameters using a finite-element procedure. A set of known heads, initial flow and boundary conditions are input and selected parameters in one or more zones of the aquifer are estimated by a least-squares-residual technique. A detailed description of the mathematical theory

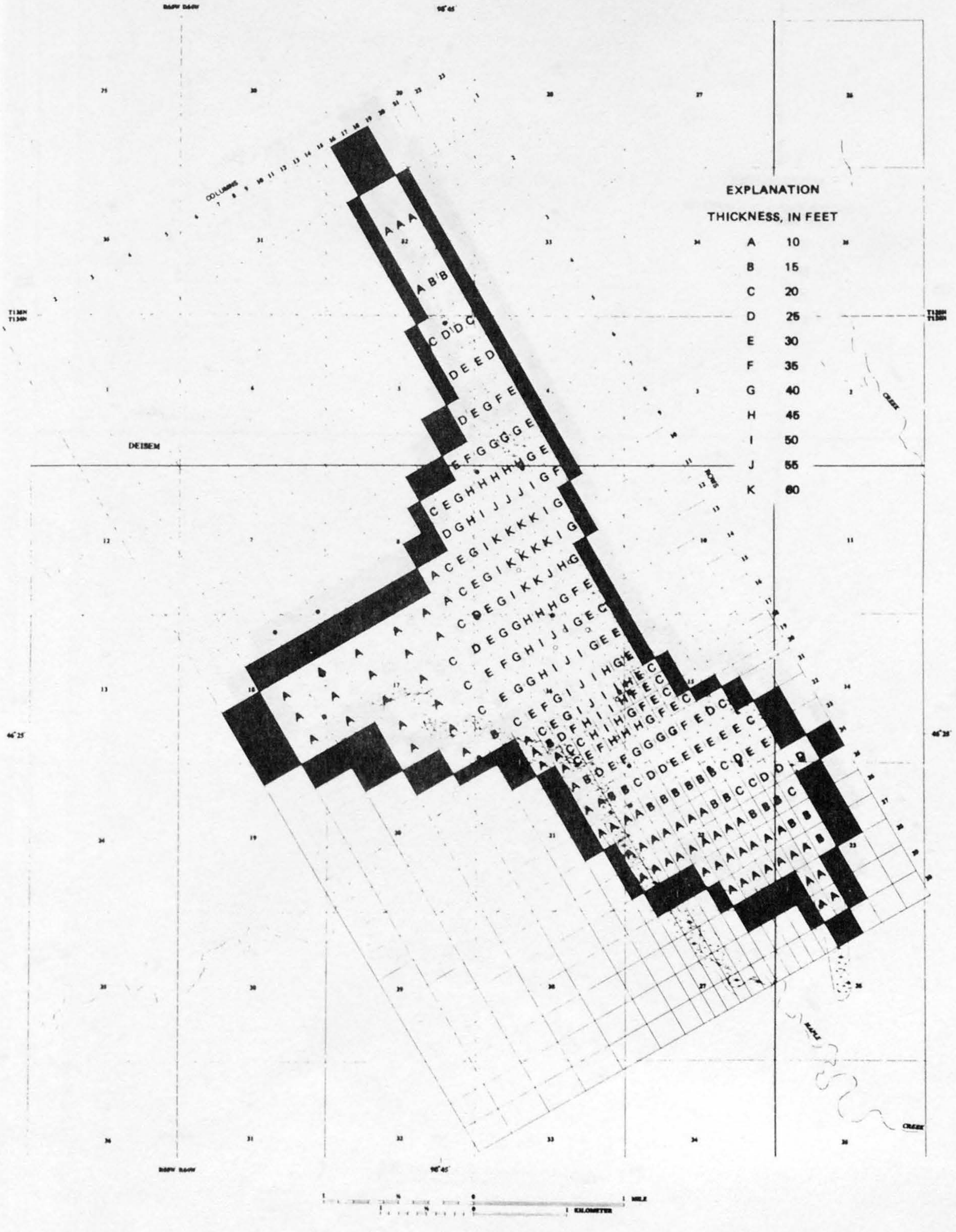

FIGURE 4.—Aquifer thickness used in simulating the Edgeley aquifer.

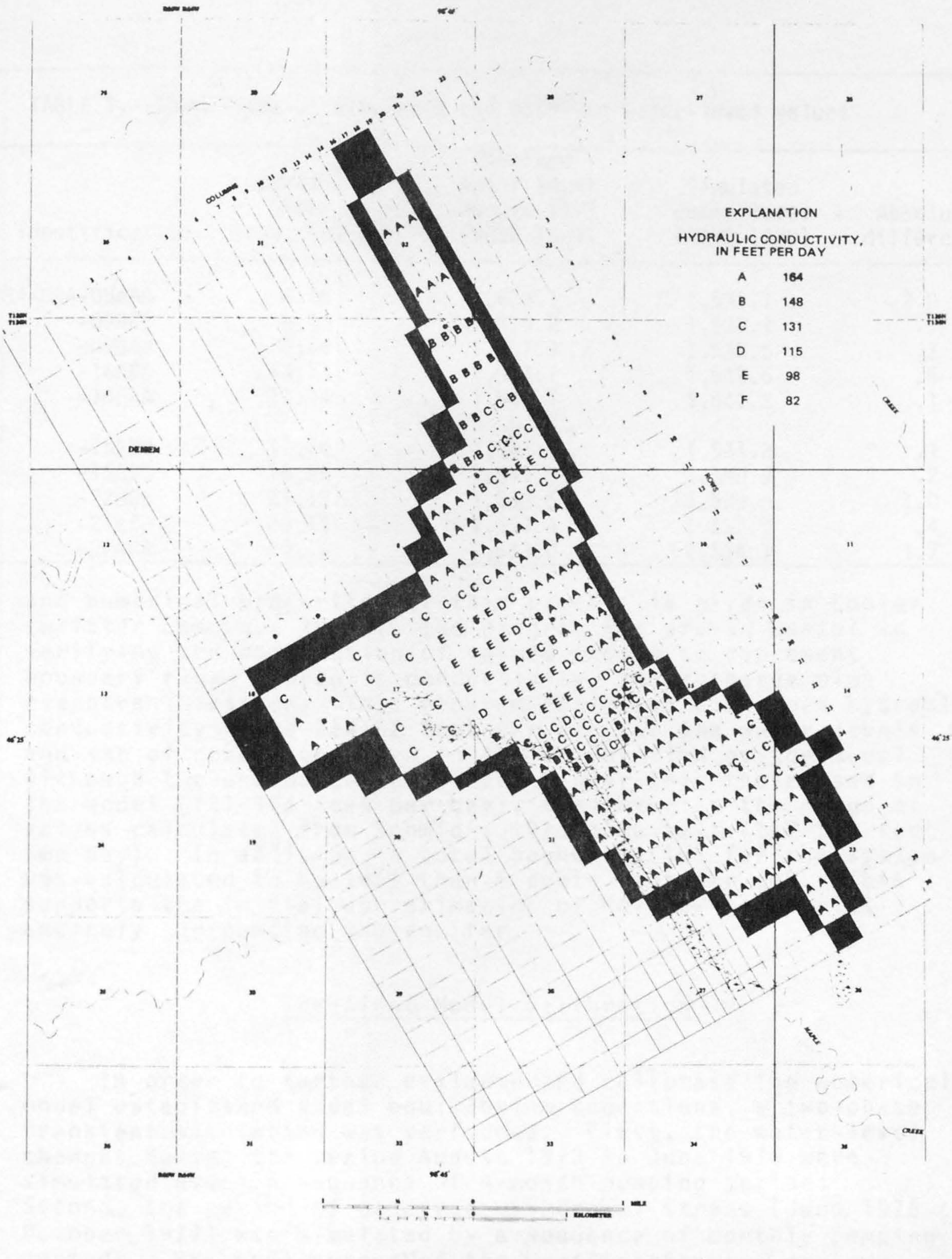

FIGURE 5.—Hydraulic conductivities used in simulating the Edgeley aquifer.

TABLE 1.--Comparison of simulated and observed water-level values

Well identification	Location by block (row, column)	Observed water level August 1973 (NGVD 1929)	Simulated water level (NGVD 1929)	Absolute difference
134-064-05AAB	4,16	1,533.1	1,531.1	2.0
-09BBB	8,13	1,539.8	1,539.1	.7
-09BAB	8,16	1,537.9	1,538.6	.7
-16ABB	13,13	1,543.1	1,542.6	.5
-16DAA	17,14	1,541.1	1,541.2	.1
-15BCC	17,15	1,541.3	1,541.2	.1
-15CBB	18,15	1,541.3	1,540.9	.2
-22BBB	21,12	1,538.6	1,539.6	1.0
-22BCB	23,11	1,537.4	1,537.0	.4
-22ABA	23,19	1,533.0	1,534.7	1.7

and numerical properties of this process is given in Cooley (written commun., 1977). The program has proved useful in verifying the combination of values chosen to represent boundary flux, hydraulic conductivity, and recharge plus evapotranspiration. This program estimated a uniform hydraulic conductivity to be 214±52 feet per day for the water levels and set of conditions used in the calibration of the model. Although the estimated values are higher than those used in the model (131-164 feet per day), they overlap the range of values calculated from Schmid's 1973 pump test (117-210 feet per day). In addition, a total boundary flux for the system was calculated to be less than 6 cubic feet per day. This supports the initial approximation of no-flow boundaries entirely surrounding the aquifer.

Transient Model Calibration

In order to further evaluate and calibrate the numerical model established under equilibrium conditions, a two-phase transient simulation was performed. First, the water-level changes during the period August 1973 to June 1975 were simulated using a sequence of 4-month pumping periods. Second, the period of observed withdrawal stress (June 1975 to October 1977) was simulated by a sequence of monthly pumping periods. For both phases of the verification the maximum evapotranspiration rate for the months of June through September was fixed at 21 inches and for the remainder of the year the rate was fixed at 6 inches. The areal recharge rate was calculated at 25 percent of the precipitation recorded at Edgeley (fig. 6). Withdrawal rates were established for each well based on total water withdrawn during the 4-month irrigation season, June through September.

The simulated water-level changes and observed water-level changes are plotted on plate 2 (in pocket). It should be noted that the simulated water-level changes represent average values for the entire block while the observed water-level changes are from single points not necessarily in the center of each block; therefore, the calculated water-level change is not expected to exactly match that in an observation well. During pumping there could be as much as 2 or 3 feet difference in water-level change across a 500-foot-wide block.

The results shown in plate 2 indicate the model duplicates the form of the observed water-level-change curves in all cases. Divergence of the simulated water-level change from the observed water-level change is greater in those blocks farthest from the pumping centers and nearest the boundaries, particularly blocks 8,16; 21,12; and 23,19. These differences contrast with the very close correlation in those areas more directly influenced by withdrawal activity (blocks 17,14; 17,15; and 13,13).

The time lead or lag in some sets of curves is due, in part, to the inability to exactly duplicate the timing and duration of recharge and periods of actual withdrawal activity.

Plate 1a illustrates the areal distribution of simulated water levels for June 1, 1975, immediately prior to initiation of the first irrigation withdrawal. Water levels measured between June 10 and 15, 1975, are shown in parentheses for comparison. Note that the observed values and simulated surface are within 2 feet of each other in all cases.

Plate 1b shows the areal distribution of simulated water levels at the end of the 1977 irrigation period. The observed water levels, measured in late October 1977, shown in parentheses, are within 2 feet of the simulated values except near block 8,16 where the difference is more than 3.5 feet.

A significant feature of plate 1b, compared to 1a, is the reduction in total area with water levels above 1,540 feet. This is particularly significant when it is noted that most of the aquifer west of section 16 is of relatively unknown thickness, but is probably less than 15 feet thick and has less than 10 feet of saturated thickness even when water levels are very high.

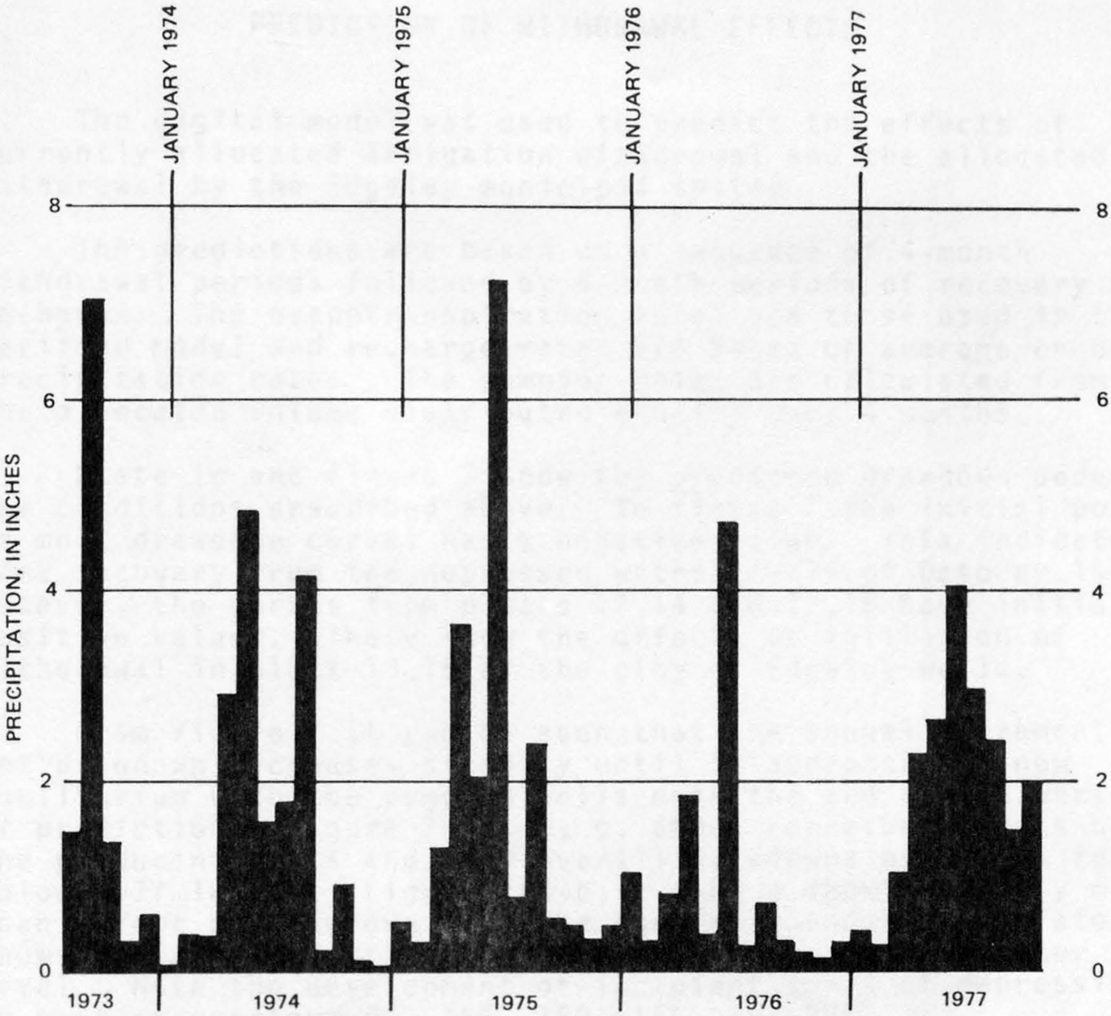

FIGURE 6.—Precipitation at Edgeley.

PREDICTION OF WITHDRAWAL EFFECTS

The digital model was used to predict the effects of currently allocated irrigation withdrawal and the allocated withdrawal by the Edgeley municipal system.

The predictions are based on a sequence of 4-month withdrawal periods followed by 8-month periods of recovery and recharge. The evapotranspiration rates are those used in the verified model and recharge rates are based on average annual precipitation rates. The pumping rates are calculated from the allocated volume distributed equally over 4 months.

Plate 1c and figure 7 show the predicted drawdown under the conditions described above. In figure 7 the initial point on most drawdown curves has a negative value. This indicates some recovery from the depressed water levels of October 1977. However, the curves from blocks 17,14 and 17,15 have initial positive values. These show the effects of initiation of withdrawal in block 18,15 by the city of Edgeley wells.

From figure 7 it can be seen that the annual increment of net drawdown decreases steadily until it approaches a new equilibrium with the pumping wells near the end of the period of prediction. Figure 7, e, f, g, and h represent blocks near the producing wells and show overall drawdowns of 2 to 4 feet below 1977 levels. Figure 7a, b, c, and d show generally more than 1 foot of drawdown near the aquifer boundaries. Plate 1c shows the areal distribution of this new equilibrium water level. Note the development of incipient cones of depression in section quarters 9C, 16A, 16D, 15C, and 22B.

An additional simulation was produced to predict the effects of a 2-year drought on the aquifer. The pumping rates used were based on present allocations; recharge was based on 25 percent of the average annual precipitation, except during the period from June 1979 to June 1981. During this period the recharge rate was set at one-half that used in the remainder of the simulation.

Figure 8 and plate 1d show the results of this prediction. Once again the effects of initiation of the municipal pumping in block 18,15 are seen in the lack of significant recovery in blocks 17,14 and 17,15. The incipient cones of depression seen on plate 1c are better developed in the drought simulation (pl. 1d).

Figure 8 shows the effects of the drought on the 10-year trend in drawdown. Because the stress of reduced recharge is distributed evenly across the entire aquifer, all the representative blocks show a significant increase in drawdown

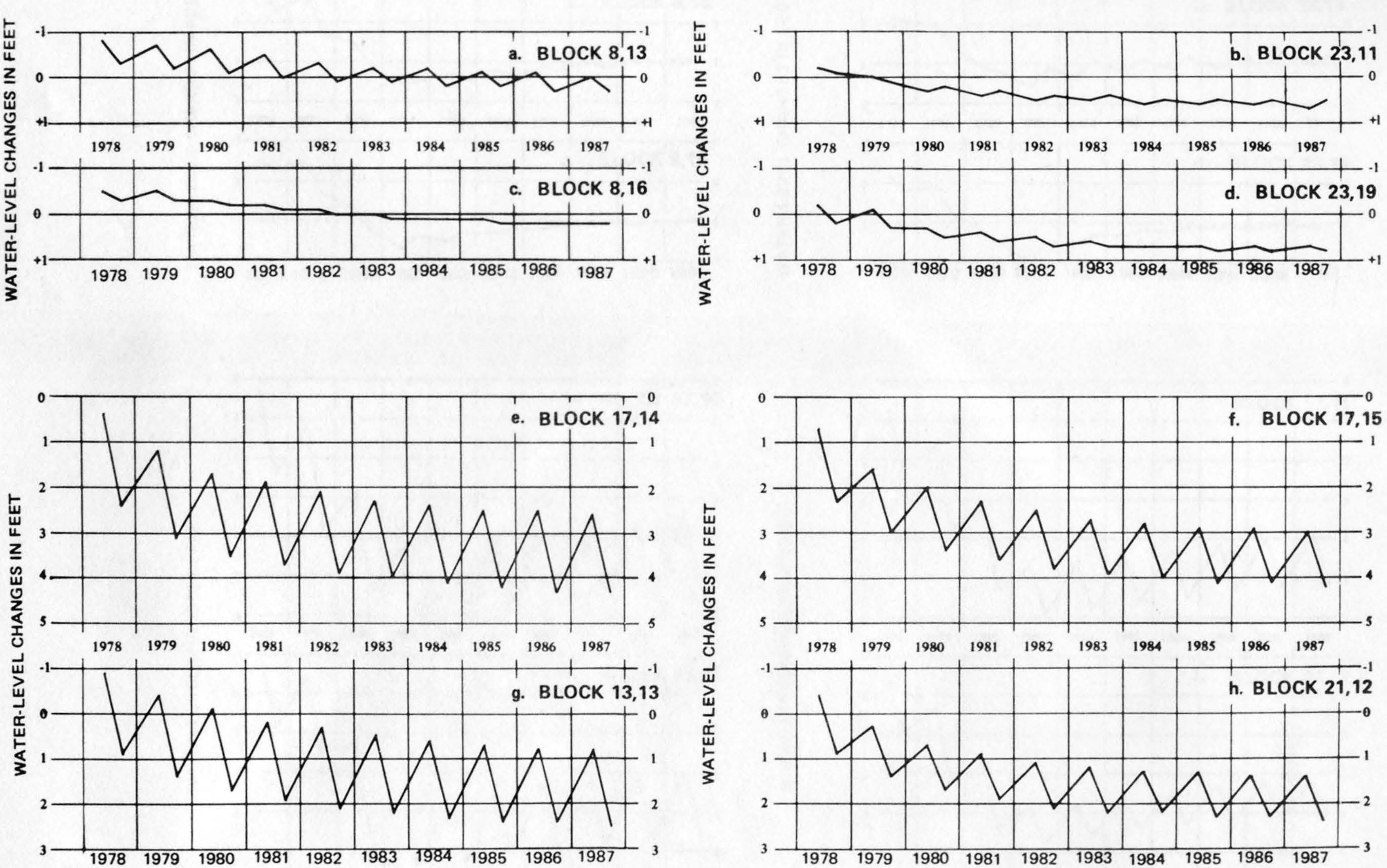

FIGURE 7.—Predicted water-level changes from 1977 datum in blocks containing observation wells.

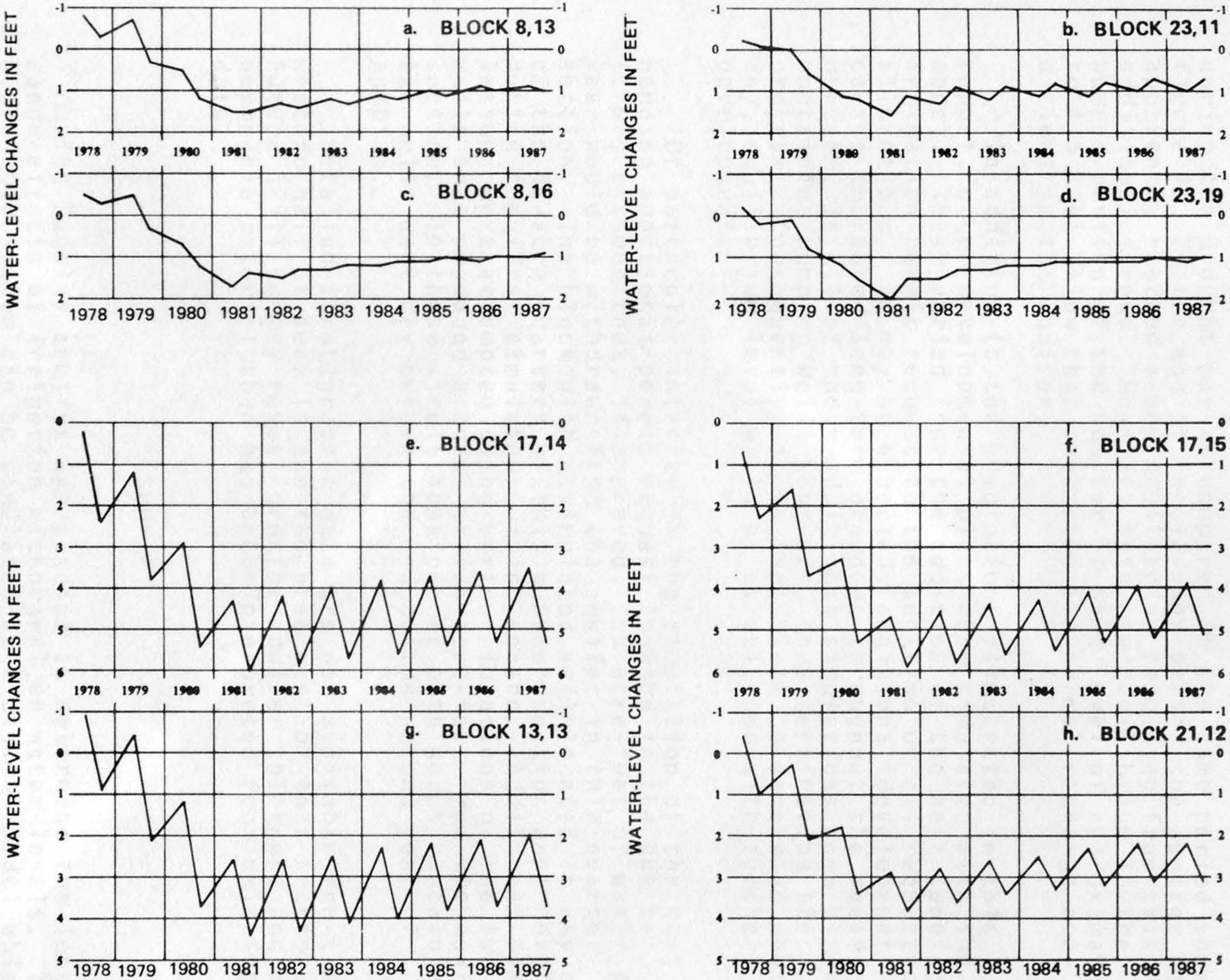

FIGURE 8.—Predicted water-level changes from 1977 datum in blocks containing observation wells assuming a 2-year drought.

during the drought period compared to the same period shown in figure 7. By the end of the 10-year period the aquifer has apparently reached a new equilibrium resulting from this additional stress. However, this new equilibrium in the pumped portion of the aquifer is at a level of approximately 1 to 1.5 feet below that predicted for normal recharge conditions in the aquifer.

In addition to the predictions illustrated in this report, other developmental plans were simulated with the model. These varied from the addition of the next pending irrigation permit request to the addition of all requested allocations. As may be expected, additional development causes increased long-term drawdown throughout the aquifer. However, in all of these additional simulations some blocks containing pumping wells went dry, thus terminating the program. Consequently, it is impossible to determine what, if any, equilibrium level would be established with further development.

Of particular interest is the simulation of the next pending additional permit request located in the NW¼ sec. 16. It was assumed that, if approved, 135 acre-feet of water per year would be withdrawn from the aquifer in this quarter section. The block with a simulated well located in any one of the 40-acre quarters of this quarter section went "dry" during the first simulated pumping season. Additional simulations were attempted using various locations of the two wells that produced a total of 135 acre-feet from the quarter section. In these simulations one or both nodes containing the wells went dry before the end of the second year of pumping.

Detailed stratigraphic data are not available for the western half of sec. 16 and the area west of this section. Future drilling may reveal greater aquifer thickness and more permeable material than has been interpreted from existing data.

SUMMARY

The Edgeley aquifer was studied to determine the long-range effects of irrigation withdrawal on water levels. The hydrologic system can be simulated by a digital model which assumes lateral and basal no-flow boundaries, recharge from precipitation, and discharge through evapotranspiration under natural conditions.

The digital model has been calibrated against steady-state water-level data measured prior to withdrawal for irrigation. Transient calibration was accomplished by comparing simulated hydrographs to water levels in observation wells collected over a 3-year period, during which a variety of wells and pumping rates were in operation. Plate 2 illustrates this comparison and plate 1 (a and b) shows the areal distribution of simulated water levels before and at the end of the verification period.

A prediction of water-level changes was made for a 10-year period using 1977 allocated withdrawal and recharge equal to 25 percent of the average annual precipitation. This prediction indicated a decline in water levels decreasing with time to a new equilibrium near the end of the 10-year period. The new equilibrium is at a level 2 to 4 feet below 1977 water levels over much of the aquifer.

An additional simulation was made for the same period using a drought of one-half the average recharge from precipitation lasting for 2 consecutive years. This simulation produced a rapid decline in water levels during the drought period with a partial recovery of water levels near the end of the 10-year simulation. However, the apparent equilibrium state at the end of the simulation is 1 to 1.5 feet below the predicted equilibrium state using recharge equal to 25 percent of the average annual precipitation through the entire 10-year period.

The results of attempts to predict the effects of additional requested withdrawal for irrigation were indeterminate. Blocks containing wells for the next pending permit request consistently went dry causing the program to terminate before the end of the simulation. The reason is that this permit request is for withdrawal in a relatively thin part of the aquifer. Further investigation may be warranted if additional data become available.

REFERENCES

Armstrong, C. A., and Luttrell, S. P., 1978, Ground-water basic data for Dickey and LaMoure Counties, North Dakota: North Dakota State Water Commission County Ground-Water Studies 28, pt. II, and North Dakota Geological Survey Bulletin 70, pt. II, 557 p.

Meyers, J. S., 1962, Evaporation from the 17 western states: U.S. Geological Survey Professional Paper 272-D, p. 71-100.

Naplin, C. E., 1976, Ground-water resources of the Edgeley area, LaMoure County, North Dakota: North Dakota State Water Commission Ground-Water Studies no. 82, 56 p.

National Weather Service, 1977, Climatological Data, North Dakota: Annual Summary 1976, v. 85, no. 13.

Ripple, C. D., Rubin, Jacob, and van Hylckama, T. E. A., 1972, Estimating steady-state evaporation rates from bare soils under conditions of high water table: U.S. Geological Survey Water-Supply Paper 2019-A, 39 p.

Schmid, R. W., 1973, Edgeley aquifer test, LaMoure County, North Dakota: North Dakota State Water Commission Open-File Report.

Thompson, D. G., and Sweeney, M. D., 1971, Soil survey of LaMoure County and parts of the James River valley, North Dakota: U.S. Department of Agriculture, Soil Conservation Service, Soil Survey Report, 118 p.

Trescott, P. C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75-438, 30 p.

Trescott, P. C., Pinder, G. F., and Larson, S. P., 1976, Finite-difference model for aquifer simulation in two-dimensions, with results of numerical experiments: Techniques of Water-Resources Investigations of the U.S. Geological Survey, book 7, chapter C1, 116 p.

U.S. Bureau of the Census, 1971, U.S. census of population, 1970, Number of inhabitants, North Dakota: U.S. Bureau of the Census final report PC(1)-A36.