# THE INFLUENCE OF VERTICAL VARIATIONS IN LITHOLOGY ON A MATHEMATICAL MANAGEMENT MODEL FOR THE OGALLALA AQUIFER, TEXAS COUNTY, OKLAHOMA

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# CHAPTER I

# INTRODUCTION

The Ogallala Formation has been used as an aquifer providing a ground-water resource to farm production and the agriculturally based industries in the High Plains Province of the United States. The formation extends from Nebraska to the Texas Panhandle. This study was restricted to the portion of the Ogallala Formation which occurs in the Oklahoma Panhandle. Although this aquifier occurs in Cimarron, Texas, and Beaver counties of the Oklahoma Panhandle, only Texas County is considered because of the availability and quality of data (see Figure 1).

Geologically, Pleistocene and Pliocene sediments crop out in the study area. The Ogallala Formation is of Pliocene age. However, because there is a lack of stratigraphic detail the name "Ogallala" was used in this study to include all Tertiary sediments. These sediments can occur either as unconsolidated or semiconsolidated sediments and are composed of discontinuous layers of sand, silt, clay, gravel, sandstone, caliche, limestone, conglomerate, and volcanic ash. Locally the units are tightly cemented by calcium carbonate while in other places, they are very poorly consolidated. These sediments are moderately permeable and provide a major source of ground water in the area. The saturated thickness ranges from 300 to 800 feet with an average thickness of 400 feet. Bedrock units of Mesozoic and Permian age subcrop under the Tertiary sediments. The bedrock within the study area is composed of vari-colored

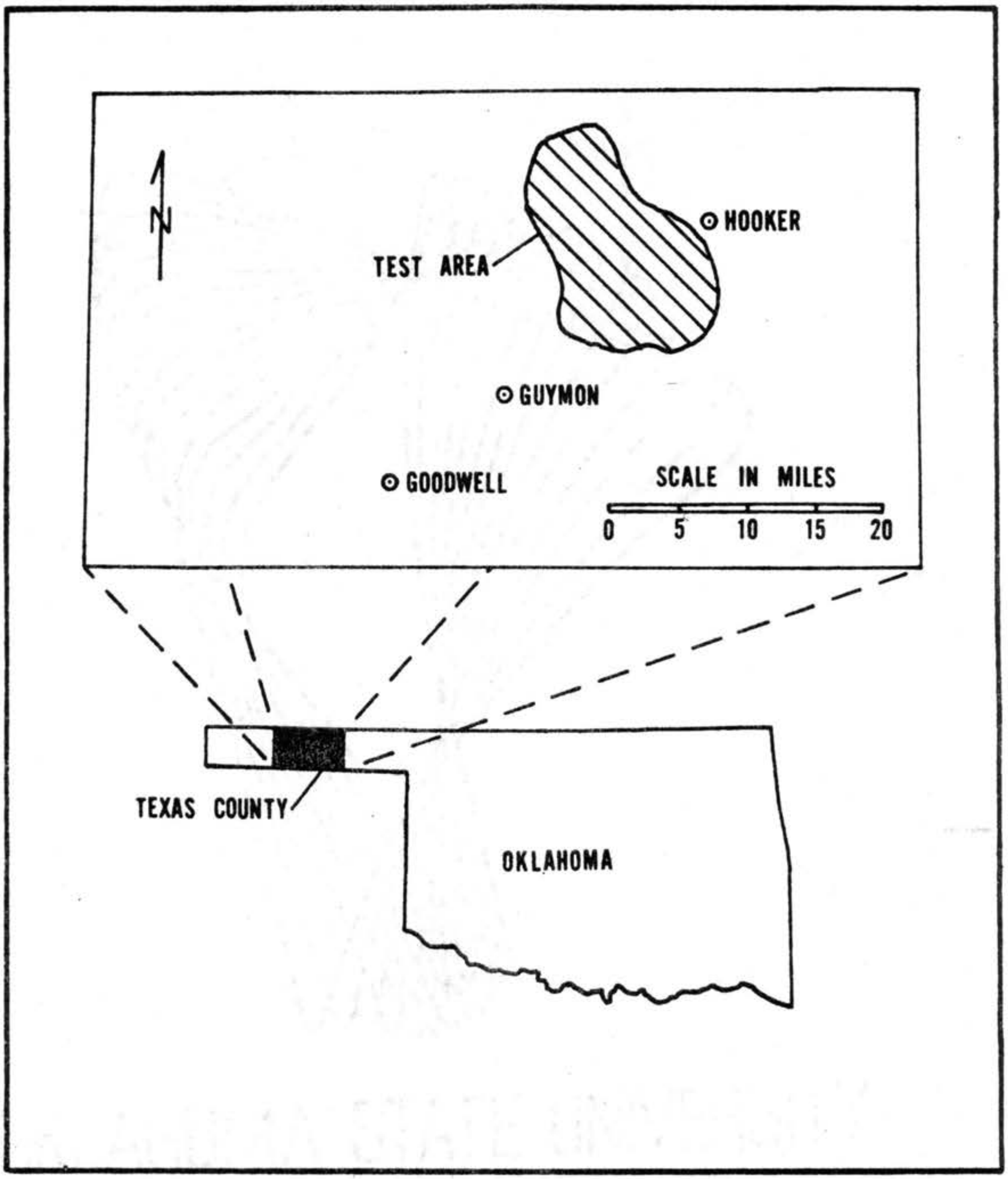

Fig. 1.-Index map of test area and Texas County, Oklahoma

shale, sandstone, siltstone, and a limited occurrence of thin discontinuous gypsum beds. With the exception of Jurassic and Cretaceous sandstones in western Texas County, the bedrock is generally too fine grained and impermeable to transmit water. Thus, the bedrock surface forms an impermeable boundary at the base of the aquifer in the study area. The bedrock surface is characterized by moderate topographic relief with numerous local depressions which are considered to be bedrock valleys.

The Ogallala aquifer is being subjected to increased water withdrawals. These withdrawals far exceed the natural recharge, especially in the Southern High Plains area. The aquifer is being mined in this area and the resulting declines in static water level are becoming critical. In order to predict these declines in the Texas Panhandle, a mathematical management model was developed by investigators of Texas Tech University's Civil Engineering and Mathematics departments and of the High Plains Underground Water Conservation District No. 1 at Lubbock, Texas (Sechrist, et al., 1970). McClain (1970) is using a similar approach to modeling the Ogallala Formation in Kansas. However, these investigators (Sechrist, et al., and McClain) are considering the Ogallala Formation as a homogeneous unit. Heterogeneous porous materials have also been considered by researchers such as Nelson and Cearlock (1967) as a homogeneous mass in which there is a statistical variation in the distribution of aquifer constants. They model the distribution of permeability irrespective of vertical variation in the aquifer and use fitting procedures to statistically determine lateral variations of permeability. A heterogeneous distribution of permeability has also been assumed by McMillan (1966) to be homogeneous with a specific range of variance.

Research by Frye (1970), Keys and Brown (1970), and Pearl (1970) has shown that the Ogallala Formation is neither homogeneous nor randomly heterogeneous but rather is discontinuously layered. The importance of considering layering as it would apply to ground-water flow models is evident in articles which have appeared since the beginning of the middle 1960's. The bulk of this research has been restricted to the analysis of multi-aquifers (several aquifers) or to aquitards between multi-aquifers. Bredehoeft and Pinder (1968, 1970), Hantush (1967), and Neuman and Witherspoon (1969, 1969) have applied mathematical models in this manner to nonhomogeneous, anisotropic, and/or leaky artesian aquifers.

Freeze and Witherspoon (1966, 1967, 1968) evaluated the effects of layering within a single aquifer (with different values of permeability) on flow net configurations within the saturated zone using the finite difference technique and the digital computer. More recently Javandel and Witherspoon (1969) have extended the layered case to consider the temporal effects of layered aquifers on drawdown associated with pump tests and their analysis. Current research concerned with mathematical modeling of a single multi-layered aquifer is being conducted by Pinder, Bredehoeft, and Bennett. They are concerned with the determination of factors and relationships that govern permeability distribution (including layering) which in turn will be useful for predicting permeability distribution by indirect means. In addition, they are considering how this information can be applied to mathematical models. However, it is apparent that no attempt is being made to specifically relate the effects of layering on semi-static water level changes which occur during the dewatering of a single unconfined aquifer over a long period of time.

Thus, this study is an evaluation of how the variation of lithology within an aquifer can affect the rate of dewatering. This variation is assumed to be a major factor contributing to the response of mathematical ground-water flow models. This would be particularly valuable when such models are used for predicting the time for a given water-level change to occur during the dewatering of an aquifer.

The determination of the relationship between aquifer constants and declines in static water levels would not only be useful in analysis of the Ogallala aquifer but also could be applied to layered alluvial aquifers (floodplain and terrace deposits, alluvial fan deposits) as well as to layered basin and coastal plain aquifers. Layered alluvial deposits are associated with many of the major streams in the State of Oklahoma.

Therefore, the major objective of this study was to compare the response of a modified version of the Texas Tech management model to multi-layered and homogeneous cases. This was accomplished by making modifications in the management model which would accommodate the multi-layered case and the assumption based on the use of weighted-average values to represent the hydraulic coefficients. Comparisons were subsequently made between the homogeneous and multilayered case using hydrographs and residual maps.

## CHAPTER II

# DESCRIPTION AND MEASUREMENT OF AQUIFER CHARACTERISTICS

In constructing the ground-water management model for the Ogallala aquifer in Texas County, hydrogeologic data were collected and analyzed. Data were evaluated in order that a basic set of assumptions could be determined and adaptations made in the mathematical model. After this was achieved, the model was tested and the results tabulated and plotted.

Most of the well data collected for Texas County were provided by the United States Geological Survey. Driller's logs and well data were on microfilms. Topographic quadrangle maps provided elevation control with an accuracy of ±2 feet in the eastern half of Texas County. Water-level records for Texas County from 1966 to 1970 were obtained from published data (Hart, 1971).

Layer codes (see Figure 2) were used to simplify log descriptions and to provide uniformity in the data. This was achieved by identifying the principle grain sizes. Subsequently the codes were used to prepare preliminary isometric diagrams for Texas County and the test area (see Figure 2). Two maps were also used to represent other hydrogeologic aspects of the test area (Figure 1). These two additional maps include the water-level map (Figure 3) and the saturated thickness map (Figure 4).

The isometric diagram was prepared to show the lithologic character-

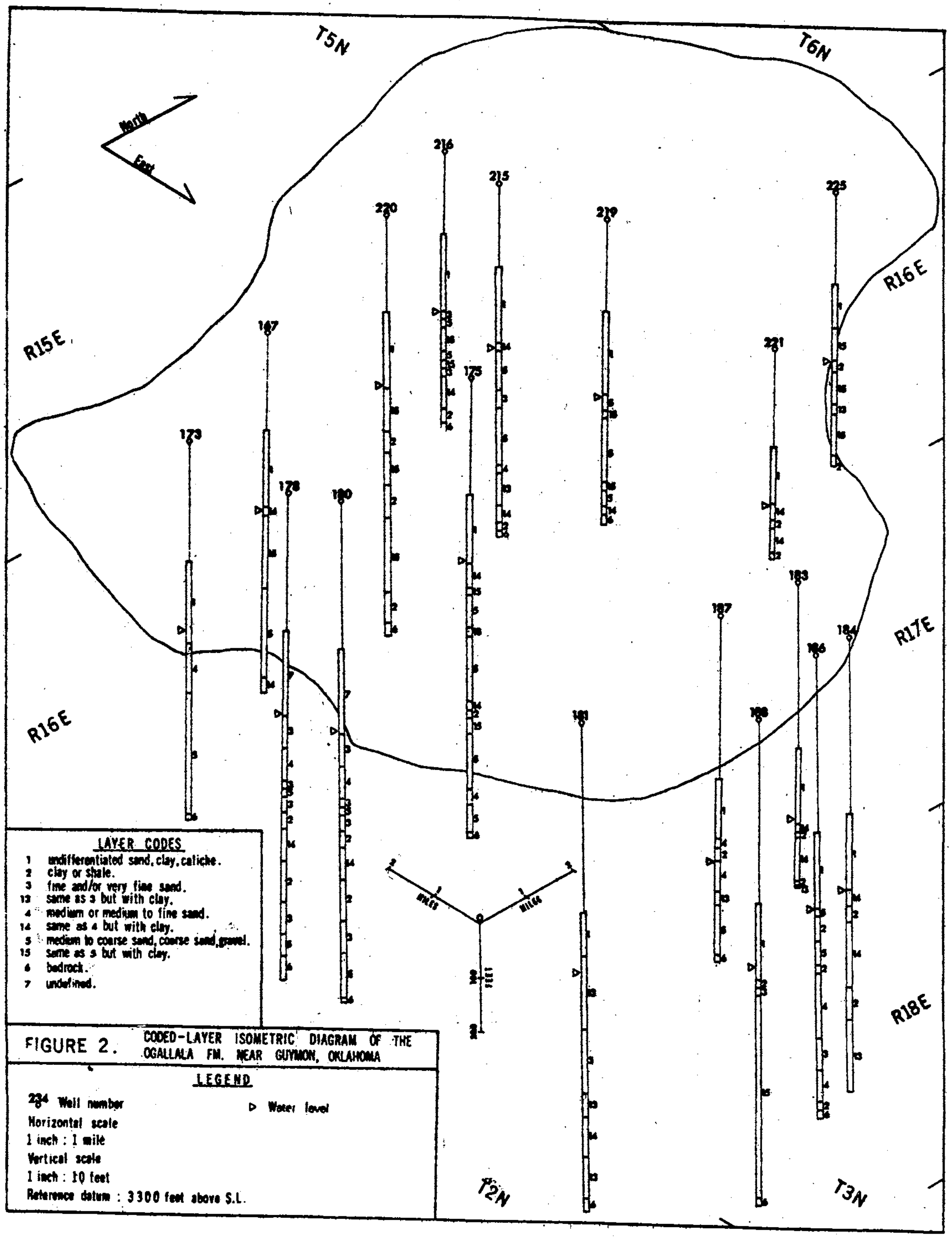

Fig. 2.-Coded-layer isometric diagram of the Ogallala Formation near Guymon, Oklahoma

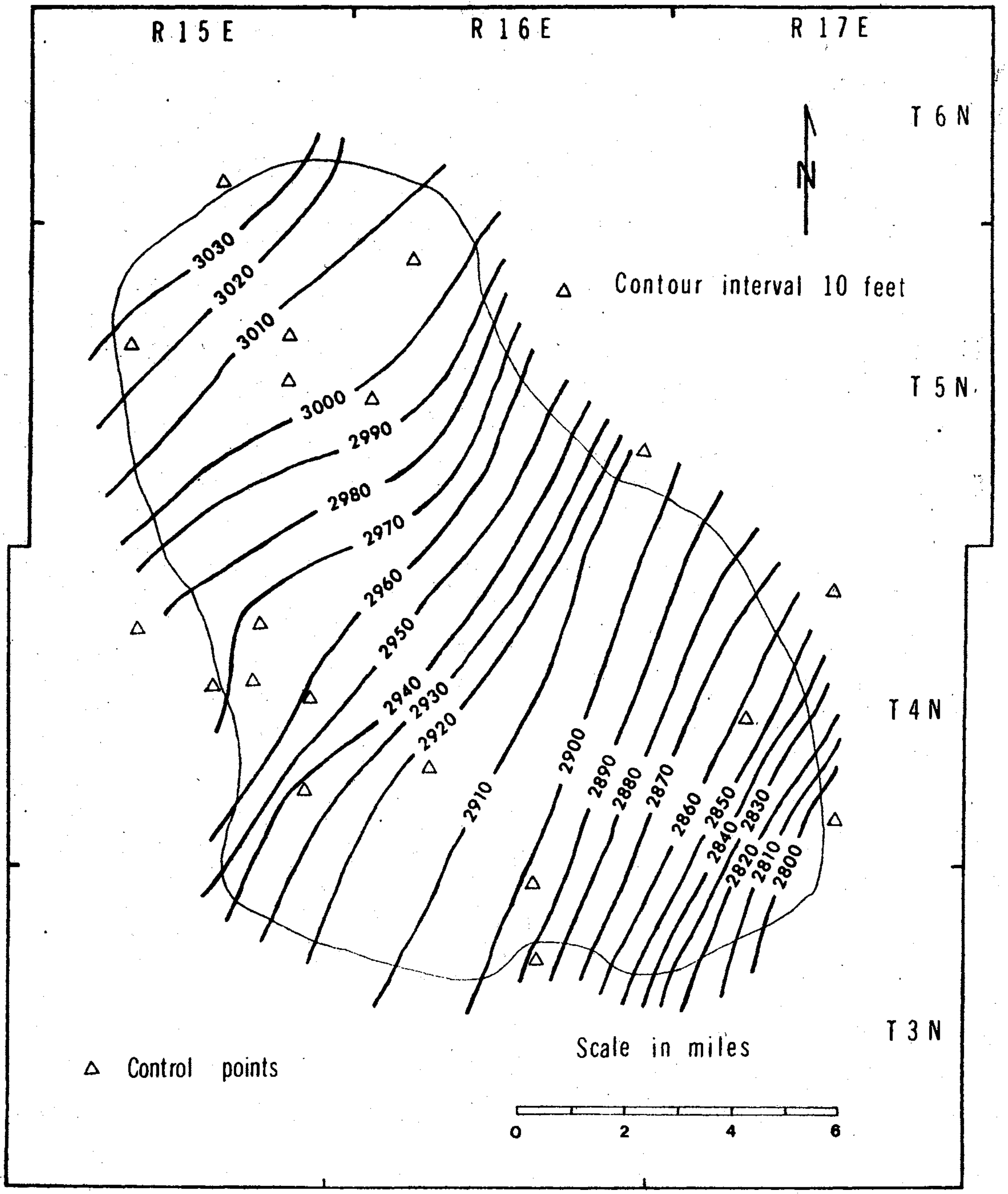

Fig. 3.-Water-level map of test area (after U.S.G.S.), March, 1966

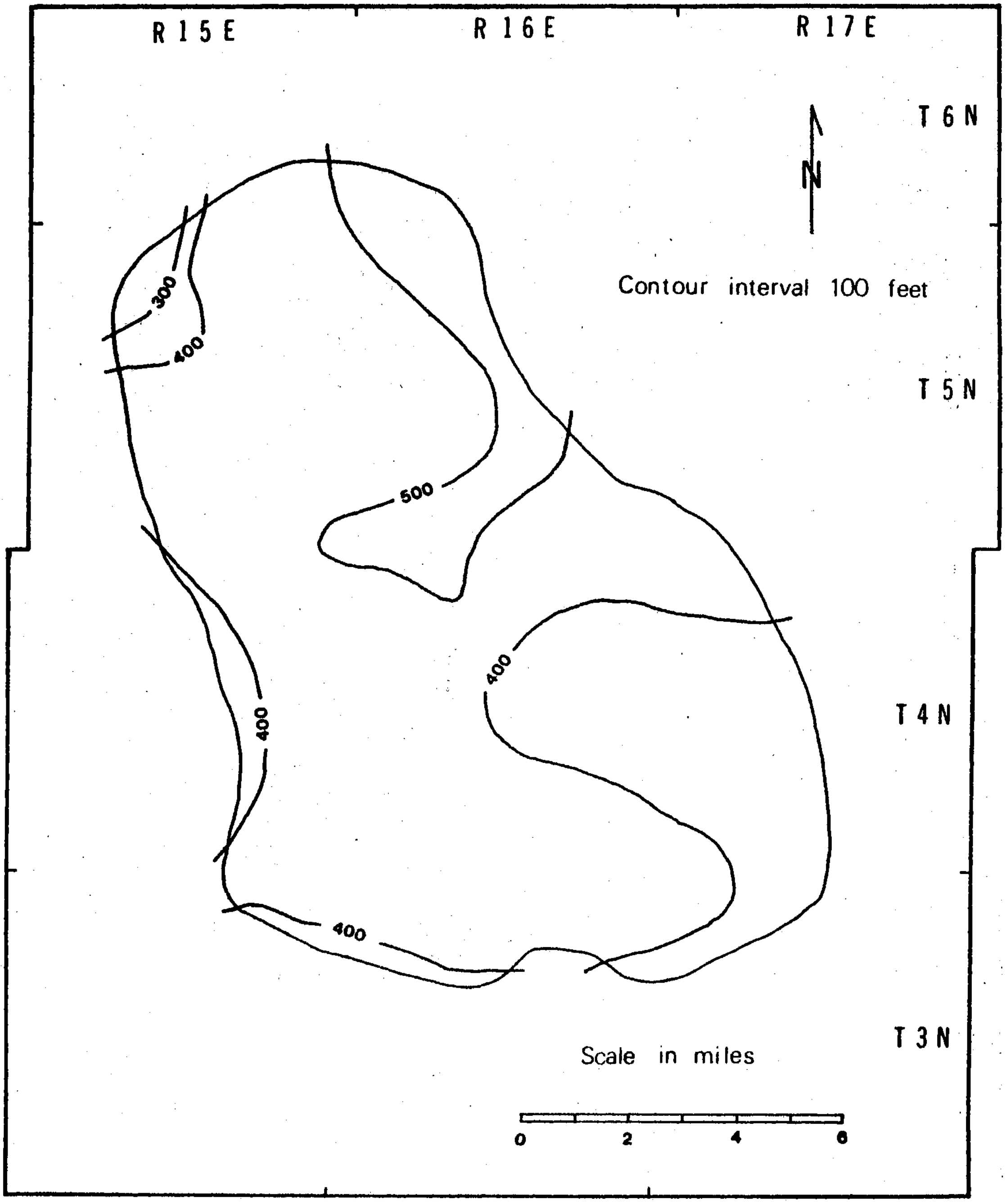

Fig. 4.-Saturated-thickness map of the Ogallala Formation in the test area (after U.S.G.S.), March, 1966

istics of the Ogallala aquifer both in Texas County and in the test area. Preparation of this diagram involved the transformation of coded layer data into a visual three-dimensional diagram. The map grid was skewed to a 30 degree angle in order to provide a three-dimensional view of the ground-water system. A reference datum of 3300 feet above sea level was used with a vertical scale of 1 inch to 100 feet and a horizontal scale of 1 inch to 1 mile. Panel diagrams were not used to show correlation between wells because of the apparent discontinuous nature of the layers.

The water-level map was used to represent the water-table configuration of the test area. All water-level records for March, 1966 were taken from published data (from Hart, 1971). A contour interval of 10 feet was used. The saturated-thickness map was a modification of one prepared by Wood and Hart (1967). A contour interval of 100 feet was used to show the distribution of saturated thickness in the test area.

In order to develop an idealized conceptual model which would represent the layered character of the Ogallala Formation, a simple statistical study was made showing the frequency of occurrence of lithology type and layer sequence. In Texas County, it was found that 37 percent of the lithology is coarse or very coarse sand, 25 percent is medium sand, and the remainder is fine sand and clay. Within the smaller test area, approximately the same percentages occur; 45 percent of the local lithology is coarse or very coarse sand; 21 percent is medium sand, and the remainder is fine sand and clay. Results of the statistical study for the test area are listed on Table I. By lumping thinner units together on the isometric map, a sequence of fine to coarse sediments generally occurred respectively from the water table to the base of the aquifer. There were 13 from a total of 17 wells within the test area which were

## TABLE I

## STATISTICAL ANALYSIS OF LITHOLOGY IN TEST AREA

| Well Number | Layer Code 2 Thickness (Feet) | Layer Code 3 and 13 Thickness (Feet) | Layer Code 4 and 14 Thickness (Feet) | Layer Code 5 and 15 Thickness (Feet) |
|---|---|---|---|---|
| 167 | 0 | 0 | 44 | 300 |
| 173 | 0 | 0 | 92 | 228 |
| 175 | 15 | 15 | 90 | 232 |
| 178 | 105 | 105 | 120 | 55 |
| 180 | 105 | 105 | 120 | 100 |
| 181 | 0 | 375 | 75 | 0 |
| 183 | 80 | 10 | 6 | 25 |
| 184 | 90 | 135 | 150 | 0 |
| 186 | 75 | 60 | 180 | 60 |
| 187 | 35 | 25 | 74 | 96 |
| 188 | 15 | 15 | 0 | 375 |
| 215 | 15 | 90 | 60 | 180 |
| 216 | 30 | 30 | 60 | 90 |
| 219 | 0 | 0 | 15 | 210 |
| 220 | 155 | 0 | 0 | 280 |
| 221 | 30 | 0 | 75 | 0 |
| 225 | 20 | 20 | 0 | 200 |
| Total Thickness | 770 | 1045 | 1161 | 2437 |
| % | 14.3% | 19.3% | 21.4% | 45% |

representative of this sequence. A similar sequence was noted when 75 of the total number of wells (112) in Texas County were studied. Based on the distribution of lithology type, it was concluded that only the medium and coarse sediments should be represented in the model using this sequence.

Samples of medium to coarse grained sands were collected from an outcrop of the Ogallala Formation at a location just west of Guymon. A generalized cross-sectional diagram of the Ogallala outcrop is shown in Figure 5. The outcrop consisted of a buried sand and gravel channel fill overlain by later Ogallala deposits and the caliche caprock which is used as the upper boundary of the Ogallala Formation. Although this channel is relatively small, it is assumed from examining the well logs that sediments of similar fluvial origin may exist nearer the base of the Ogallala. Therefore, sand types at the outcrop were considered to be representative of the saturated interval and were subsequently used in the mathematical model (see Figure 5). Four layers of uniform thickness were used to describe the mathematical model. The thickness of each was 100 feet in order that the total thickness of 400 feet would correspond with the average thickness represented on the saturated-thickness map (see Figure 4). In order to simplify the model, it was also assumed that the layers were homogeneous when extended uniformly in the lateral direction. Although this assumption is an over simplification, it was considered necessary before more complex models could be developed.

Four sand samples from the outcrop near Guymon were identified as being representative of the A, B, C, and D sands respectively (see Figure 5). The measured properties of these samples were used to represent hydraulic coefficients of the Ogallala aquifer. Sieve analysis and

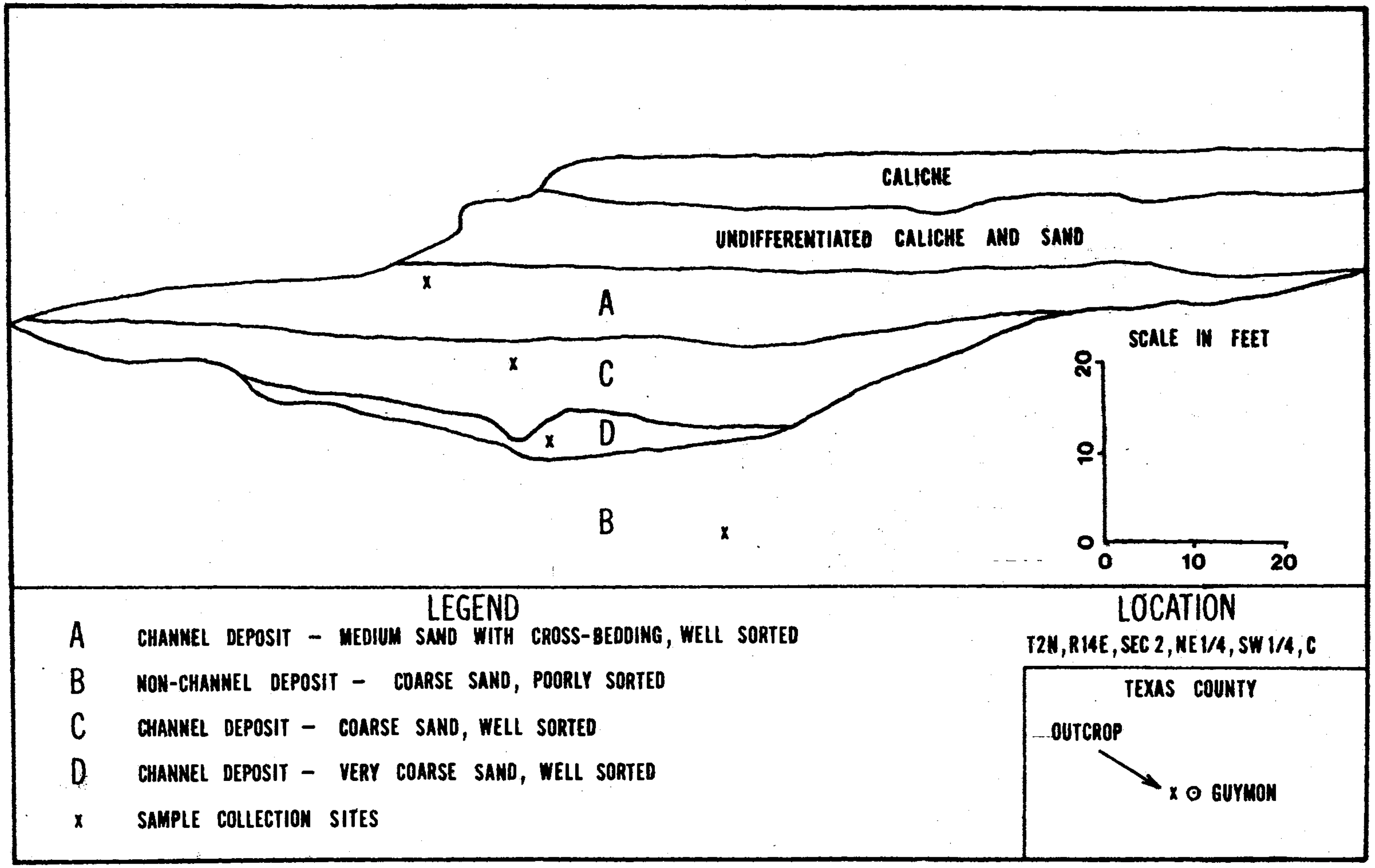

Fig. 5.-Cross-sectional diagram of Ogallala Formation outcrop near Guymon, Oklahoma

permeability tests were conducted using conventional sieve analysis techniques and a Soiltest model K-670 high pressure permeameter. The A sand was the finest of the 4 samples and the D sand was the coarsest. Samples were oven-dried before testing. A nest of 10 sieve pans were used representing the following United States Standard Sieve numbers: 10, 18, 35, 45, 60, 70, 80, 100, 140, and 170. The results were plotted as a cumulative weight percentage (% passing) versus the passing grain size. The Wentworth Classification for grain sizes was used. The cumulative curves representing the four sand samples are shown in Figures 6, 7, 8, and 9. The A, B, C, and D sands were classified as medium, coarse, coarse, and very coarse sands, respectively, on the basis of the medium grain size (50% passing). All but the B sand were well sorted.

Permeability tests procedures were those used by Levings (1971). Both constant head and falling head methods were used for the analysis of each sample. Coefficient of permeability values were computed using the following equations:

$$\text{Constant Head } K = \frac{QL}{AH} \tag{2.1}$$

where $K$ = coefficient of permeability, cm/sec;
$Q$ = rate of discharge, $cm^3$/sec;
$L$ = length of sample, cm;
$A$ = area of sample, $cm^2$;
$H$ = pressure head, cm.

$$\text{Falling Head } K = \frac{2.3aL}{AT} \log_{10} \frac{H_0}{H} \tag{2.2}$$

where $K$ = coefficient of permeability, cm/sec;

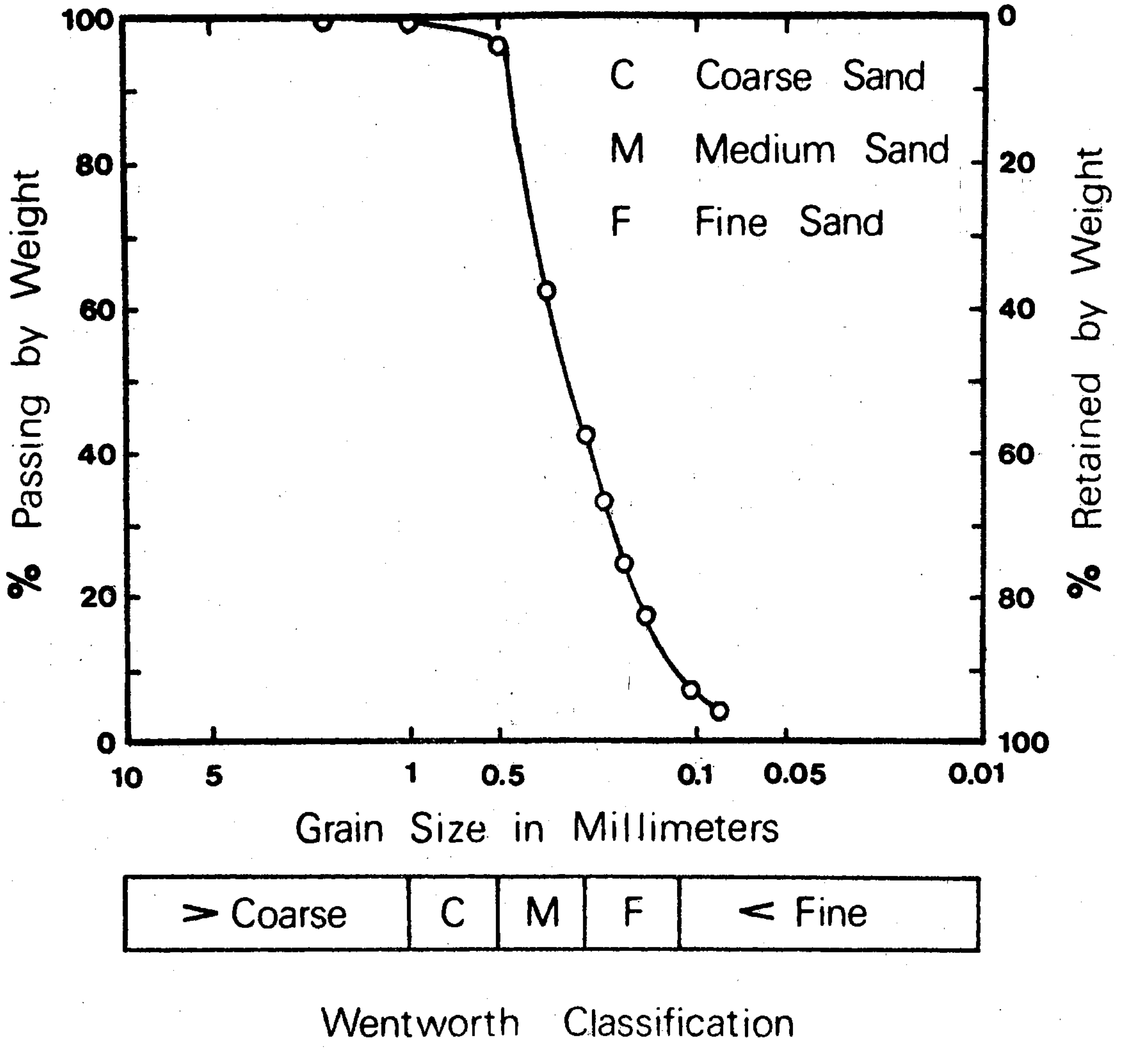

Fig. 6.—Grain-size distribution curve for A sand

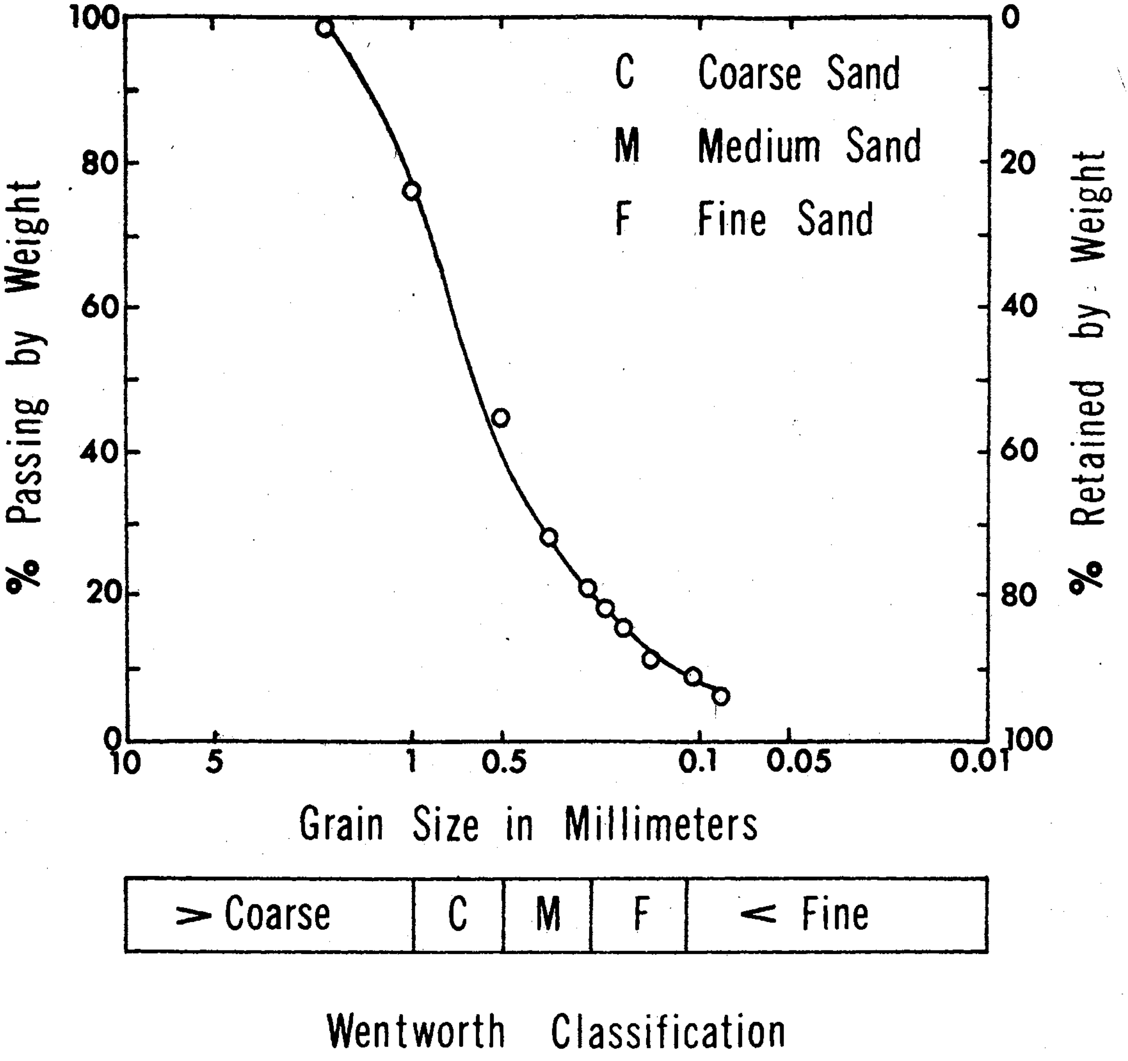

Fig. 7.-Grain-size distribution curve for B sand

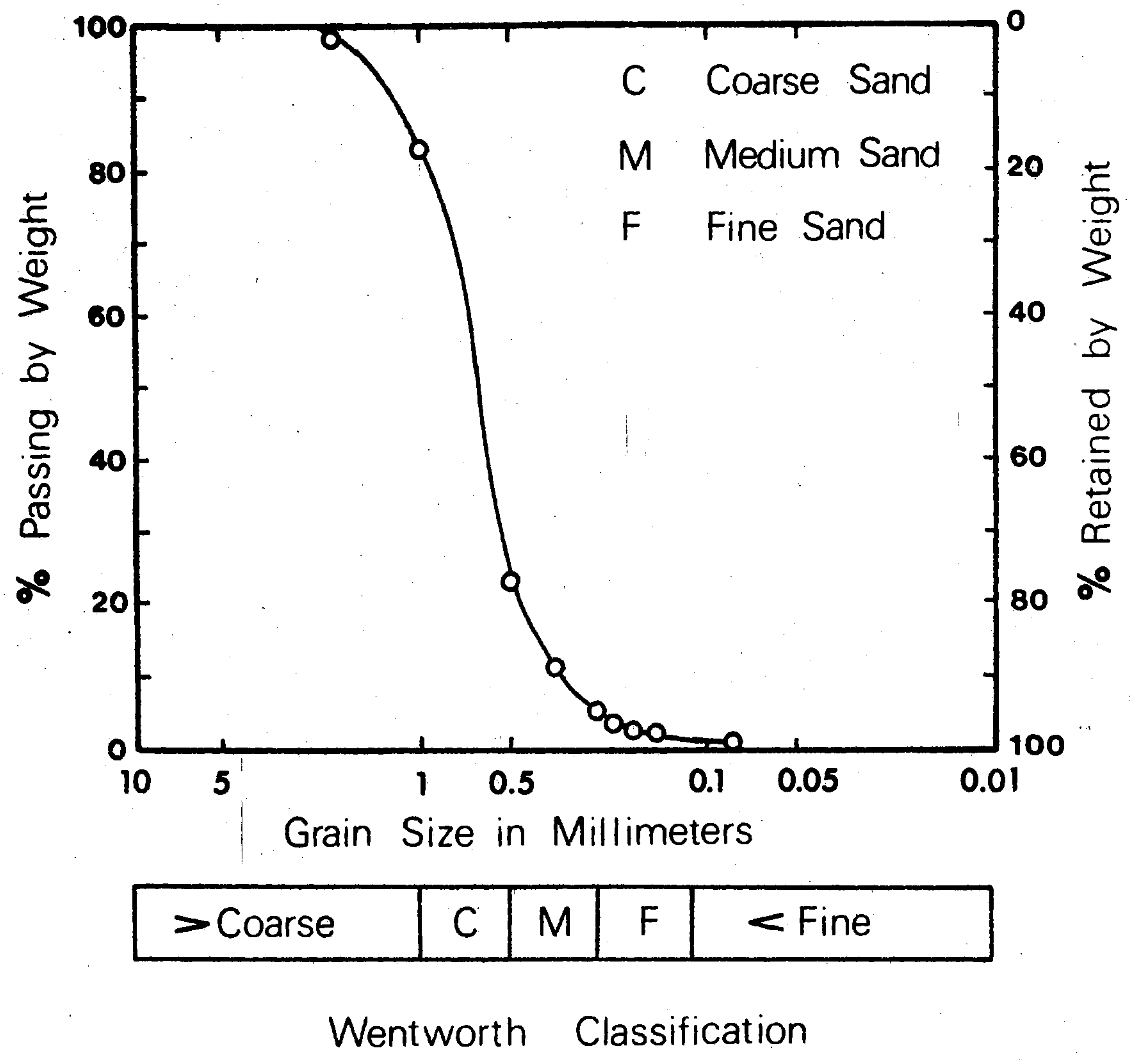

Fig. 8.-Grain-size distribution curve for C sand

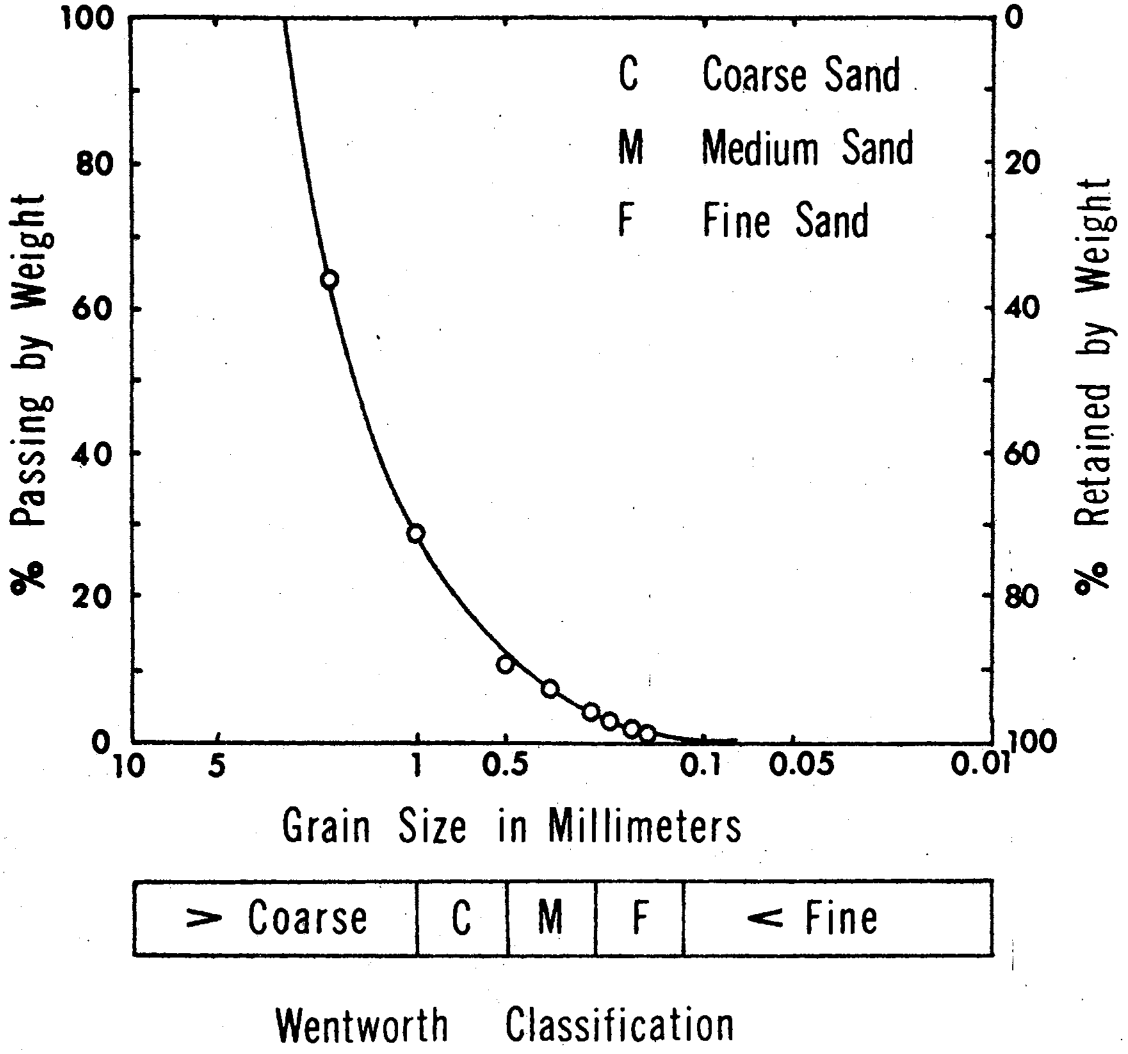

Fig. 9.—Grain-size distribution curve for D sand

a = cross sectional area of pipette, $cm^2$;

L = length of sample, cm;

A = area of sample, $cm^2$;

T = time of test, sec;

$H_0$ = pressure head at beginning of test, cm;

H = pressure head at end of test, cm.

Results are tabulated in Table II. The overall average coefficient of permeability representing the four samples is 400 $gpd/ft^2$. This average is identical to the coefficient of permeability value which was derived from pump test analysis and used in the original Texas Tech model. Therefore, the coefficient of permeability values for each sand were considered to be representative and were subsequently used in the modified management model.

TABLE II

COMPUTED COEFFICIENT OF PERMEABILITY BASED ON LABORATORY TESTS

| Sand Sample | Falling Head Method $GPD/ft^2$ | Constant Head Method $GPD/ft^2$ | Mean Value $GPD/ft^2$ |
|---|---|---|---|
| A | 229 | 70 | 150 |
| B | 297 | 175 | 236 |
| C | 280 | 475 | 277 |
| D | 870 | 800 | 835 |
| Mean of All Samples | 420 | 380 | 400 |

Specific yield values were estimated for each layer. Because an average specific yield value of 0.15 was used previously in the Texas Tech model, it was considered reasonable to assign approximate specific yield values from which an average value of 0.15 could be obtained. The sands (A - D) were assigned values of 0.07, 0.11, 0.17 and 0.25 respectively.

# CHAPTER III

## ADAPTATION OF AQUIFER CHARACTERISTICS TO MANAGEMENT MODEL

Because preliminary geologic and hydrologic data were used, a simplified conceptual model was considered. Therefore, the basic assumptions used in the modified version of the management model were the following:

1) The aquifer is multilayered and is ideally represented by 4 uniform layers of equal thickness.

2) Each layer is horizontally homogeneous.

3) The bedrock topography underlying the Ogallala aquifer is considered to be relatively smooth and slopes approximately 14 feet per mile in a south-easterly direction.

4) The bedrock and water table surfaces are approximately parallel, and are used as the lower and upper boundaries respectively.

5) Weighted averaged values of permeability and specific yield assigned at each time step is a close approximation for the aquifer during that particular time period.

6) There is no recharge or discharge through the bedrock.

7) Recharge and discharge at the surface or boundary of the study area are accounted for by adjustments in pump withdrawal from nodes nearest anyone of several discharge or recharge zones.

A hypothetical grid of well nodes was designed and subsequently adapted to the study area. Within this area, 24 nodes were assigned having fixed coordinates. In addition, 17 nodes were located around the perifery of the area and were used as an aid in defining the boundary conditions. The 24 internal nodes were used to divide the study area into a polygonal grid system. The Thiessen method (Linsley, et al., 1958), used for averaging the distribution of precipitation, was applied to the formation of polygons. This involved bisecting lines between adjacent nodes and subsequently connecting the bisectors together to form 24 polygons within the outer boundary (see Figure 10).

A computer program developed by Lamirand (1971) was used to calculate the surface area of each polygon as well as the ratio of width and length between each common polygon face between adjacent nodes. These computations were used as part of the input data for the computer program of the management model.

In order to quantitatively adjust the boundary conditions relative to natural recharge and discharge, adjustments were made on the pump withdrawal of each node. A weighted-average method based on the area of a polygon was used to account for irrigation well withdrawal from each polygon and to account for gain or loss of ground water from those polygons which are adjacent to the outer boundary of the grid. Irrigation withdrawal from each polygon, and natural recharge or discharge estimates are shown in Table III. Total pump withdrawal from all polygons was equivalent to the sum of the pump capacity for each well within the grid. Natural recharge and discharge values at the edge of the test area were accounted for by nodes adjacent to the boundary. The calculation of natural recharge and discharge included the assumption that an average coefficient of permeability of 400 gpd/ft$^2$ and an average saturated

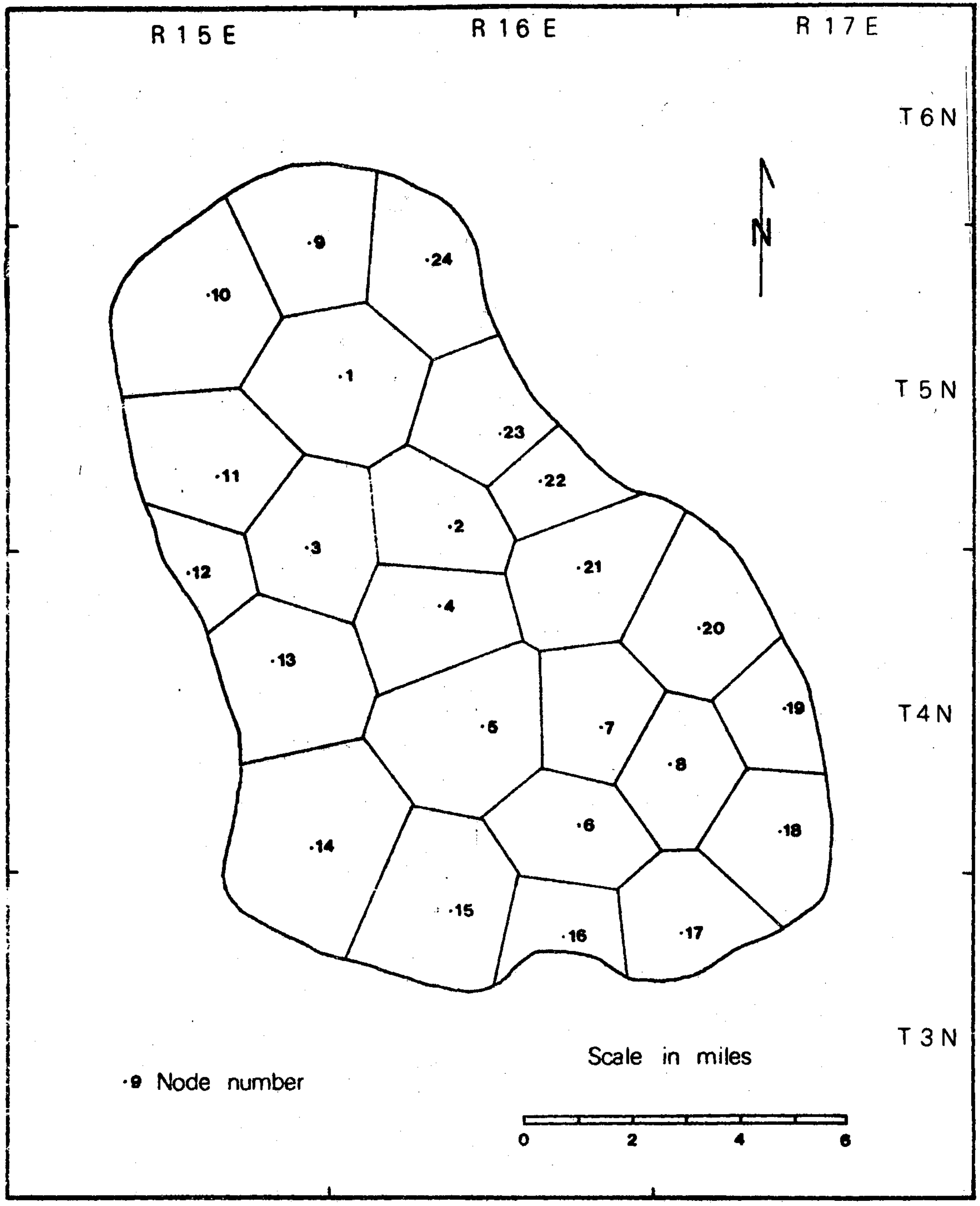

Fig. 10.-Polygon distribution in test area

## TABLE III

## NODE WITHDRAWAL ADJUSTMENTS

|  | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Node | Withdrawal* of Irrigation Wells | Boundary Discharge or Recharge* | Sum* of Columns 1 and 2 | Adjusted Seasonal Withdrawal* (Weighted Average) |
| 1 | 920 | 0 | 920 | 725 |
| 2 | 1320 | 0 | 1320 | 452 |
| 3 | 400 | 0 | 400 | 580 |
| 4 | 932 | 0 | 932 | 564 |
| 5 | 1602 | 0 | 1602 | 790 |
| 6 | 0 | 0 | 0 | 514 |
| 7 | 0 | 0 | 0 | 445 |
| 8 | 0 | 0 | 0 | 449 |
| 9 | 0 | - 646 | - 646 | 666 |
| 10 | 960 | - 946 | 14 | 1153 |
| 11 | 480 | - 270 | 210 | 733 |
| 12 | 0 | - 224 | - 224 | 282 |
| 13 | 1080 | - 445 | 635 | 752 |
| 14 | 460 | - 916 | - 456 | 962 |
| 15 | 0 | 101 | 101 | 739 |
| 16 | 0 | 336 | 336 | 262 |
| 17 | 400 | 1346 | 1746 | 522 |
| 18 | 440 | 1952 | 2392 | 576 |
| 19 | 880 | 1216 | 2090 | 417 |
| 20 | 568 | 476 | 1038 | 736 |
| 21 | 0 | 0 | 0 | 650 |
| 22 | 0 | 197 | 197 | 319 |
| 23 | 360 | 449 | 809 | 491 |
| 24 | 400 | 612 | 1012 | 601 |
| Total | 11202 | 3226 | 14428 | 14500 |

*All units are in acre-ft/0.25 year.

thickness of 200 feet existed at the edge of the grid throughout the entire period of the dewatering process. The water-table gradient for segments on the grid boundary was estimated using the water-level map (Figure 3). Measureable boundary segments were defined as perimeter lengths that are perpendicular to the water-table gradient (parallel to the water-level contour lines). Calculation of boundary recharge or discharge was based on the following equation:

$$Q = KAi \tag{3.1}$$

where $Q$ = the discharge or recharge in acre-feet;

$K$ = the permeability value express on a seasonal basis in terms of acre-feet/0.25 year/ft$^2$;

$A$ = the effective cross-sectional area of the boundary segment;

$i$ = the gradient perpendicular to the boundary.

The resulting natural discharge and recharge values were proportionately assigned, based on boundary segment length, to the outer most polygons in the grid and are listed in Table III. Positive and negative values represent discharge and recharge respectively. The sum of groundwater withdrawal per season from each polygon was obtained by summing algebraically the estimates of pump discharge and natural discharge and recharge. This sum was then divided among polygon nodes depending on their area (weighted-average method). These values for each node are shown in Table III as adjusted seasonal withdrawal. The adjusted withdrawal values were used in the modified computer program.

# CHAPTER IV

# COMPUTER PROGRAMMING OF MANAGEMENT MODEL

The basic program used in this study was originally written by Weber (1968) and later revised by Sechrist, Claborn, Rayner, and Wells (1970). The program was subsequently adapted to the 360-65 at Oklahoma State University by Lamirand (1971). In all preceding uses of the program, the homogeneous case was assumed. In this study, where the multilayered case was also considered, vertical variations of permeability and specific yield values were introduced into the program as a subprogram. Additional revisions were made within the main program and included adaptations for modifying boundary conditions and for electronic plotting of well hydrographs and residual maps. A simplified flow diagram of the modified program is shown in Figure 11. Modifications of the computer management program were two-fold in purpose:

1) To compare results of the program when applied to two situations: a homogeneous aquifer and a multilayered aquifer.
2) To predict the life expectancy of the Ogallala aquifer within the test area when treated as a multilayered aquifer.

There were two types of input data used in the program: data initialized within the program and data input by cards. Initialized data included values of the coefficients of permeability and specific yield, and elevation above sea level for the top of each layer. Either the homogeneous or the multilayered case could be used with the selec-

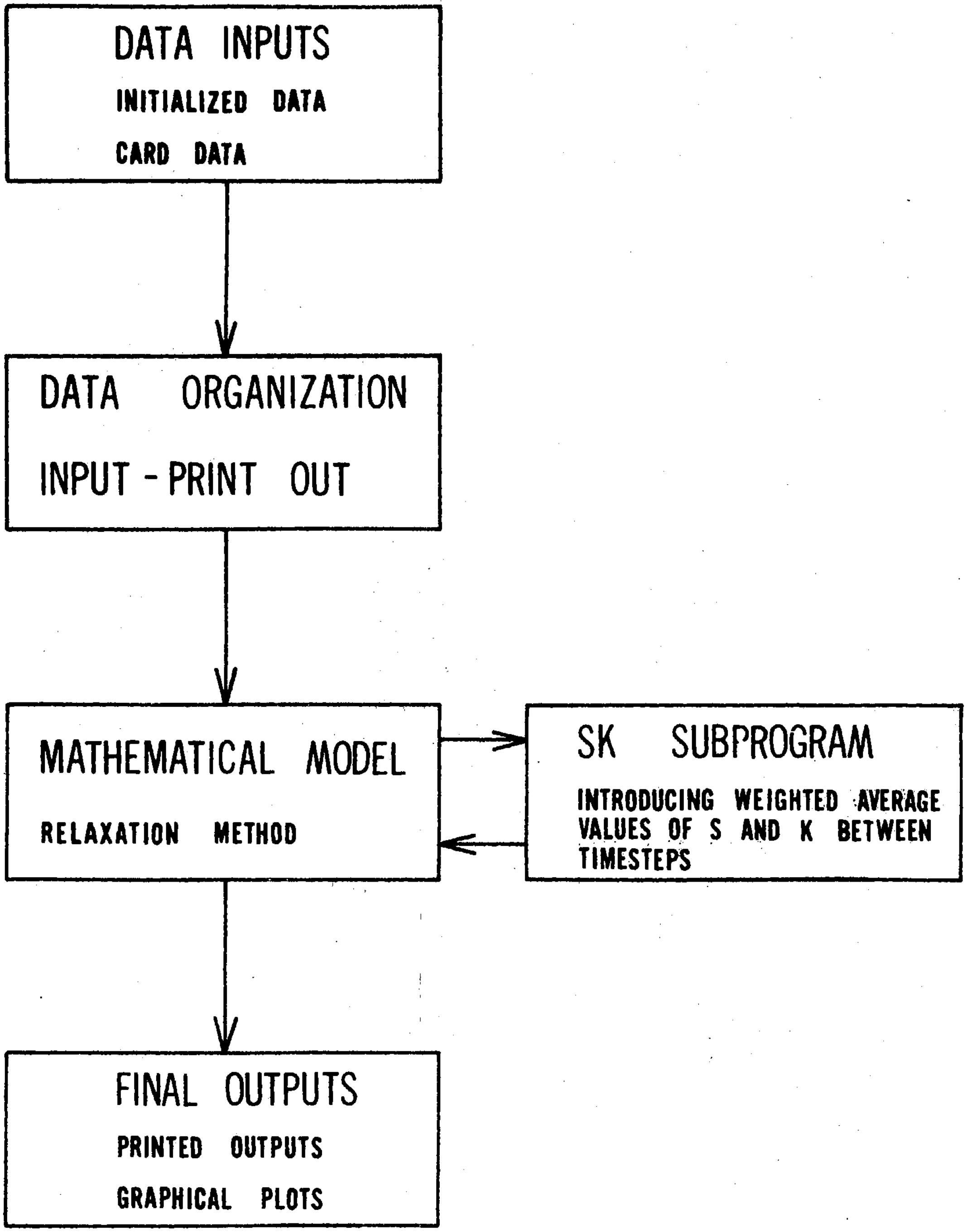

Fig. 11.-Generalized flow diagram of modified computer management program

tion of the appropriate initialized data. Input data by cards included duration of study or of dewatering, starting time, coordinates of nodes, adjusted node withdrawal values, ratios of width and length between nodes sharing polygon faces, areas of nodes, bottom and top elevations of aquifer at nodes, and initial water-level elevation of nodes. In this study, all input data was considered to be the same for the four seasonal periods (Oct.-Dec., Jan.-Mar., April-June, July-Sept.). Definitions of all terms used in the program are shown in the documented program which is listed in Appendix A. The formats used for punching the data input onto cards are listed in Appendix B.

The mathematical model was used to define water-level elevations with respect to time during the dewatering process. New weighted-average values of permeability and specific yield were introduced into the model before each new time step. Thus, the effect of vertical variation in lithology on rates of dewatering could be evaluated when comparing the multilayered and homogeneous cases. The water-level elevation at each node was directly affected by pump withdrawal and flow across polygon faces. Based on Darcy's Law and the concept of continuity, the basic continuity equation for any one node such as the one shown in Figure 12 can be written in the form:

$$-Q_1 - Q_2 - Q_3 + Q_4 - Q_5 - Q_p = AS \frac{\partial h}{\partial t} \tag{4.1}$$

where

$Q_i$ = the amount of flow across the ith face during $\partial t$ time,

$Q_p$ = the net adjusted pump withdrawal during $\partial t$ time,

$A$ = the surface area associated with the node,

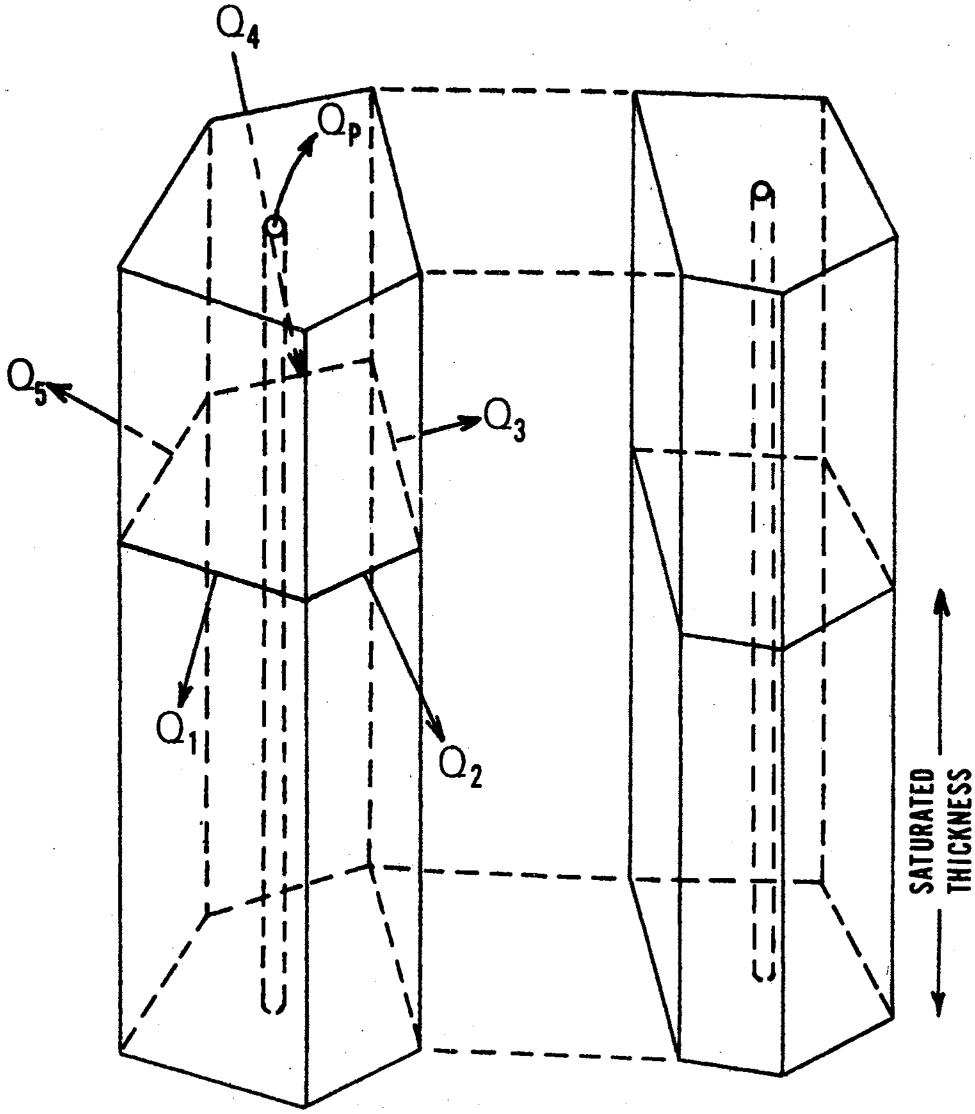

Fig. 12.-Elemental polygon and ground water flux

$S$ = the specific yield value of the aquifer,

$\partial h$ = the increment of change in water-level elevation at the node during $\partial t$ time,

$\partial t$ = the period of time represented by time step.

The $\partial h$ term of Equation (4.1) is approximated by:

$$\partial h \approx H_m^J - H_m^{J-1} \tag{4.2}$$

where:

$H_m^J$ = water-level elevation of the node computed during the present time step.

$H_m^{J-1}$ = water-level elevation of the node at the end of the previous time step.

The amount of flow at the ith face can be defined by Darcy's law:

$$Q_i = K_i H_i W_i \frac{\partial E_i}{L_i} \tag{4.3}$$

where:

$K_i$ = the permeability value at ith face,

$H_i$ = the saturated thickness at ith face,

$W_i$ = the width of the ith face,

$\partial E_i$ = the difference between water-level elevations of nodes sharing the ith face,

$L_i$ = the distance between nodes which share the ith face.

The $H_i$ term in Equation (4.3) is approximated by the following relationship:

$$H_i \simeq \frac{H_m^J + H_n^J}{2} - B_i \tag{4.4}$$

where:

$H_m^J$ = the water-level elevation of the node concerned computed during present time step,

$H_n^J$ = the water-level elevation of the adjacent node computed during present time step,

$B_i$ = the bottom elevation of the aquifer at the ith face which is common to both nodes.

The $\partial E_i$ term of Equation (4.3) is approximated by:

$$\partial E_i \simeq H_m^J - H_n^J \tag{4.5}$$

Finally, by substituting Equations (4.2), (4.3), (4.4), and (4.5) into Equations (4.1), the following equation is obtained:

$$\begin{aligned} K \sum_{i=1}^{a} \left(\frac{H_m^J + H_n^J}{2} - B_i\right) \cdot W_i \cdot \left(\frac{H_m^J - H_n^J}{L_i}\right) - Q_p \\ = AS \left(\frac{H_m^J - H_m^{J-1}}{\partial t}\right) \end{aligned} \tag{4.6}$$

where in addition:

a = the number of faces that the node in concern has.

However, Equation (4.6) represents only one node. If there are X number of nodes in a grid, it is then necessary to use Equation (4.6) sequentially for X number of nodes for any one timestep and then to solve the equations simultaneously for $H_m^J$.

A relaxation method was used to solve the set of simultaneous equations in the form of Equation (4.6). This is a numerical-differencing technique which is often used in solving finite-difference equations. The relaxation procedure is used at each timestep. Within each timestep, water-level elevations of all nodes are adjusted through a series of iterative steps until the difference between the right-hand side of Eqn. (4.6) and the $Q_p$ term on the left-hand side becomes less than the value of a specified degree of error (4 acre-feet was arbitrarily used in this study). Other terms on the left-hand side of the equation should equal zero when the flow between polygons within the grid boundary are balanced. Therefore, the difference between the two sides of the question will theoretically converge to zero. The adjusted water-level elevations for all nodes will be introduced into the next timestep and considered as the term $H_m^{J-1}$ for each node.

New weighted-average values of the coefficient of permeability and specific yield are computed in a subprogram between timesteps. The two hydraulic coefficients are averaged using the following equations:

$$K = \frac{\sum_{i=1}^{n} K_i M_i}{\sum_{i=1}^{n} M_i} \tag{4.7}$$

$$S = \frac{\sum_{i=1}^{n} S_i M_i}{\sum_{i=1}^{n} M_i} \tag{4.8}$$

where:

$n$ = the number of layers,

$K_i$ = the coefficient of permeability value of ith layer,

$S_i$ = the specific yield value of ith layer,

$M_i$ = the saturated thickness of ith layer.

The term $M_i$ is the difference between the elevation at the base of the middle point in the grid and the average of the water-level values ($H_m^{J-1}$) computed at the end of the previously executed timestep.

An example for computing the new weighted average of the coefficients of permeability and specific yield can be cited. It will be assumed that the aquifer has been dewatered from a saturated thickness of 400 feet to 250 feet. The hydraulic coefficients constants used for the 4 layers are the following:

$K_1$ = 150 gpd/ft$^2$ $S_1$ = 0.07
$K_2$ = 236 gpd/ft$^2$ $S_2$ = 0.11
$K_3$ = 377 gpd/ft$^2$ $S_3$ = 0.17
$K_4$ = 835 gpd/ft$^2$ $S_4$ = 0.25

Layer 1 represents the top of the saturated aquifer. Assuming the aquifer has achieved a saturated thickness of 250 feet, only layers 2, 3, and 4 would be involved in the calculation. The weighted-average values of permeability and specific yield for this hypothetical timestep would be calculated in the following manner:

$$K = \frac{(236 \text{ x } 50) + (377 \text{ x } 100) + (835 \text{ x } 100)}{250} \text{ gpd/ft}^2$$

$$= 532 \text{ gpd/ft}^2$$

$$S = \frac{(0.11 \text{ x } 50) + (0.17 \text{ x } 100) + (0.25 \text{ x } 100)}{250}$$

$$= 0.19$$

Final output from the computer program of the mathematical model was in the form of printed output and included average coefficients of permeability and specific yield, water-level elevations and accumulative drawdown values for each timestep, as well as residual water-level values of selected time periods. These results were also electronically plotted in the forms of hydrograph plots for each node and residual maps for different time periods.

# CHAPTER V

# RESULTS

Two sets of results were obtained from the computer program of the modified computer-management model. The first set included a comparison of hydrographs representing nodes in both homogeneous and multilayered cases. In addition, a sensitivity analysis of the coefficient of permeability and specific yield was conducted. The second set of results included predictions of water-level change over time within the test area near Guymon, Oklahoma.

Comparison of homogeneous and multilayered cases were made using the original and modified programs respectively. A permeability value of 400 gpd/ft$^2$ and a specific yield value of 0.15 was used for the homogeneous case. Weighted-average values of permeability and specific yield were introduced between timesteps for the multilayered case. An initial saturated thickness of 400 feet was used in both cases. Accumulative drawdown over time was extended until the water level of any one node reached the base of the aquifer. Accumulative drawdown over time was obtained in the form of X-Y plots representing hydrographs for each node.

Hydrographs representing the same node for both homogeneous and multilayered cases were then overlaid on one another and a residual curve was drawn which represented the residual difference between the two curves. This was repeated for all 24 nodes. Representative hydrographs are shown in Figures 13, 14, and 15. These plots are representa-

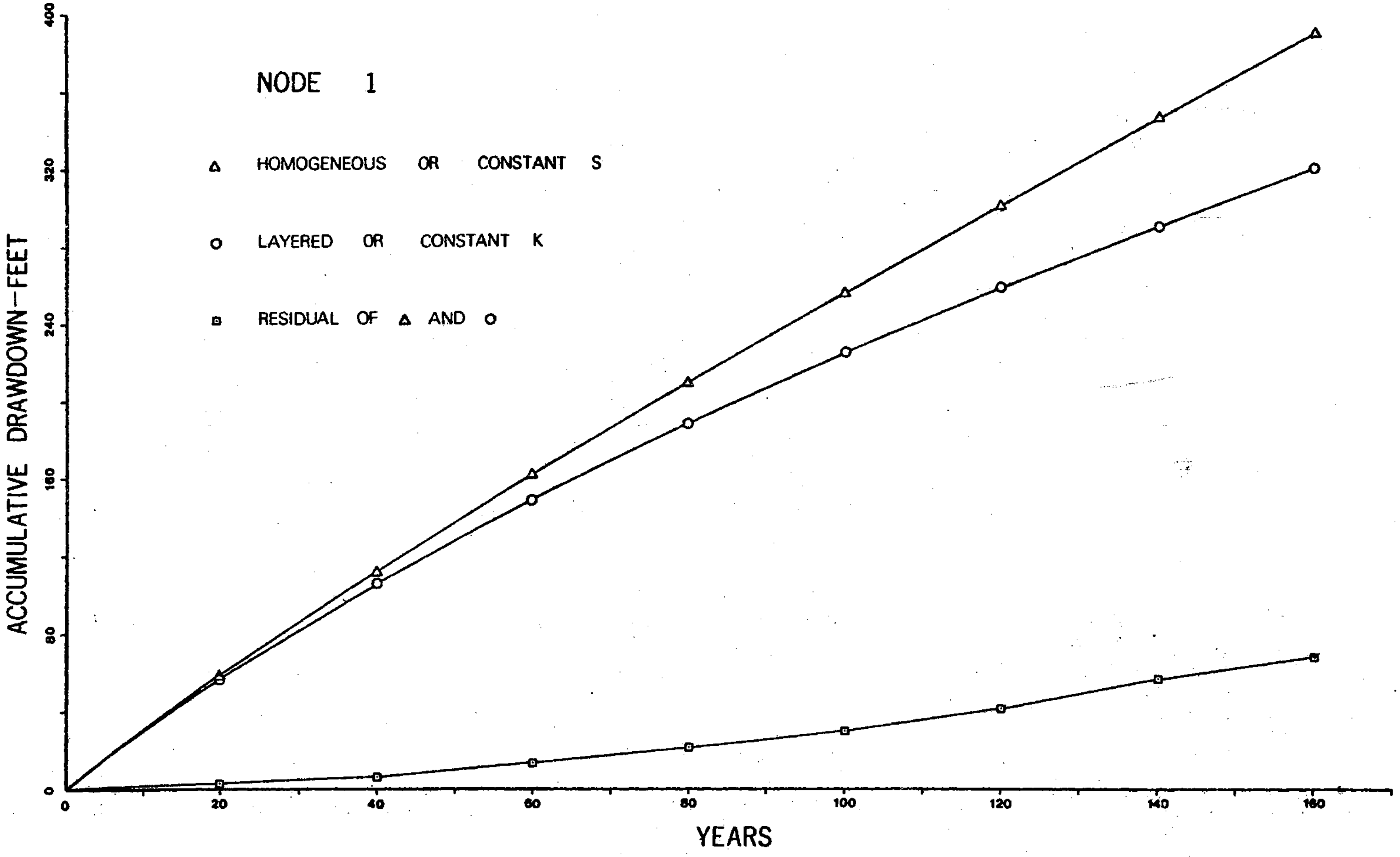

Fig. 13.-Representative hydrographs of node 1

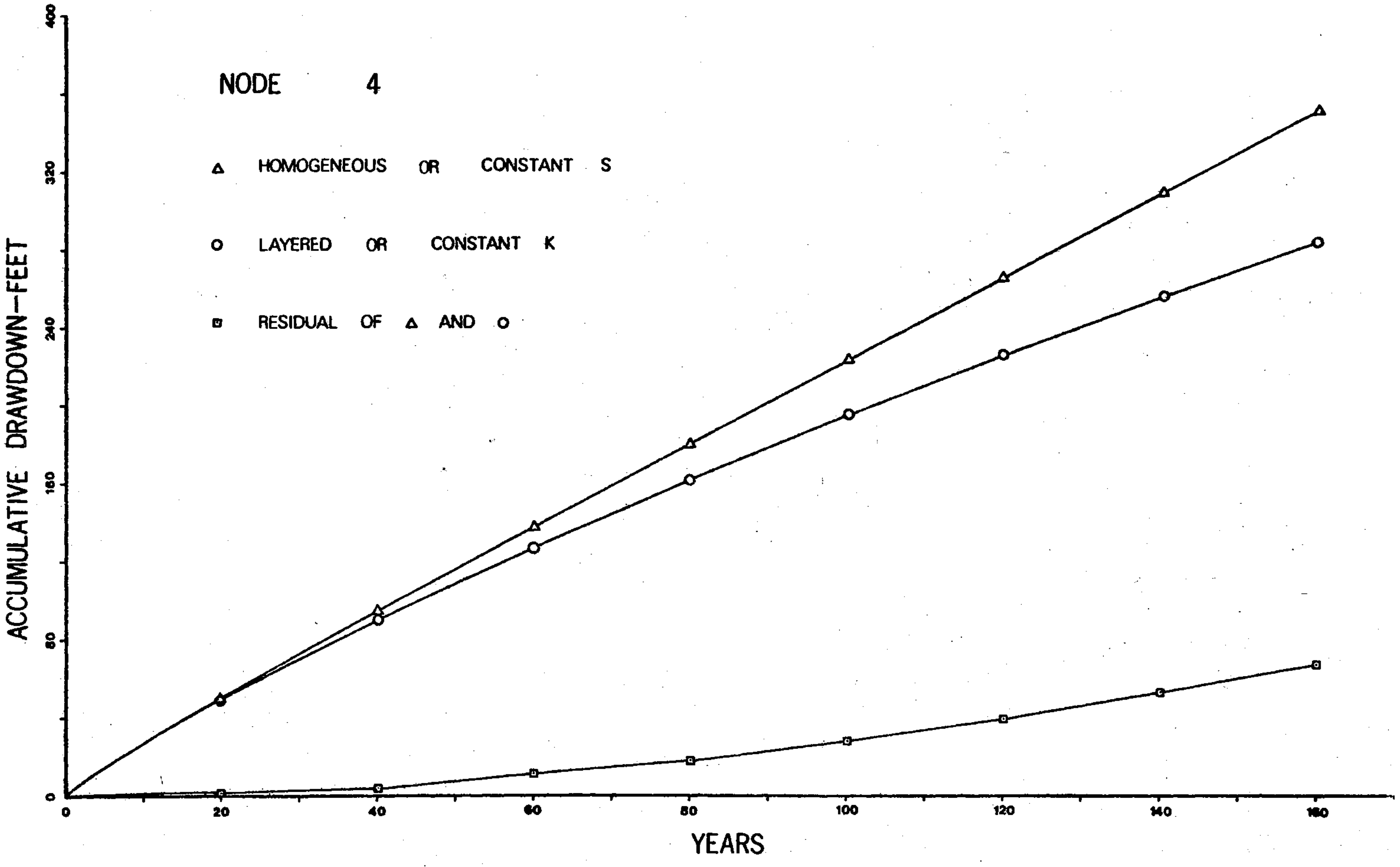

Fig. 14.-Representative hydrographs of node 4

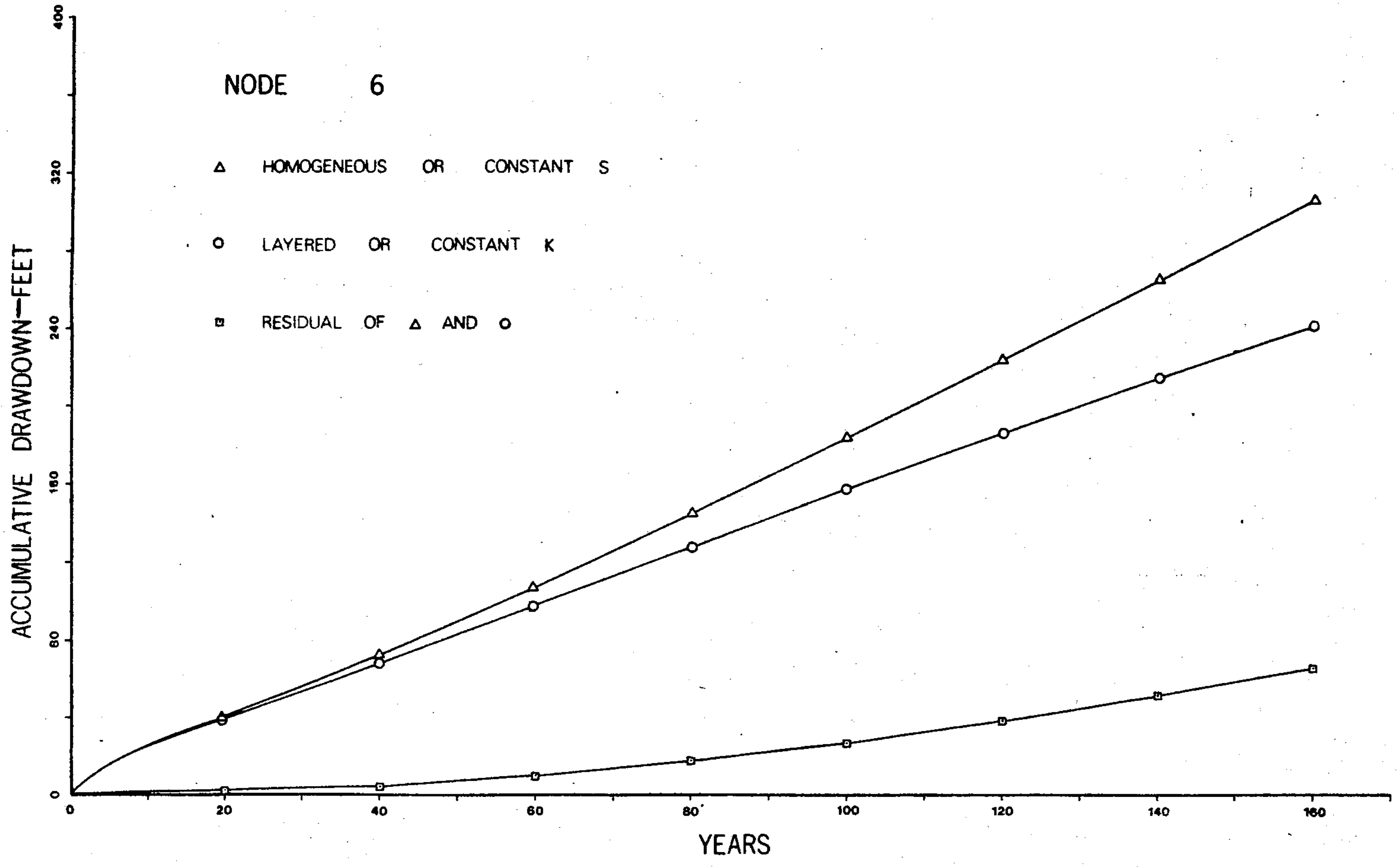

Fig. 15.-Representative hydrographs of node 6

tive of the upper, central, and lower portions of the grid area respectively. A significant difference between the homogeneous and the multilayered cases can be noted in all three hydrographs. The residual difference is clearly indicated by the residual curve. Envelope curves were prepared to represent hydrographs for all nodes for both homogeneous and multilayered cases. These are shown in Figure 16. Four residual maps were prepared (Figures 17, 18, 19, and 20) in order to evaluate the areal variation of the residual differences between hydrographs for the two cases. An accumulative time period is represented on each map. The residual values for the first 40 years (Figure 17) indicates that a difference of approximately 6 feet of drawdown occurred between the homogeneous and the multilayered cases throughout the area. Similarly, differences of approximately 18 feet, 39 feet and 66 feet occurred for periods of 80, 120, and 160 years respectively (see Figures 18, 19, and 20). The maximum difference of 66 feet occurred at the time when any one of the polygons was completely dewatered. The small difference in residual values between nodes for any one time period is apparently the result of the following assumptions: 1) Each layer is uniformally thick and homogeneous in the lateral directions, and 2) an averaging technique was used for determining the distribution of pump discharge for each polygon.

The sensitivity of the program to the coefficients of permeability and specific yield was evaluated by keeping either of the two variables constant throughout the period of dewatering while using the multilayered case. When specific yield was varied, it was noted that the water-level changes were clearly different in the two cases (see Figures 13, 14, and 15). Conversely, the model response was identical to that of the homo-

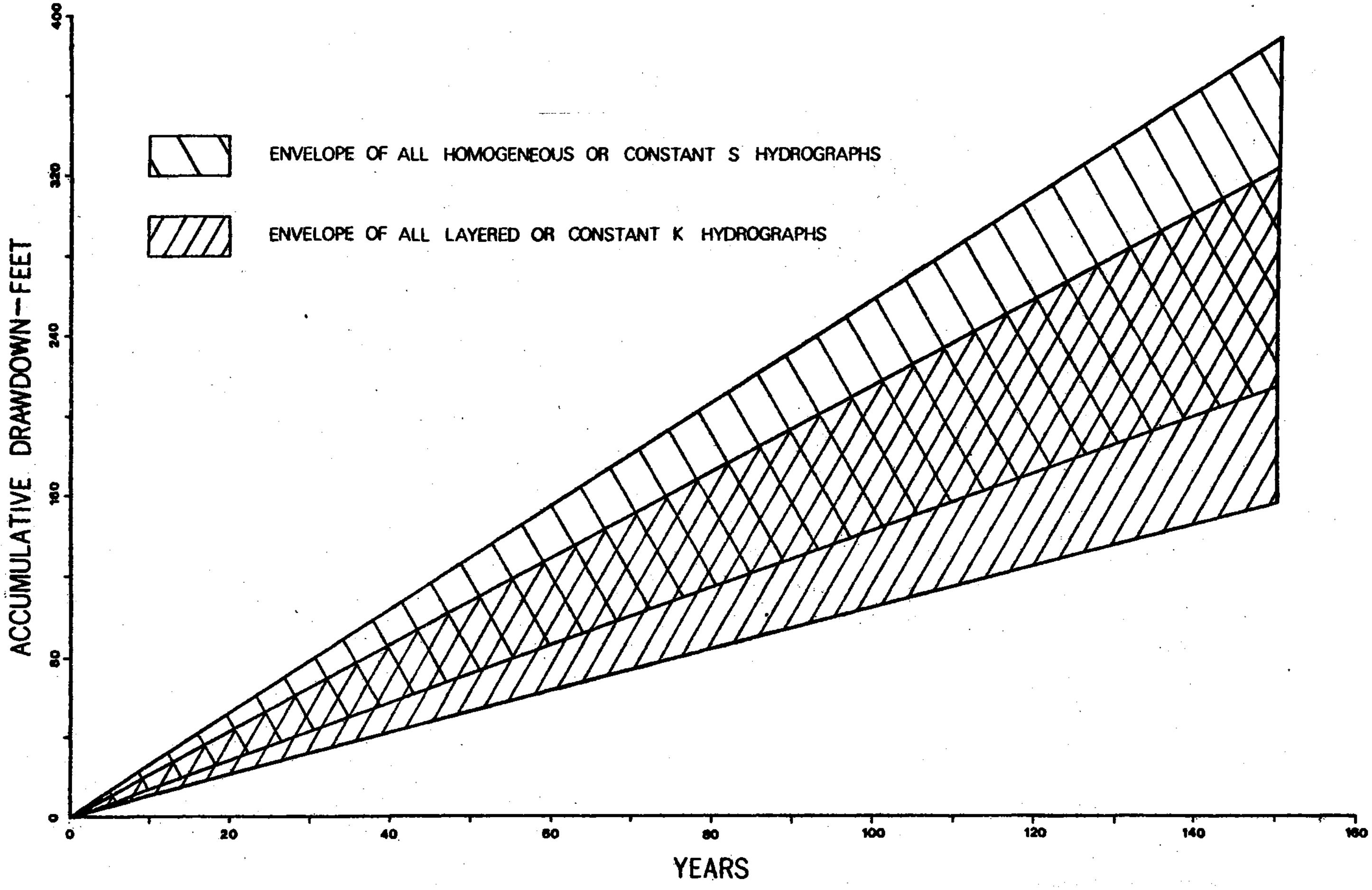

Fig. 16.-Envelopes of hydrographs of all nodes

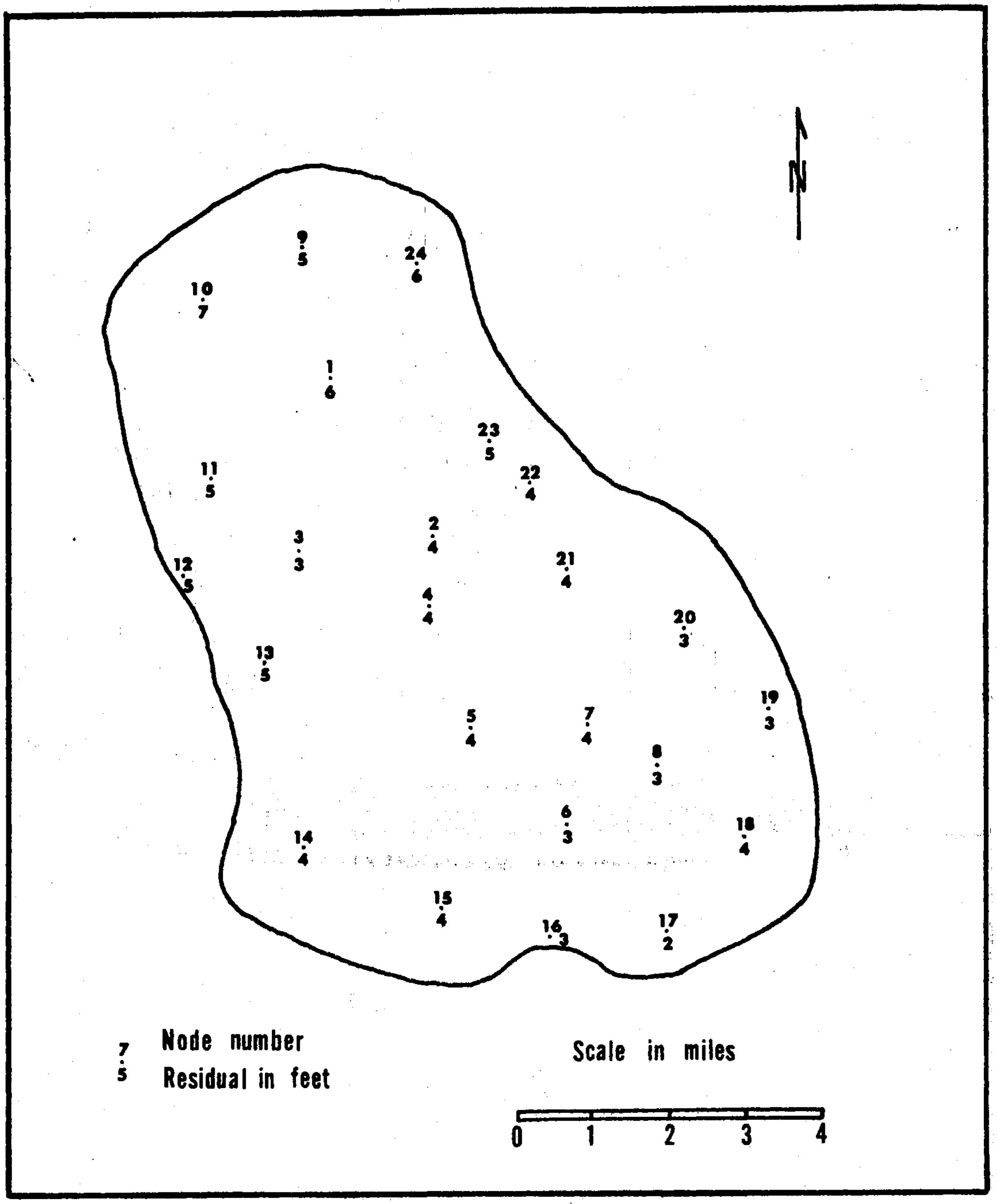

Fig. 17.-Forty-year residual map

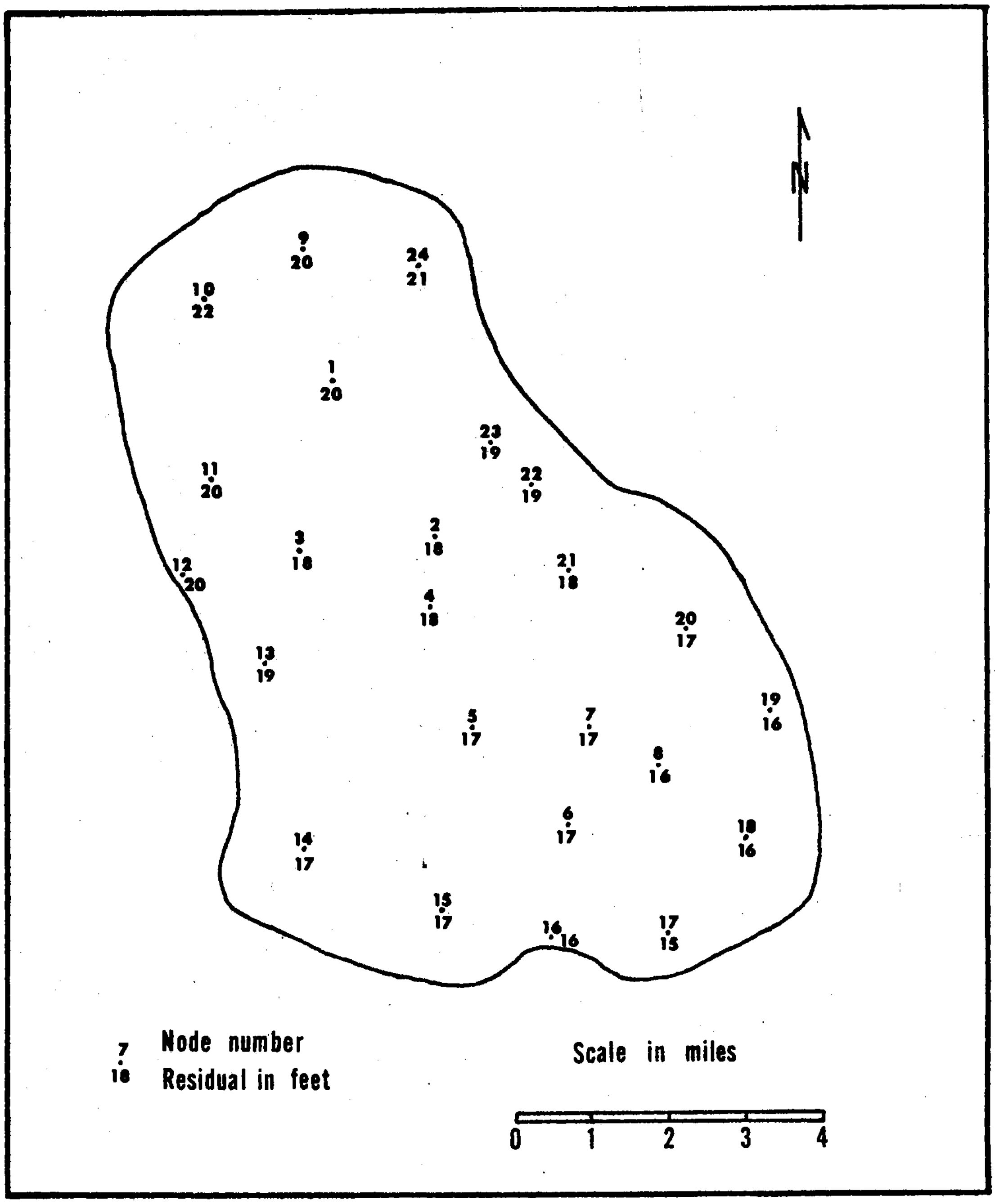

Fig. 18.-Eighty-year residual map

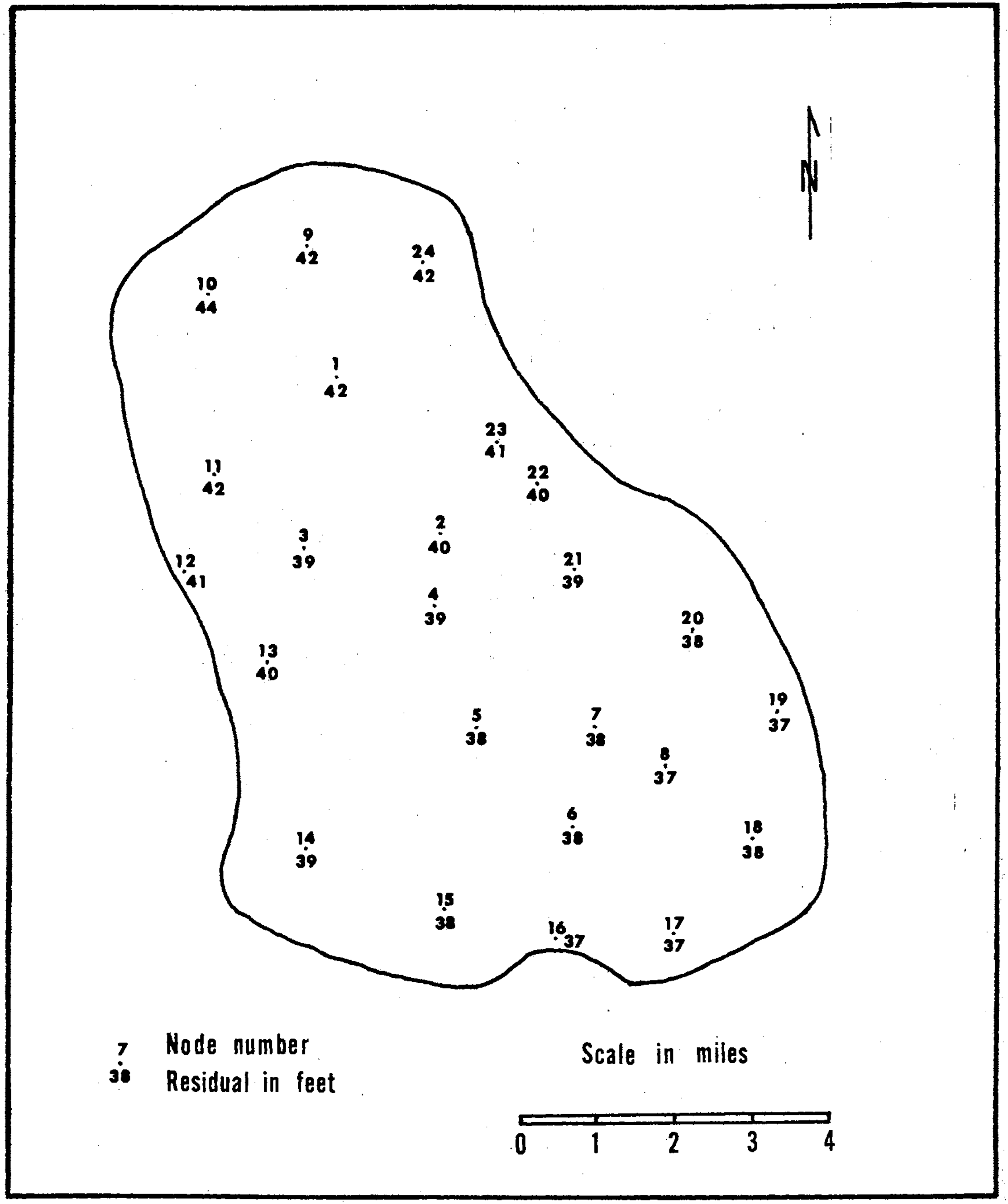

Fig. 19.-One-hundred and twenty-year residual map

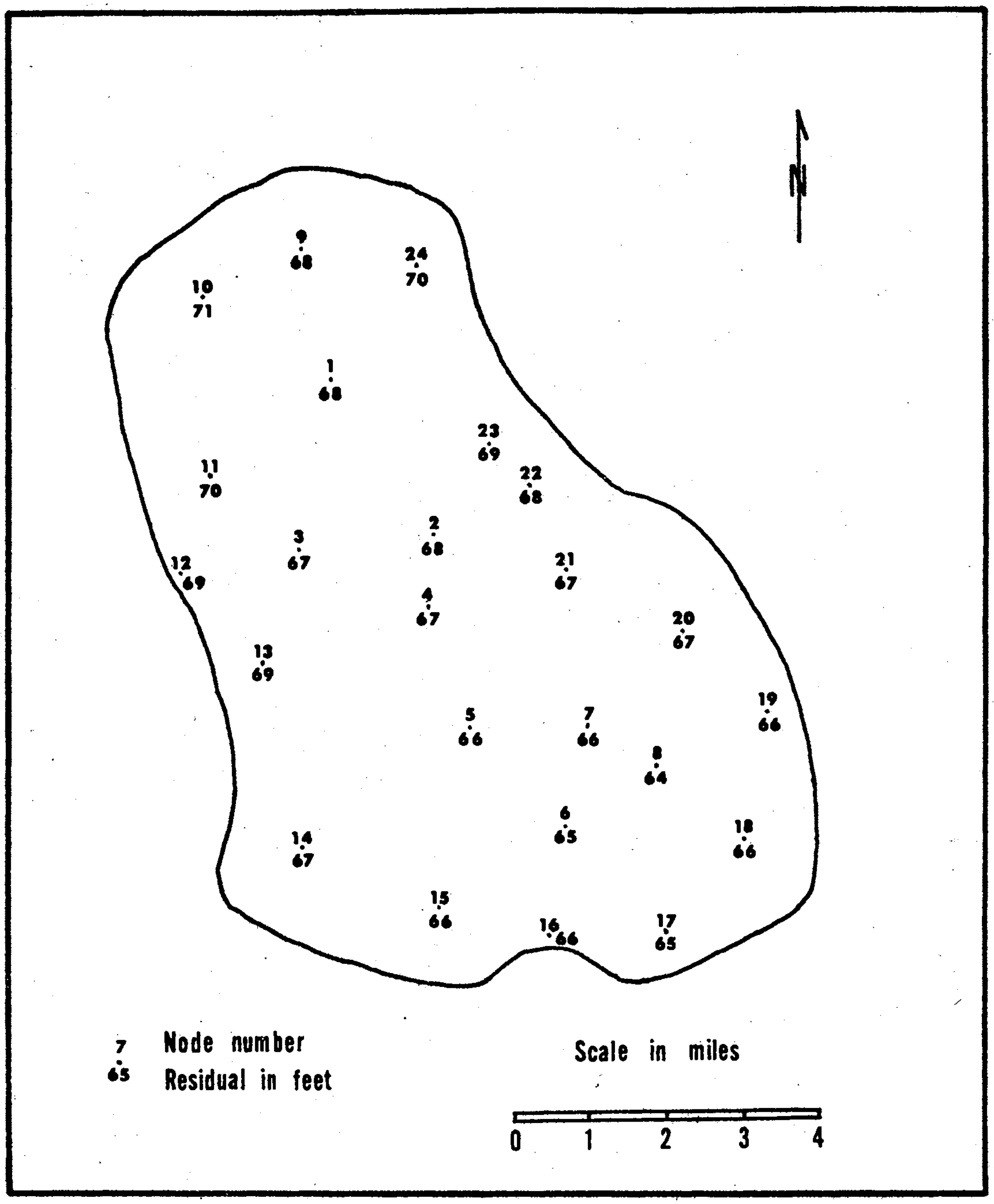

Fig. 20.-One-hundred and sixty-year residual map

geneous case if specific yield was held constant. It was concluded from these results that the program is insensitive to changes of the average coefficient of permeability over time but is sensitive to changes of the average specific yield over the same period of time.

The area just north of Guymon (see Figure 1) was chosen as a test for the model predictions of water-level change over time because of the uniformity of saturated thickness and the heavy density of irrigation wells. Predictions of future water levels were obtained for both homogeneous and multilayered cases using an estimate of the present pump rate. In the case of a homogeneous aquifer, the minimum life expectancy of the aquifer was computed to be approximately 300 years assuming no increase in the ground-water withdrawal rate during the dewatering period. Similarly, dewatering to the base of the aquifer was computed to take approximately 400 years in the case of the multilayered aquifer.

Residual values representing the difference in water levels between 1966 to 1970 for wells located in the test area were obtained from published data (Hart, 1971). These data were used for verification of the model. Residual values of all nodes for the same four year period were available from printed output for both homogeneous and multilayered cases in the test area. A comparison of these residual values are shown on Table IV. Residual values for both cases are identical because the same average values are used for the coefficients of permeability and specific yield in both cases during the initial timestep and because the model is insensitive to changes occurring within such a short period of time. It is apparent that not enough recorded ground-water levels are available for an adequate comparison to be made. Also, the time period represented is too short for any statistical analysis to be made of the

# TABLE IV

## COMPARISON OF WATER LEVEL RESIDUAL VALUES

| Node | Homogeneous* | Multilayered* | USGS Water Level* Residual 1966 - 1970 |
|---|---|---|---|
| 1 | 12.4 | 12.4 | 9.6 |
| 2 | 10.1 | 10.1 | 22.0 |
| 3 | 6.5 | 6.5 | No Data |
| 4 | 9.2 | 9.2 | 9.2 |
| 5 | 3.0 | 3.0 | 8.3 |
| 6 | 9.2 | 9.2 | No Data |
| 7 | 5.9 | 5.9 | No Data |
| 8 | 2.1 | 2.1 | No Data |
| 9 | 11.8 | 11.8 | No Data |
| 10 | 17.2 | 17.2 | No Data |
| 11 | 8.8 | 8.8 | No Data |
| 12 | 6.8 | 6.8 | No Data |
| 13 | 11.3 | 11.3 | 6.4 |
| 14 | 6.8 | 6.8 | - 0.9 |
| 15 | 4.5 | 4.5 | No Data |
| 16 | 3.2 | 3.2 | - 0.6 |
| 17 | -16.3 | -16.3 | No Data |
| 18 | -38.5 | -38.5 | 10.8 |
| 19 | - 9.5 | - 9.5 | 12.4 |
| 20 | - 2.3 | - 2.3 | No Data |
| 21 | - 0.1 | - 0.1 | No Data |
| 22 | 5.4 | 5.4 | No Data |
| 23 | 3.4 | 3.4 | No Data |
| 24 | 8.7 | 8.7 | 5.4 |
| Average | 2.8 | 2.8 | 8.5 |

*All units are in feet.

comparison. It is apparent, however, that the magnitude of the computed and actual residual values are approximately the same. More recorded well data representing a much longer period of record are needed to make a valid verification of the model.

# CHAPTER VI

# CONCLUSIONS

Results from the mathematical model indicate that a significant difference can be obtained when comparing the homogeneous and multilayered approaches to aquifer management. Therefore, it can be concluded that layering in an aquifer should be considered in any management model which will be used for management of the ground-water resource. However, the assumption that the layers are considered to be of equal thickness and laterally homogeneous, is as previously stated, an over-simplification. Before more complex layering can be considered, additional data and further modifications in the program will be required. Lateral variations in lithology may produce results in which the polygons behave more independently resulting in a greater variation in drawdown at any one time-step. Furthermore, more complex layering may produce results in which drawdown estimates would occur in the range between the values computed for the two cases considered in this study. If this can be shown by including other variations in the model, the model estimates for the homogeneous and multilayered cases might provide an envelope within which the actual values would occur. By using such an envelope, both conservative and liberal predictions of water-level change over time could be provided.

Problems encountered in this study included the following: estimates of natural recharge and discharge at the boundary of the grid and of distributed pump withdrawal, estimation of the coefficients of permeability and specific yield, and lack of water-level and borehole data. A better definition of boundary conditions could result by including the computations of flow across outer boundaries between timesteps instead of using an average value for the entire dewatering period. Thus, new estimates of gradient and saturated thickness at the outer boundary could be computed for each succeeding timestep as the aquifer is being dewatered. Additional data outside of the grid boundary would improve these estimates. A more accurate estimate of pump withdrawal should not be averaged but rather consist of total pump withdrawal from each node for only the wells inside of each corresponding polygon. However, this improvement will require additional pump discharge values and a better method for estimating them.

Better estimates of the coefficients of permeability and specific yield can be achieved by 1) laboratory analysis of a greater number of field samples from outcrops, 2) laboratory analysis of core samples, and 3) pump test data within the areas being modeled. The logic of using weighted-average values for the coefficients at each new timestep should also be verified by simulating pump tests using sand models. Research using this approach is currently being conducted by R. N. DeVries and D. C. Kent at Oklahoma State University.

Additional borehole control will be necessary in order to enhance verification of the model and to more carefully define both vertical and horizontal variations in lithology. If the management model is to be used for more accurate predictions, both vertical and horizontal variations will have to be considered because only vertical variations were considered in this study.

The present model has been useful in providing information for the determination of additional field work and model adjustments. Improvements of the management model which are based on the above recommendations will provide a more accurate prediction of water-level changes in layered aquifers. However, in the development of a good aquifer management model, social, legal, and economic constraints should to be quantitized and subsequently adapted to the model as additional input data. This will provide the necessary link between mathematical programming and the application of the model to current and future demands for ground water.

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# APPENDIX A

# COMPUTER PROGRAM LISTING

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                                 80/80 LIST

00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
//LOC    JOB (12295,465-92-2823,4,20),'WALTER LOO',CLASS=B
// EXEC FORTGCLG,REGION.GO=338K,TIME.GO=4
//FORT.SYSIN DD *
C******************************************************************************C
C                                                                              C
C        A MODIFIED TEXAS TECH GROUNDWATER MANAGEMENT MODEL                    C
C                       BY WALTER WEI-TO LOO                                   C
C                               1972                                           C
C                       OKLAHOMA STATE UNIVERSITY                              C
C                               IBM 360/65 MODEL                               C
C                                                                              C
C******************************************************************************C
C                                                                              C
C        THIS IS A PROGRAM TO MODEL FLOW WITHIN A MULTILAYERED AQUIFER         C
C        WEIGHED AVERAGE VALUE OF PERMEABILITY & SPECIFIC YIELD FOR            C
C        REMAINING SATURATED THICKNESS WILL BE ASSIGNED AT EACH TIMESTEP       C
C        BASIC ASSUMPTIONS:                                                    C
C                         1  THE AQUIFER IS MULTILAYERED AND IS IDEALLY        C
C                            REPRESENTED BY 4 UNIFORM LAYERS OF EQUAL THICKNESSC
C                         2  EACH LAYER IS HORIZONTALLY HOMOGENEOUS            C
C                         3  WEIGHTED AVERAGE VALUES OF PERMEABILITY AND       C
C                            SPECIFIC YIELD ASSIGNED AT EACH TIMESTEP IS A     C
C                            CLOSE APPROXIMATION FOR THE AQUIFER DURING THAT   C
C                            PARTICULAR TIME PERIOD                            C
C                         4  THE BEDROCK TOPOGRAPHY IS RELATIVELY SMOOTH AND   C
C                            IS SLANTED ABOUT 14 FEET PER MILE                 C
C                         5  THE BEDROCK AND WATER TABLE SURFACES ARE APPROX.  C
C                            PARALLEL                                          C
C                         6  THERE IS NO RECHARGE OR DISCHARGE THROUGH THE     C
C                            BEDROCK                                           C
C                         7  RECHARGE AND DISCHARGE AT SURFACE OR BOUNDARY OF  C
C                            STUDY AREA ARE ACCOUNTED FOR BY ADJUSTMENTS ON    C
C                            WITHDRAWAL FROM NODES                             C
C                                                                              C
C******************************************************************************C
C                                                                              C
C                                    ARRAYS                                    C
C                                                                              C
C        A(I)=  AS(I)*SY  (ACRES)                                              C
C        AO(I)=  WITHDRAWAL  FROM  NODE(I)  (ACRE-FT/TIMESTEP)                 C
C        AQS(I)=  NET  SURFACE  FLOW  OF  NODE(I)  AT  TIMESTEP  (ACRE-FT)     C
C        AS(I)=  AREA  OF  A  POLYGON(I)  (ACRES)                              C
C        B(I)=  ELEVATION  OF  BEDROCK  AT  POLYGON  INTERFACE(I)  (FEET)      C
C        BL(I)=  BEDROCK  ELEVATION  AT  NODE(I)  (FEET)                       C
C        COEFF(I)=  PERMEABILITY  OF  SATURATED  MATERIAL  UNDER  NODE(I)  AT  C
C                    A  TIMESTEP  (ACRE-FT/TIMESTEP/SQ.FT)                     C
C        D(I)=  THICKNESS  OF  AQUIFER  AT  POLYGON  INTERFACE(I) (FEET)       C
C        DH(I,J)=  ACCUMULATIVE  DRAWDOWN  AT NODE(I)  AND                     C
C                 AT  TIME  TSTEP(1,I)  (FEET)                                 C
C        EL(I)=  ELEVATION  OF  TOP  OF  LAYER(I)  (FEET)(DATUM= 0.0)          C
C        H(I)=  WATER  TABLE  ELEVATION  AT  POLYGON(I)  (FEET)                C
C        HINIT(I)=  INITIAL  WATER  LEVEL  AT  NODE(I)  (FEET)                 C
C        HO(I)=  INITIAL  WATER  TABLE  ELEVATION  AT  NODE(I)  (FEET)         C
C        HS(I,J)=  WATER TABLE  ELEVATION  OF  NODE(I)  AT  TSTEP(1,J)  (FEET) C
```

```
                                   80/80 LIST

          00000000011111111112222222222333333333344444444445555555555666666666677777777778
          12345678901234567890123456789012345678901234567890123456789012345678901234567890
CARD
0055    C           NODE1(I),NODE2(I)=  FLOWPATH  EXISTS  BETWEEN  CENTER  NODF1(I)       C
0056    C                               AND  ADJACENT  NODE  NODE2(I)                     C
0057    C            N1(I),N2(I)=  SAME  AS  NODE1,NODE2                                  C
0058    C           NWELLC(I)=  WELL NUMBER  OF  NODE(I)                                  C
0059    C           P(I)=  CONSTANT  FOR  FLOWPATH(I)  SO  THAT  FLOW  CAN  BE CALCULATED C
0060    C           PL(I)=  PERMEABILITY  OF  LAYER(I)  (ACRE-FT/TIMESTEP/SQ.FT)          C
0061    C           Q(I)=  FLOW  FROM  ONE  POLYGON  TO  ANOTHER  DURING  ONE  TIMESTEP   C
0062    C                 (ACRE-FT)                                                       C
0063    C           QS(I)=  VOLUME  OF  WATER  ABOVE  GROUND  SURFACE  OF  NODE(I)        C
0064    C                  (ACRE-FT)                                                      C
0065    C           RELAX(I)=  STORAGE  CHANGE  AT  NODE(I)  PER  TIMESTEP                C
0066    C                    (ACRE-FT/TIMESTEP)                                           C
0067    C           RES(I)=  RESIDUAL  ERROR  AT  NODE(I)  AFTER  BALANCING  ALL  FLOWS   C
0068    C                              (BY  FINITE  DIFFERENCING)  PER  TIMESTEP          C
0069    C                              (COMPARISUN  OF  VOLUME  OF  CRAFT  WITH  VOLUME   C
0070    C                               REPRESENTED  BY  DRAWDOWN  FOR  EACH  NODE  &     C
0071    C                              TIMESTEP)  (ACRE-FT/TIMESTEP)                      C
0072    C           S(I)=  NET  WITHDRAWAL  AT  NODE(I)  FOR  A  TIME  STEP  (ACRE-FT)    C
0073    C           SCL(I)=  STORAGE  COEFFICIENT  OF  LAYER(I)                           C
0074    C           SL(I)=  SURFACE  ELEVATION  AT  NODE(I)  (FEET)                       C
0075    C           SLX(I)=  SURFACE  ELEVATION  AT  NODE(I)  (FEET)                      C
0076    C           TSTEP(1,I)=  TIME  CORRESPOND  TO  A  TIMESTEP  (CALFNDER  YEAR)      C
0077    C           XNODE(I)=  X  COORDINATE  VALUE  OF  NODE(I)  (MILES)                 C
0078    C           Y(I)=  WIDTH  OF  FACE/DISTANCE  BETWEEN  NODES                       C
0079    C           YNODE(I)=  Y  COORDINATE  VALUF  OF  NODE(I)  (MILES)                 C
0080    C                                                                                 C
0081    C ******************************************************************************C
0082    C                                                                                 C
0083    C                              VARIABLE  NAMES                                    C
0084    C                                                                                 C
0085    C           AH=  AVERAGE  WATER  TABLE  ELEVATION  FOR A PARTICULAR  TIMESTEP (FEET)C
0086    C           AT=  AVERAGE  SAT.  THICKNESS  OF  AQUIFER  AT  A  PARTICULAR TIMESTEPC
0087    C           BEL=  ZERO  DATUM  &  TOP  OF  BEDROCK                                C
0088    C           COEFFA=  FIELD  PERMEABILITY  FOR  A  PARTICULAR  TIMESTEP            C
0089    C           DELTA=  TIMESTEP  PERIOD    (YEAR)                                    C
0090    C           ERROR=  CLOSURE  ALLOWANCE  FOR  A  TIMESTEP  (ACRE-FT)               C
0091    C           ITER=  NUMBER  OF ITERATIONS  DONE                                    C
0092    C           LIST=  NUMBER  OF  YEARS  OF  STUDY                                   C
0093    C           LMAX=  NUMBER  OF  FLOWPATHS  AT  POLYGON  INTERFACES                 C
0094    C           MAJOR=  NUMBER  OF  TIMESTEPS  WITHIN  A  YEAR                        C
0095    C           MESS=  ERROR  MESSAGE                                                 C
0096    C           MINOR=  NUMBER  OF  MINOR  TIMESTEPS  WITHIN  MAJOR                   C
0097    C           MM=  TOTAL  NUMBER  OF  TIMESTEPS  TO  BE  PERFORMED                  C
0098    C           MMAX=  NUMBER  OF  WELLS  UNDER  STUDY                                C
0099    C           SK=  NAME  OF  SUBPROGRAM  TO  COMPUTE  AVERAGE  COEFFA  &  SY        C
0100    C               FOR  A  TIMESTEP                                                  C
0101    C           SY=  STORAGE COEFFICIENT  OR  SPECIFIC  YIELD                         C
0102    C                FOR  A  PARTICULAR  TIME  PERIOD                                 C
0103    C           TIME=  INITIAL  TIMESTEP     (CALENDER YEAR)                          C
0104    C           TIME2=  FIRST  TIMESTEP    (CALENDER YEAR)                            C
0105    C           ALL  OTHER  INTEGER  &  REAL  VARIABLE  NAMES=  COUNTERS              C
0106    C                                                                                 C
0107    C ******************************************************************************C
0108          DIMENSION AS(24),H(24),PL(4),SCL(4),AQ(24),EL(4),A(24)
```

```
                                   80/80 LIST

00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890

      DIMENSION S(24),COEFF(24),QS(24),HD(24),Y(106),Q(106),SLX(24)
      DIMENSION NODE1(106),NODE2(106),B(106),D(106),P(106)
      DIMENSION N1(106),N2(106)
      DIMENSION HINIT(24)
      DIMENSION PL(24),SL(24),RELAX(24),RES(24)
      DIMENSION XNODE(44),YNODE(44),NWELLC(44),AQS(24),DRY(24)
      DIMENSION TSTEP(1,1520),DH(24,1520),HS(24,1520)
C******************************************************************************C
C                                                                              C
C          INITIALIZED INPUT DATA                                              C
C          CARD INPUT DATA                                                     C
C          DATA PREPARATION FOR MODEL                                          C
C                                                                              C
C******************************************************************************C
      PL(1)=0.0420225
      PL(2)=0.066154
      PL(3)=0.10561655
      PL(4)=0.23392525
      SCL(1)=0.07
      SCL(2)=0.11
      SCL(3)=0.17
      SCL(4)=0.25
      EL(1)=400.0
      EL(2)=300.0
      EL(3)=200.0
      EL(4)=100.0
      PEL=0.0
      KK=1
      KKK=1
      KA=1
      KB=1
      ITER=0
      DATA LMAX,MMAX /106,24/
      READ(5,101)LIST,MAJOR,MINOR  ①
      MM=LIST*MAJOR                ②
      READ(5,102)ERROR,TIME
      DO 1211 I=1,MMAX
      READ(5,1210) XNODE(I),YNODE(I),NWELLC(I)    ③
 1211 CONTINUE
      DO 131 M=1,MMAX
  131 READ(5,14)N1(M),AO(M)        ④
C
C  CHECK DATA FOR CORRECT ORDER
C
      DO 140 M=1,MMAX
      IF(N1(M)-NWELLC(M))139,140,139
  139 MESS=1
      II=N1(M)
      III=M
      JJ=NWELLC(M)
      JJJ=M
C
C  MESSAGE=1 FEED DATA FOR A WELL NOT IN CLASS C OR OUT OF ORDER
C
```

```
80/80 LIST

000000000111111111122222222223333333333444444444455555555556666666666777777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
      GO TO 10000
  140 CONTINUE
      DELTA=1./FLOAT(MAJOR*MINOR)
      DO 15 M=1,MMAX
      IF(AQ(M))640,15,15
  640 AQ(M)= AQ(M)*.2
   15 AQ(M)=-AQ(M)
      READ(5,100)(NODE1(L),NODE2(L),Y(L),L=1,LMAX)
      READ(5,104)(N1(M),BL(M),SL(M),AS(M),H(M),M=1,MMAX)
      CALL       SK(AS,H,PL,SCL,BL,COEFFA,BEL,KK,TIME,ITER,EL,A)
C
C  CHECK FOR OUT OF ORDER CARDS
C
      DO 105 M=1,MMAX
      IF(N1(M)-NWELLC(M))106,105,106
  106 MESS=2
      II=N1(M)
      III=M
      JJ=NWELLC(M)
      JJJ=M
C
C  MESSAGE=2 PHYSICAL WELL DATA FOR A WELL NOT IN CLASS C OR OUT OF ORDER
C  WELL WAS READ
C
      GO TO 10000
  105 CONTINUE
      DO 103 M=1,MMAX
  103 COEFF(M)=COEFFA
  999 DO 998 M=1,MMAX
  998 SLX(M)=SL(M)
C
C  IDENTIFY THE POSITION IN THE NWELLC ARRAY OF THE WELL NUMBERS IN THE NODE1
C  AND NODE2 ARRAYS.  STORE THIS POSITION NUMBER IN N1 AND N2
C
      DO 1400 M=1,LMAX
      IF(M-1)990,990,985
  985 IF(NODE1(M)-NODE1(M-1))990,986,990
  986 N1(M)=N1(M-1)
      GO TO 1105
  990 DO 1000 L=1,MMAX
      IF(NODE1(M)-NWELLC(L))1000,1100,1000
 1000 CONTINUE
      MESS=4
      II=NODE1(M)
      III=M
      JJ=NWELLC(L)
      JJJ=L
C
C  MESSAGE=4 NODE1 WAS NOT FOUND IN THE CLASS C WELLS
C
      GO TO 10000
 1100 N1(M)=L
 1105 DO 1200 L=1,MMAX
      IF(NODE2(M)-NWELLC(L))1200,1300,1200
```

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                                   80/80 LIST

00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
 1200 CONTINUE
      MESS=5
      II=NODE2(M)
      III=M
      JJ=NWELLC(L)
      JJJ=L
C
C  MESSAGE=5 NODE2 WAS NOT FOUND IN THE CLASS C WELLS
C
 1300 N2(M)=I
 1400 CONTINUE
      DO 108 L=1,LMAX
      M=N1(L)
      N=N2(L)
      B(L)=(BL(M)+BL(N))*.5
  989 D(L)=(SLX(M)+SLX(N))/2.-B(L)
      P(L)=Y(L)*COEFFA
  108 CONTINUE
C******************************************************************************C
C                                                                              C
C        OUTPUT OF INITIAL CONDITION DATA & HEADINGS                           C
C                                                                              C
C******************************************************************************C
      WRITE(6,200)
      WRITE(6,670)
      WRITE(6,201)(M,NWELLC(M),A(M),SL(M),BL(M),H(M),M=1,MMAX)
      WRITE(6,202)
      WRITE(6,203)(L,NODE1(L),NODE2(L),P(L),B(L),D(L),L=1,LMAX)
      WRITE(6,204) LIST,MAJOR,MINOR,ERROR,COEFFA
      TIME2=TIME+FLOAT(LIST)
      WRITE(6,205) TIME,TIME2
      DO 666 I=1,MMAX
  666 HINIT(I)=H(I)
      DO 150 L=1,LMAX
      B(L)=2.*B(L)
  150 P(L)=.5*P(L)
C******************************************************************************C
C                                                                              C
C        START OF MATH MODEL           START OF MATH MODEL                     C
C                                                                              C
C******************************************************************************C
      DO 600 LISTS=1,LIST
      DO 601 M=1,MMAX
      DRY(M)=0.
  601 AQS(M)= 0.
      JDRY =0
      DO 500 MAJORS=1,MAJOR
      ITER=0
      DO 400 MINORS=1,MINOR
    1 TIME=TIME+DELTA
      DO 2 M=1,MMAX
      HO(M)=AMAX1(BL(M),H(M))
    2 AQ(M)=AQ(M)+AQS(M)
      IDRY = 0
```

80/80 LIST

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00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
    3 DO 4 M=1,MMAX
      RELAX(M)=A(M)/DELTA
      S(M)=RELAX(M)*(AMAX1(BL(M),H(M))-HO(M))
    4 RES(M)=AQ(M)-S(M)
      ITER=ITER+1
      IF(ITER.GT.30)WRITE(6,598)
      IF(ITER.GT.30)STOP
      DO 5 L=1,LMAX
      N=N1(L)
      M=N2(L)
      Y(L)=P(L)*AMAX1(0.,H(M)+H(N)-B(L))
C
C  PREVENT FLOW FROM A DRY POLYGON
C
      IF (H(N)-H(M))701,703,711
C
C  FLOW FROM M TO N, M MUST NOT BE DRY
C
  701 IF(H(M)-BL(M))703,703,705
  703 Q(L)=0.
      GO TO 770
C
C  FLOW FROM N TO M, N MUST NOT BE DRY
C
  711 IF(H(N)-BL(N))703,703,705
  705 CONTINUE
      Q(L)=Y(L)*(H(M)-H(N))
  770 CONTINUE
      RELAX(M)=RELAX(M)+Y(L)
      RELAX(N)=RELAX(N)+Y(L)
      RES(M)=RES(M)-Q(L)
    5 RES(N)=RES(N)+Q(L)
    8 DO 12 M=1,MMAX
      RELAX(M)=1.0/RELAX(M)
      H(M)=AMAX1((H(M)+RELAX(M)*RES(M)),BL(M))
      IF(QS(M))12,9,9
    9 IF(H(M)-SL(M))11,11,10
   10 QS(M)=RES(M)
      RES(M)=0.
      H(M)=SL(M)
      GO TO 12
   11 QS(M)=0.
   12 CONTINUE
      DO 13 M=1,MMAX
      IF(ERROR-ABS(RES(M)))33,13,13
   33 IF(H(M)-BL(M))3,34,3
   34 IDRY=IDRY+1
   13 CONTINUE
      IF(IDRY)400,400,390
  390 DO 395 M=1,MMAX
      IF(H(M)-BL(M))391,391,395
  391 JDRY=1
      DRY(M)=DRY(M)+RES(M)
  395 CONTINUE
```

80/80 LIST

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00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
CARD
  400 CONTINUE
      TSTEP(1,KB)=TIME
      KB=KB+1
C******************************************************************************C
C                                                                              C
C        CALL FOR COEFFA & SY FOR A NEW TIMESTEP                               C
C                                                                              C
C******************************************************************************C
      CALL       SK(AS,H,PL,SCL,BL,COEFFA,BEL,KK,TIME,ITER,EL,A)
      IF(ITER.EQ.-1)MM=IFIX(TIME-1966.0)*4
      IF(ITER.EQ.-1)GO TO 900
  549 DO 548 I=1,MMAX
  548 HS(I,KKK)=H(I)
      DO 550 I=1,MMAX
  550 DH(I,KA)=HINIT(I)-H(I)
      KA=KA+1
      KKK=KKK+1
      QST=0.
      DO 403 M=1,MMAX
      IF(QS(M))403,403,401
  401 WRITE(6,402)M,QS(M)
      QST=QST+QS(M)
  403 CONTINUE
  500 CONTINUE
      IF(JDRY) 5010, 5010, 5000
 5000 DO 5005 M=1,MMAX
      IF(DRY(M))5003,5005,5003
 5003 DRY(M)=AQ(M)-DRY(M)*DELTA
      WRITE(6,5002)M,NWELLC(M),AQ(M),DRY(M)
 5005 CONTINUE
 5010 CONTINUE
  600 CONTINUE
C******************************************************************************C
C                                                                              C
C        END OF MATH MODEL            END OF MATH MODEL                        C
C                                                                              C
C******************************************************************************C
C                                                                              C
C        FINAL OUTPUT :     WATER LEVEL VS TIMESTEP                            C
C                           ACCUMULATIVE DRAWDOWN VS TIMESTEP                  C
C                           (PRINTED OUTPUT & PLOTS)                           C
C                                                                              C
C******************************************************************************C
  900 WRITE(6,301)
      WRITE(6,667)
      LL=1
      DO 510 L=10,MM,10
      WRITE(6,545)((TSTEP(I,J),I=1,1),J=LL,L)
      DO 529 I=1,3
  529 WRITE(6,543)
      DO 511 I=1,24
  511 WRITE(6,544)I,(HS(I,J),J=LL,L)
      DO 530 I=1,3
  530 WRITE(6,543)
```

80/80 LIST

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00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
  510 LL=LL+10
      WRITE(6,301)
      WRITE(6,668)
      NN=1
      DO 512 N=10,MM,10
      WRITE(6,545)((TSTEP(I,J),I=1,1),J=NN,N)
      DO 675 I=1,3
  675 WRITE(6,543)
      DO 513 I=1,MMAX
  513 WRITE(6,542)I,(DH(I,J),J=NN,N)
      DO 514 I=1,3
  514 WRITE(6,543)
  512 NN=NN+10
      WRITE(6,301)
      CALL PLOTS
      CALL '     APLOT(TSTEP,DH,MM)
      CALL        RPLOT(XNODE,YNODE,HINIT,HS,MM)
C******************************************************************************C
C                                                                              C
C        FORMAT  STATEMENTS                    FORMAT  STATEMENTS              C
C                                                                              C
C******************************************************************************C
   14 FORMAT(I7,F8.0)
  100 FORMAT(2(I7,1X,I7,1X,F10.2,1X),I7,1X,I7,1X,F10.2)
  101 FORMAT(3I10)
  102 FORMAT(3F13.4)
  104 FORMAT(I7,5X,F7.0,6X,F7.0,6X,F11.0,11X,F11.0)
  200 FORMAT('     MATHEMATICAL  MODEL  OF  GROUNDWATER  FLOW  IN  A  MU
     QLTILAYER  CASE'///'     24  INTERIOR  NODES  AND  106  POLYGON  CO
     QNTACT  FACES'///)
  201 FORMAT(I4,11X,I7,10X,4HAS= ,F8.1,4X,4HSL= ,F8.1,4X,4HBL = ,F8.1,4X
     C,8HHINIT = ,F8.1)
  202 FORMAT(//////7H BRANCH,4X,20HBETWEEN WELL NUMBERS 4X,19HPSEUDO-PER
     2MEABILITY,3X,17H BOTTOM ELEVATION,6X,10H THICKNESS//)
  203 FORMAT(I6,9X,I7,3X,I7,7X,3HK= ,F8.4,10X,3HB= ,F8.1,9X,3HD= ,F8.1)
  204 FORMAT(/////7H LIST =I6/8H MAJOR =I5/8H MINOR =I5/8H ERROR =F8.2/
     19H COEFFA =F7.4)
  205 FORMAT(/////16H SIMULATION FROM ,F8.2,3H TO,F8.2)
  301 FORMAT(1H1)
  402 FORMAT(5H NODE,I4,3X,4HQS= F8.1)
  405 FORMAT(/22H TOTAL SURFACE FLOW = F10.1)
  542 FORMAT(I10,10F10.5)
  543 FORMAT(1H0)
  544 FORMAT(I10,10F10.2)
  545 FORMAT('  WELL NO ',10F10.2)
  598 FORMAT('            OVERFLOW        ')
  667 FORMAT('        DISPLAY  OF  WATER  LEVEL  CORRESPOND  TO  TIME  ST
     QEP'////)
  668 FORMAT('        DISPLAY  OF  ACCUMULATIVE  DRAWDOWN  VS  TIMESTEP'/
     Q//)
  670 FORMAT(' NODE           WELL NO                   AREA    SURFACE EL
     QEV    BEDROCK ELEV    WATER LEVEL'////)
 1210 FORMAT(2F10.2,I5)
 5002 FORMAT(1H 4HNODE I5,16H STATE WELL NO. I9,31H WITH EXPECTED WITHDR
```

80/80 LIST

```
0000000001111111111222222222233333333334444444444555555555566666666667777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
     1RAWALS OF F10.0,19H ACRE FT REDUCED TO F10.0, 8H ACRE FT)
11000 FORMAT(1H ,19HTROUBLE AT MESSAGE  I4,9HWELL NO. I7,11H SUBSCRIPT
     1I4,14H AND WELL NO. I7,11H SUBSCRIPT I4)
11100 FORMAT(1H ,10F12.1)
      STOP
10000 WRITE(6,11000) MESS,II,III,JJ,JJJ
      STOP
      END
      SUBROUTINE SK(AS,H,PL,SCL,BL,COEFFA,BEL,KK,TIME,ITER,EL,A)
      DIMENSION AS(24),H(24),PL( 4),SCL(24),BL(24),EL(4),A(24)
      NLA=5
C
C        NL INDICATES THE NUMBER OF LAYERS USED IN THE MODEL
C
      NL=4
      AVH=0.0
      DO 1 I=1,24
C
C        CHECK IF WATER LEVEL HIT BEDROCK , IF SO, STOP OPERATION
C
      IF(H(I).LE.BL(I))WRITE(6,9)I,H(I),TIME
    9 FORMAT('   WELL   NO   ',I5,'   HAS   REACHED   BOTTOM   AT
     02F10.2)
      IF(H(I).LE.BL(I))ITER=-1
      IF(H(I).LE.BL(I))RETURN
    1 AVH=AVH+(H(I)-BL(I))
      AH=AVH/24.0
      AT=AH-BEL
C
C        COMPUTATIONS OF WEIGHED AVERAGE VALUES OF K & SY
C
      IF(NL.EQ.1)GO TO 23
      DO 20 I=2,NLA
      IF(I.EQ.NLA)GO TO 23
      IF (AH.GE.EL(I)) ML=I
      IF(AH. GE. EL(I)) GO TO 21
   20 CONTINUE
   23 IF(AH.GE.BEL)COEFFA=PL(NL)
      IF(AH.GE.BEL)SY=SCL(NL)
      GO TO 10
   21 COEFFA=PL(ML-1)*(AH-EL(ML))+PL(NL)*(EL(NL)-BEL)
      SY=SCL(ML-1)*(AH-EL(ML))+SCL(NL)*(EL(NL)-BEL)
      IF(ML.EQ.NL)COEFFA=COEFFA/AT
      IF(ML.EQ.NL)SY=SY/AT
      IF(ML.EQ.NL) GO TO 10
      COEFF=0.0
      SPY=0.0
      NNN=NL-ML
      DO 22 I=1,NNN
      COEFF=PL(ML)*(EL(ML)-EL(ML+1))+COEFF
      SPY=SCL(ML)*(EL(ML)-EL(ML+1))+SPY
   22 ML =ML+1
      COEFFA =(COEFF+COEFFA)/AT
      SY=(SPY+SY)/AT
```

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                                80/80 LIST

00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
CARD
C
C          COMPUTE WITHDRAWAL FROM NODES FOR A TIMESTEP
C
   10 DO 3 I=1,24
    3 A (I)=AS(I)*SY
      IF(ITER.EQ.0)RETURN
      IF(KK.GT.4)KK=1
      WRITE (6,100)TIME,KK,AH,COEFFA,SY,ITER
  100 FORMAT(1H0,'     TIME=',F10.2,'     SEASON=',I5,'     AVE  SAT  THICK
     ONESS=',F10.2/'     AVE  PERMEABILITY=',F10.6,'    AVE  SY=',F10.6,'
     0    ITERATION=',I5)
      KK=KK+1
      RETURN
      END
      SUBROUTINE APLOT(TSTEP,DH,MM)
C******************************************************************************C
C                                                                              C
C                       HYDROGRAPH  PLOTTING  ROUTINE                          C
C                                                                              C
C******************************************************************************C
      DIMENSION TSTEP(1,802),DH(24,802),X(802),Y(802)
C
C          NP INDICATES NUMBER OF  HYDROGRAPHS TO BE PLOTTED
C
      NP=24
      J=MM
      J1=J+1
      J2=J+2
      XIN=FLOAT(J/40)+2.0
      XAX=0.0
      DO 1 I=1,J
    1 X(I)=TSTEP(1,I)
      X(J1)=1970.0
      X(J2)=10.0
C
C          START  OF  PLOTTINGS
C
      DO 2 I=12,NP
      DO 3 L=1,J
    3 Y(L)=DH(I,L)
      Y(J1)=0.0
      Y(J2)=40.0
      CALL PLOTC(XAX,-11.0,-3)
      XAX=0.0
      CALL PLOTC(XAX,0.5,-3)
      CALL AXIS(0.0,0.0,'TIME YEAR',-9, XIN,0.0,X( J1),X( J2))
      CALL AXIS(0.0,0.0,'ACCUMULATIVE DRAWDOWN FT',24,10.0,90.0,Y( J1),Y
     0(J2))
      CALL LINE(X,Y,  J,1,0,64)
      FPN=FLOAT(I)
      CALL SYMBOL(1.0,9.0,0.35,'WELL ',0.0,5)
      CALL NUMBER(999.0,999.0,0.35,FPN,0.0,-1)
      CALL PLOTC(XAX,-11.0,-3)
      XAX=XIN+3
```

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                                 80/80 LIST

000000000111111111122222222223333333333444444444455555555556666666666777777777778
123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
    2 CONTINUE
C
C        END  OF  PLOTTINGS
C
      RETURN
      END
      SUBROUTINE RPLOT(XNODE,YNODE,HINIT,HS,MM)
C******************************************************************************C
C                                                                              C
C                  RESIDUAL  MAP  PLOTTING  ROUTINE                            C
C                                                                              C
C******************************************************************************C
      DIMENSION XNODE(44),YNODE(44),HINIT(24),HS(24,802),R(24, 30)
      DIMENSION TS(1,30)
C
C        NP INDICATES NUMBER OF RESIDUAL MAPS TO BE PLOTTED
C        NB IS THE TIME PERIOD THAT RESIDUAL VALUES ARE TO BE COMPUTED
C
      NB=4
      NP=MM/(NB*4)
      T=1966.0
      SCALE=2.0
      JA=2
      NA=NB*NP
      NC=NB*2
C
C        COMPUTATION OF RESIDUAL VALUES
C
      DO 1 I=1,24
    1 R(I,1)=HS(I,NB)-HINIT(I)
      DO 2 J=NC,NA,NB
      DO 5 I=1,24
      L=J-NB
    5 R(I,JA)=HS(I,J)-HS(I,L)
    2 JA=JA+1
      WRITE(6,10)NB
   10 FORMAT(20X,'DISPLAY OF ',I3,'   YEAR RESIDUAL VALUES')
      DO 12 I=1,3
   12 WRITE(6,11)
   11 FORMAT(1H0)
      DO 13 I=1,NP
   13 TS(1,I)=T+FLOAT(NB*I)
      JJ=1
      NPP=NP
      LLP=10
      LPP=0
      LP=10
  100 IF(NPP.LT.10)LLP=NPP
      IF(NPP.LT.10)LP=LLP
      DO 15 II=LP,LLP,LP
      WRITE(6,14)((TS(1,J),I=1,1),J=JJ,II)
      LPP=LPP+LP
      DO 16 I=1,2
   16 WRITE(6,11)
```

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                                  80/80 LIST

00000000011111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890
      DO 17 I=1,24
   17 WRITE(6,18)I,(P(I,J),J=JJ,II)
      DO 19 I=1,3
   19 WRITE(6,11)
   15 CONTINUE
      NPP=NP-LPP
      IF(NPP)100,100,101
  101 JJ=JJ+10
      GO TO 102
   14 FORMAT(10X,10F10.2)
   18 FORMAT(I10,10F10.3)
  100 XNODE(25)=0.0
      XNODE(26)=SCALE
      YNODE(25)=0.0
      YNODE(26)=SCALE
C
C           START  OF  PLOTTINGS
C
      XAX=0.0
      DO 3 J=1,NP
      CALL PLOTC(XAX,-11.0,-3)
      XAX=0.0
      CALL PLOTC(XAX,0.5,-3)
      CALL AXIS(0.0,0.0,'X COORDINATE MILES',-18,10.0,0.0,XNODE(25),XNOD
     QE(26))
      CALL AXIS(0.0,0.0,'Y COORDINATE MILES',18,10.0,90.0,YNODE(25),YNOD
     QE(26))
      CALL LINE(XNODE,YNODE,24,1,-1,3)
      T=T+FLOAT(NB)
      FPN=T
      CALL SYMBOL(1.0,9.0,0.35,'RESIDUAL MAP ',0.0,13)
      CALL NUMBER(999.0,999.0,0.35,FPN,0.0,-1)
      DO 4 I=1,24
      X=XNODE(I)/SCALE+0.1
      Y=YNODE(I)/SCALE+0.1
      YY=YNODE(I)/SCALE-0.1
      F=FLOAT(I)
      CALL NUMBER(X,Y,0.07,F,0.0,-1)
      CALL NUMBER(X,YY,0.07,R(I,J),0.0,3)
    4 CONTINUE
      CALL PLOTC(XAX,-11.0,-3)
      XAX=12.0
    3 CONTINUE
C
C           END  OF  PLOTTINGS
C
      RETURN
      END
//GO.PLOTOUT DD UNIT=PLOT,SPACE=(TRK,(10,10)),DISP=(,KEEP),
//     DSN=PLOT.ACT11938.PLOT46
//GO.SYSIN DD *
```

# APPENDIX B

# CARD INPUT DATA

Input data cards for the modified computer-management program listed in Appendix A are divided into six different groups. Each group represents those cards needed to accommodate a specific "READ" statement occurring in the program. The format for these cards are as follows:

### GROUP I

It consists of only one data card (general for total grid). The "READ" statement for these data occurs on line 142 in the computer-program listing.

| Column | |
|---|---|
| 8 to 10 | Number of years of intended dewatering process |
| 20 | Number of timesteps within a year |
| 30 | Number of steps within a timestep |

### GROUP II

It consists of only one data card (general for total grid). The "READ" statement for these data occurs on line 144 in the computer-program listing.

| Column | |
|---|---|
| 8 to 13 | Error limit in acre-feet |
| 28 to 36 | Starting time of dewatering in calendar year |

### GROUP III

It consists of 24 data cards (one for each node). The "READ" statement for these data occurs on line 146 in the computer-program listing.

| Column | |
|---|---|
| 6 to 10 | X coordinate in miles |
| 16 to 20 | Y coordinate in miles |
| 24 to 25 | Node number |

## GROUP IV

It consists of 24 data cards (one for each node). The "READ" statement for these data occurs on line 149 in the computer-program listing.

| Column | |
|---|---|
| 6 to 7 | Node number |
| 11 to 16 | Adjusted withdrawal in acre-feet |

## GROUP V

It consists of 36 data cards (one for every three interfaces between polygons). The "READ" statement for these data occurs on line 170 in the computer-program listing.

| Column | |
|---|---|
| 6 to 7 | Node number |
| 14 to 15 | Adjacent node number |
| 23 to 26 | Ratio of width of face in contact and length between nodes |
| 33 to 34 | Node number |
| 41 to 42 | Adjacent node number |

| Column | |
|---|---|
| 50 to 53 | Ratio of width of face in contact and length between nodes |
| 60 to 61 | Node number |
| 68 to 69 | Adjacent node number |
| 77 to 80 | Ratio of width of face in contact and length between nodes |

## GROUP VI

It consists of 24 data cards (one for each node). The "READ" statement for these data occurs on line 171 in the computer-program listing.

| Column | |
|---|---|
| 6 to 7 | Node number |
| 15 to 19 | Bottom elevation in feet |
| 28 to 32 | Surface elevation in feet |
| 43 to 49 | Area of node in acres |
| 67 to 71 | Water level elevation |

# VITA

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Master of Science

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